# BOND BEHAVIOUR OF FIBRE REINFORCED POLYMER (FRP) REBARS IN CONCRETE

by

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# Abstract

Recently, fibre reinforced polymer (FRP) rebars have been extensively used in construction instead of steel rebars due to their non-corrosive nature and high tensile strength. Bond between FRP rebars and concrete is a critical design parameter that controls the performance of reinforced concrete members at serviceability and ultimate limit states. In order to prevent a bond failure, an adequate anchorage length should be provided. The anchorage length is derived using a bond stress-slip ( $\tau - s$ ) constitutive law.

The objective of this study is to investigate the effect of different parameters such as the type of fibre, the rebar surface and the confinement provided by the transverse reinforcement on the bond behaviour of FRP rebars in concrete. Based on the analysis, a generalized bond stress-slip relationship will be developed and a new design equation for the required anchorage length of FRP rebar in concrete will be derived.

A database was created on the bond stress-slip behaviour of FRP rebars in concrete from the available literature up to 2009. The data was statistically analyzed to investigate the effect of the different parameters on the bond performance of FRP rebars.

It was observed that an increase in the confinement provided by the transverse reinforcement increased the bond strength of FRP rebars in concrete. This signifies that the presence of transverse reinforcement affects the bond behaviour of FRP rebars in concrete and hence, it should be taken into consideration while developing design equations for FRP rebars. Type of fibre and rebar surface does not affect the bond stress, but the latter affects the slip corresponding to the peak bond stress. Based on the results, a nonlinear regression analysis was performed to develop the bond stress-slip model for splitting mode of failure and a design equation for determining the development length of the FRP rebars in concrete was derived. The proposed development length equation can save about 10%-15% of the development length than that required by different code equations. This can save a considerable amount of FRP materials, which will eventually reduce the overall cost of construction and thereby, encourage the use of FRP reinforcing bars in the construction of concrete structures.

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| | |
|---|---|
| $A_{f,bar}$ | Area of longitudinal reinforcement, mm2 |
| $A_{tr}$ | Area of transverse reinforcement, mm2 |
| c | Concrete cover, mm |
| $d_b$ | Bar diameter, mm |
| $f_c'$ | Compressive strength of concrete, MPa |
| $f_F$ | Maximum stress in reinforcing bar, MPa |
| $l_{embed}$ | Embedment length of reinforcing bar, mm |
| $l_d$ | Embedment length required to develop a tensile stress of $f_F$, mm |
| n | Number of bars being developed along the plane of splitting |
| s | Spacing of transverse reinforcement, mm |
| $\tau_m$ | Peak bond stress of reinforcing bar in concrete, MPa |
| $\tau_{tr}$ | Transverse reinforcement contribution to peak bond stress, MPa |
| $s_m$ | Slip corresponding to peak bond stress, mm |
| $\alpha$ | Rebar surface modification factor for bond stress-slip curve |
| $\eta$ | Rebar surface modification factor for slip corresponding to peak bond stress |
| $\chi$ | Bar location modification factor |

# Acknowledgements

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The author also pays his deepest homage to his parents, whom he believes to be cardinal source of inspiration for all his achievement.

# Dedication

To my wife who has given me support at every step of my life!

# Chapter 1: Introduction

## 1.1 Problem Statement

In presence of corrosive environments, reinforcing steel bars in concrete structures may suffer severe deterioration due to corrosion. Therefore, it has been a primary concern for researchers and engineers to control the corrosion of steel reinforcing bars or substitute steel rebars with some alternative reinforcement which will be able to provide the desirable characteristics of steel rebars as well as to prevent corrosion. It has been found that fibre reinforced polymer (FRP) rebars have a great potential to fill such a need (Neale and Labossiére, 1992; Nanni, 1993; Nanni and Dolan, 1993; Tighiouart et *al.*, 1998). FRP reinforcing bars have several advantages over conventional reinforcing steel, namely non-corrosiveness, high tensile strength, light weight, fatigue resistance, nonmagnetic electrical insulation, small creep deformation and specific gravity (Hao *et al.*, 2006). As a result, FRP reinforcing bars have been introduced as reinforcement for different concrete structures subjected to aggressive environments such as chemical and wastewater treatment plants, sea walls, floating docks, and under water structures (Benmokrane and Rahman, 1998; Saadatmanesh and Ehsani, 1998; Dolan *et al.*, 1999; Razaqpur, 2000).

In spite of the advantages of FRP reinforcement over conventional steel reinforcement, a direct substitution between FRP and steel rebar is not possible due to various differences in the mechanical and physical properties between the two materials. The main problems that prevent the use of FRP rebars on a wide scale as a reinforcing materials for concrete structures are,

- When subjected to tensile force in the direction of fibres, FRP exhibits linear elastic behaviour up to failure. Therefore, it does not have any yield point which means it exhibits no ductility;
- The modulus of elasticity for some types of FRP, namely aramid fibre reinforced polymer (AFRP) and glass fibre reinforced polymer (GFRP) is much lower than steel, hence deflection and crack widths may control the design of reinforced concrete structures;

- The bond behaviour of FRP rebars with concrete is different than that of steel rebars due to the non-isotropic material properties and the different surface texture of the FRP rebars (ACI 440.1R-06).
- Higher cost of FRP compared to steel, lack of familiarity with the new technology and limited availability of literature contributed to the slow adaptation of FRP as concrete reinforcement (Okelo and Yuan, 2005).

The performance of a reinforced concrete member, both at the ultimate limit state (strength) and the serviceability limit state (crack and deflection), depends on the transfer of forces between the concrete and the reinforcement, which, in turn, depends on the quality of bond between the two materials. The resistance of a reinforced concrete member under flexure, shear and torsion forces is directly related to the force developed in the reinforcement. Moreover, many serviceability checks (e.g., crack width and member deflections) require evaluation of the effects of tension stiffening, which directly arises from the bond behaviour. Therefore, the development of adequate bond (or force transfer mechanism) is always a critical aspect of the structural design, regardless of the type of reinforcement (Chaallal and Benmokrane, 1993; Benmokrane *et al.*, 1996; Tighiouart *et al.*, 1998; Pecce *et al.*, 2001). As a result, considerable experimental research has been conducted to understand the bond behaviour of FRP rebars in concrete environment. Despite the numerous experimental investigations, the bond behaviour of FRP rebars with concrete is not fully understood yet. This is attributed to the complexity of the parameters influencing the bond behaviour (e.g., diameter of the rebar, concrete cover, embedment length, concrete confinement and the concrete compressive strength), and the different types and properties of the currently commercially available FRP rebars (Okelo and Yuan, 2005). Design equations have been developed for designing concrete structures reinforced with FRP rebars based on the available experimental data up to 2002. Since then considerable research has been conducted and therefore, it has become essential to assess the effects of different parameters on the bond performance of FRP rebars to update the guidelines for the design of concrete structures reinforced with FRP rebars.

## 1.2 Thesis Overview

This thesis is organized in six chapters. Chapter 1 gives an overview of the research. Chapter 2 reviews the available literature on the bond between concrete and FRP. This chapter discusses the effect of different parameters on the bond behaviour of FRP rebars in concrete, the available code equations to predict the peak bond stress (bond strength) and also, the existing formulations of bond stress-slip relationship for FRP rebars in concrete. It highlights the gaps in the available literature on the bond behaviour of FRP rebars in concrete and thereby, sets the research objectives. A brief description of the accumulated database is presented in Chapter 3. Chapter 4 presents the results of the statistical analysis of the accumulated database, along with the analytical modeling of the peak bond stress and the corresponding slip equations. The comparisons of the predicted models with the experimental results are also presented in Chapter 4. Based on these models, an equation to calculate the development length of FRP rebars is proposed to be used in design codes. Chapter 5 presents an analytical modeling of the bond stress-slip relationship based on the available database. It also presents the results from a finite element analysis for studying the effect of confinement. Chapter 6 furnishes the conclusions and the limitations of this study and recommends some future research.

# Chapter 2: Literature Review and Research Objectives

## 2.1 What is FRP

Fibre reinforced polymers (FRP) are composite materials that typically consist of strong fibres embedded in a resin matrix. The fibres provide strength and stiffness to the composite and generally carry most of the applied loads. The thermosetting matrix - typically epoxies, polyesters and vinylesters - acts to bond and protect the fibres and to provide for transfer of forces from fibre to fibre through shear stresses (ACI 440R-07). Generally, there are three types of fibres used in structural engineering applications (Figure 2.1)-glass (GFRP), carbon (CFRP) and aramid (AFRP). FRP used in construction have fibre concentration greater than 30% by volume.


**Figure 2.1 Glass, carbon and aramid fibres.**

### 2.1.1 FRP in Structural Engineering

In the last 20 years, composite materials have developed into economically and structurally viable construction material for buildings and bridges. Today, FRP are used in structural engineering in a variety of forms: reinforcement material for new concrete construction, strengthening material for existing structures, and structural members for new construction.

The FRP material can be used in new construction as internal rebars, prestressing tendons, and stay-in-place formwork. The surface of the FRP rebars are either sand coated, helically wound spiral outer surface, indented, braided, or with ribs. Figure 2.2 shows some commercially available FRP rebar with different surface textures. Extensive research has been conducted since the mid 1990s to study the behaviour of beams and slabs reinforced with various FRP rebars (ACI 440.1R-06).

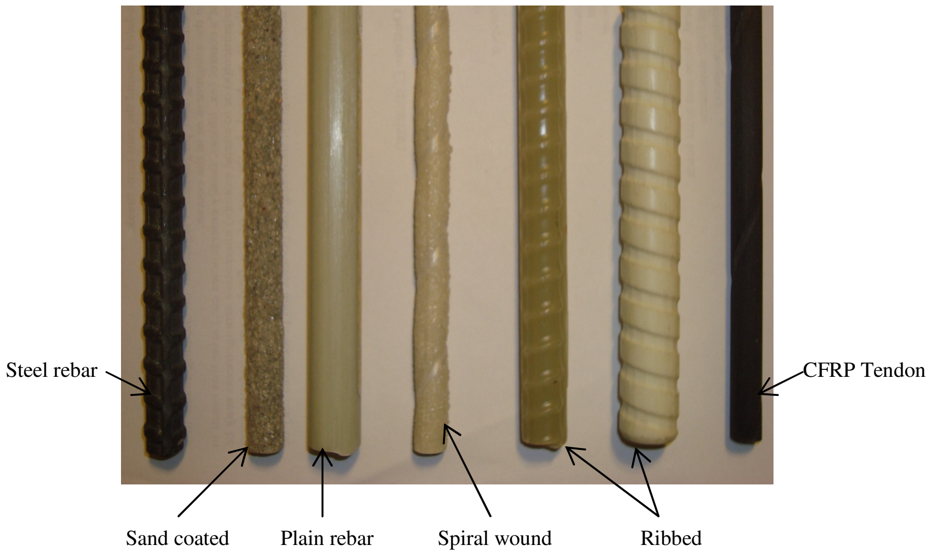



**Figure 2.2 Different types of commercially available FRP rebar.**

FRP prestressing tendons were first used in Europe in the 1980s primarily to eliminate corrosion. The use of FRP prestressing is still hindered by the fact that the conventional steel anchor could not be used due to the low transverse strength of the FRP tendons (Erki and Rizkallak, 1993; Nanni *et al.*, 1995; Soudki, 1998). FRP stay-in-place formwork has been explored for some years (Dieter *et al.*, 2002; Ringelstetter *et al.*, 2006; Ozbakkaloglu and Saatcioglu, 2007). Columns and beams made from FRP tubular shapes and filled with concrete has been gaining popularity lately (Mirmiran *et al.*, 2000; Fam and Rizkalla, 2002; Zhu, 2004; Fam *et al.*, 2005).

FRP has been used on concrete, steel, masonry and timber structures to increase their existing flexural, shear, or confinement strength. Materials used are either prestressing tendons, pre-manufactured rigid FRP strips adhesively bonded to the surface of the structure, or hand layup sheets that consists of in situ forming of FRP composite on the surface of the structural member using flexible, dry FRP sheets and a polymer resin (Figure 2.1). In the last few years, near surface mounted (NSM) method has been explored, where an FRP tendon or strip (prestressed or non-prestressed) is inserted and then bonded adhesively into a machined groove at the surface of the concrete member.

### 2.1.2 Properties of FRP

The properties of the currently available FRP systems vary significantly depending on their specific formulation, constituents, and manufacturing method. They are highly directionally dependent. The properties of the FRP composite materials are usually obtained by experimental testing of the FRP material and products. Experimental procedures are given in CSA S806, ACI 440.3 and different ASTM standards. In general, FRP has some special characteristics that make them suitable to be used in the construction industry.

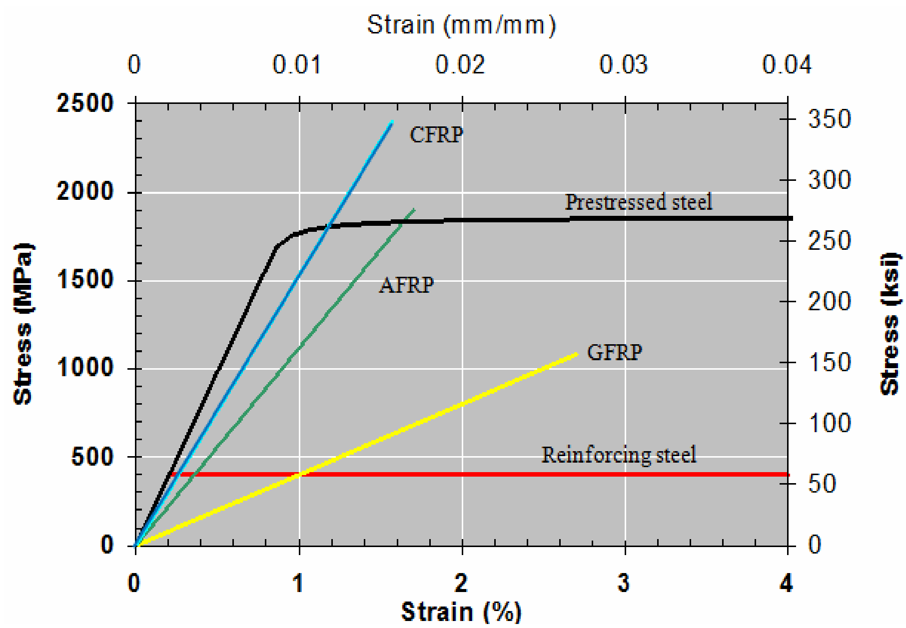



**Figure 2.3 Stress-strain plots of FRP (ACI 440R-96).**

These characteristics include-high strength, non-corrosive nature, light weight, fatigue resistant, non-magnetic, electrical insulation and small creep deformation. All FRP systems exhibit linear elastic tensile stress-strain behaviour (in the direction of the fibres). From the typical stress-strain curve shown in Figure 2.3, it is noted that FRP systems have no yielding, and except for some carbon fibre reinforced polymers (CFRP) systems, they have lower modulus of elasticity compared to steel. In Table 2.1, Table 2.2 and Table 2.3, typical properties of the FRP rebars, strips and sheets are listed respectively.

**Table 2.1 Typical properties of commercially available FRP reinforcing bars (Bank, 2006)**

| | GFRP-vinylester | CFRP-vinylester | CFRP-epoxy |
|---|---|---|---|
| Fibre volume (%) | 50-60 | 50-60 | 50-60 |
| Fibre architecture | unidirectional | unidirectional | unidirectional |
| Tensile strength, longitudinal (MPa) | 500-700 | 2070 | 2255 |
| Tensile modulus, longitudinal (MPa) | 41-42 | 124 | 145 |
| Shear strength, out of plane (MPa) | 22-27 | -- | -- |
| Bond strength (MPa) | 1.7 | 9 | -- |
| Coefficient of thermal expansion, longitudinal ($10^{-6}$ °$C^{-1}$) | 6.7-8.8 | -7.2-0 | 0.7 |
| Coefficient of thermal expansion, transverse ($10^{-6}$ °$C^{-1}$) | 22.0-33.7 | 73.8-104.4 | -- |
| Density (g/$cm^3$) | 2.1 | -- | 1.6 |

**Table 2.2 Typical properties of commercially available FRP strengthening strips (Bank, 2006)**

| | Standard modulus CFRP epoxy | High modulus CFRP epoxy | GFRP epoxy | CFRP vinylester |
|---|---|---|---|---|
| Fibre volume (%) | 65-70 | 65-70 | 65-70 | 60 |
| Fibre architecture | Unidirectional | unidirectional | unidirectional | unidirectional |
| Nominal thickness (mm) | 1.2-2.9 | 1.2 | 1.4-1.9 | 2.0 |
| Width (mm) | 50-100 | 50-100 | 50-100 | 16 |
| Tensile strength, longitudinal (MPa) | 2690-2800 | 1290 | 900 | 2070 |
| Tensile strain (max), longitudinal (%) | 1.8 | -- | 2.2 | 1.7 |
| Tensile modulus, longitudinal (MPa) | 155-165 | 300 | 41 | 131 |

## 2.2 Bond Mechanism

For an optimal design of reinforced concrete structures, the force between the reinforcement and the concrete should be transferred efficiently and reliably through the bond between the two materials. In reinforced concrete members, the transfer of forces between a reinforcing bar and concrete occurs by three mechanisms: (1) chemical adhesion between the bar and the concrete, (2) frictional forces arising from the roughness of the interface between the bar and the surrounding concrete, and (3) mechanical interlocking arising from the textures on the rebar surface (Figure 2.4). The addition of these forces can be resolved into an outward component (radial splitting force) and a shear component, parallel to the bar that is the effective bond force (Figure 2.5).

**Table 2.3 Typical properties of commercially available FRP strengthening sheets (Bank, 2006)**

| | **Standard modulus CFRP** | **High modulus CFRP** | **GFRP epoxy** |
|---|---|---|---|
| Thickness (mm) | 0.165-0.33 | 0.165 | 0.35 |
| Width (mm) | 600 | 600 | 1200 |
| Fibre architecture | Unidirectional | Unidirectional | Unidirectional |
| Tensile strength, longitudinal (MPa) | 3790 | 3520 | 1520-3240 |
| Tensile strain (max), longitudinal (%) | 1.67-1.7 | 0.94 | 2.1-2.45 |
| Tensile modulus, longitudinal (MPa) | 230 | 370 | 72 |

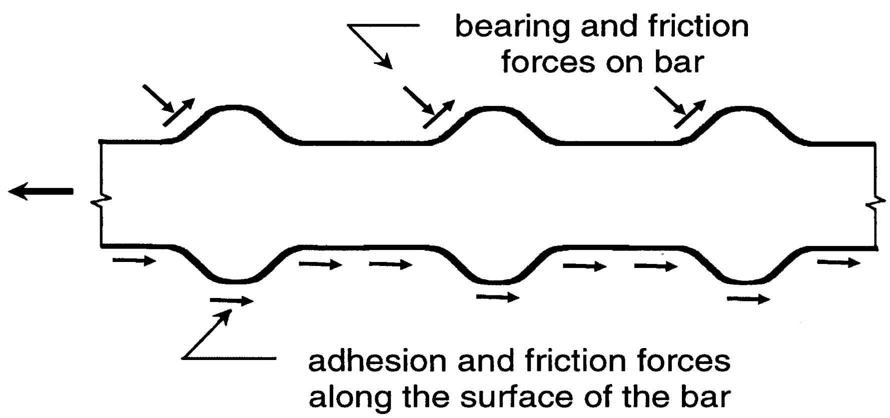



**Figure 2.4 Bond force transfer mechanism.**

To prevent bond failure, the rebar must be anchored long enough in the concrete or should have enough confinement (concrete cover or transverse reinforcement). In this case, the radial and tangential stresses developed along the bar length will be less than the concrete capacity and the bar can achieve its design tensile strength. In such cases, the failure is initiated by different failure mode (concrete crushing, shear, bar rupture). If adequate anchorage length of the rebar or sufficient confinement to the concrete is not provided, then radial and shear forces may be higher than the concrete capacity which can lead to bond failure (ACI 408R-03).

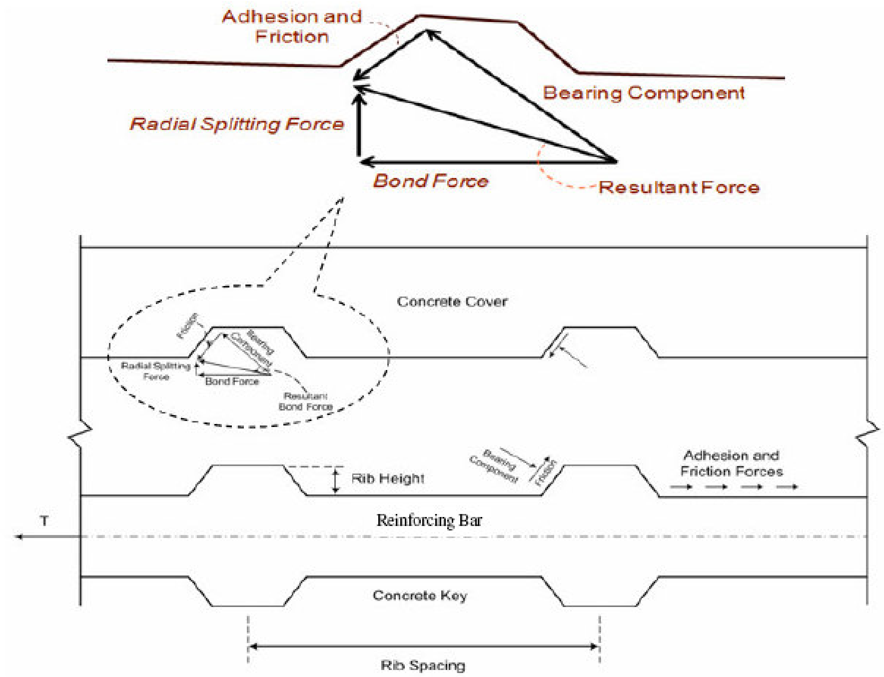
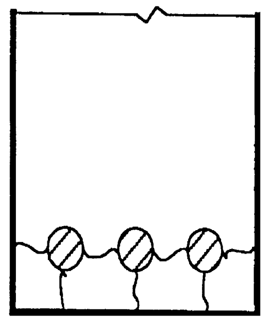



**Figure 2.5 Bond and radial forces.**

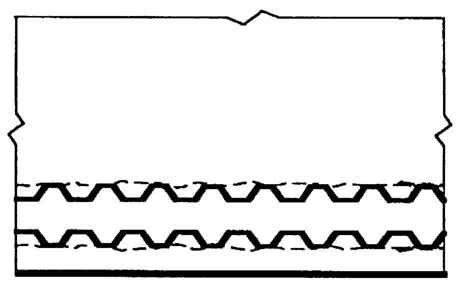
Bond failures are divided into either pullout failure or splitting failure:

**Splitting Failure:** This type of failure occurs when the concrete surrounding the reinforcing bar splits without reinforcing bar rupturing (Figure 2.6a). As reinforcing bars are loaded, the bars exert radial pressure on the surrounding concrete. If the surrounding concrete and/or the transverse reinforcement are not enough to resist this pressure, a splitting crack initiates at the concrete-rebar interface, and propagates towards the surface leading to the failure of the concrete by concrete cover splitting. Splitting failure results in cracking in plane that are both perpendicular and parallel to the reinforcement (Figure 2.6a).

**Pullout Failure:** This type of failure occurs when the bar pulls out of the concrete without concrete splitting or without bar rupturing (Figure 2.6b). This happens when the radial forces from the bar being loaded are lower than what the surrounding concrete and/or transverse reinforcement can resist, but tangential forces are higher compared to the resistance of the concrete. Pullout failure results in shearing along a surface at the top of the ribs around the bars (Figure 2.6b).



**(a) Cross-sectional view of a concrete member showing splitting cracks between bars and through the concrete cover**



**(b) Side view of a member showing shear crack and/or local concrete crushing due to bar pullout**

**Figure 2.6 Cracking and damage mechanisms in bond.**

Both bond failures are associated with slip of the rebar relative to the concrete. However, pullout failure occurs at higher bond strength than the splitting failure as the concrete is well confined and therefore, the radial splitting cracks need more energy to reach the outer surface of the concrete. Bond stress-slip relationship can be a good way to represent the bond behaviour of reinforcing bar with the concrete. It also helps in determining the required anchorage length to achieve the desired strength of the reinforcing bar. Figure 2.7 shows the bond stress-slip envelope for the pull out and the splitting failure for steel rebar. Both the splitting failure and pullout failure envelopes consist of four phases that explain the bond behaviour during static loading. As loads are applied, the initial stiffness of the bond in a splitting bond failure is similar to that of a pullout failure. The first phase of the bond in a splitting failure ends when an increase in the residual stress component of the bond force results in the development of splitting tensile cracks. Once a splitting crack develops the behaviour of the bond stress-slip relation deviates from the pull out behaviour due to the decrease in the bond stiffness as the crack propagates in the concrete cover. The second phase of the bond in a splitting failure ends when the crack has expanded to the surface and the splitting of the concrete cover takes place. This indicates a complete deterioration of the bond ($s_{max}$, $u_{max}$). On the other hand, the second phase of the bond in a pullout failure is a constant bond following the peak bond stress ($u_1$). The third phase of the bond behaviour for both splitting and pullout failures shows a significant drop in the bond stress (Figure 2.7). The fourth phase of the bond in a pullout failure is a constant bond and in a splitting failure, it is a decreasing branch which ends at zero bond due to the expansion of the splitting cracks in the concrete (Harajli *et al.*, 2004). However, while both the bond failures are brittle and should be avoided, splitting failure is more common for the development length ($l_d > 30d_b$) and the concrete cover ($d_b \le c \le 3d_b$) used in practice.

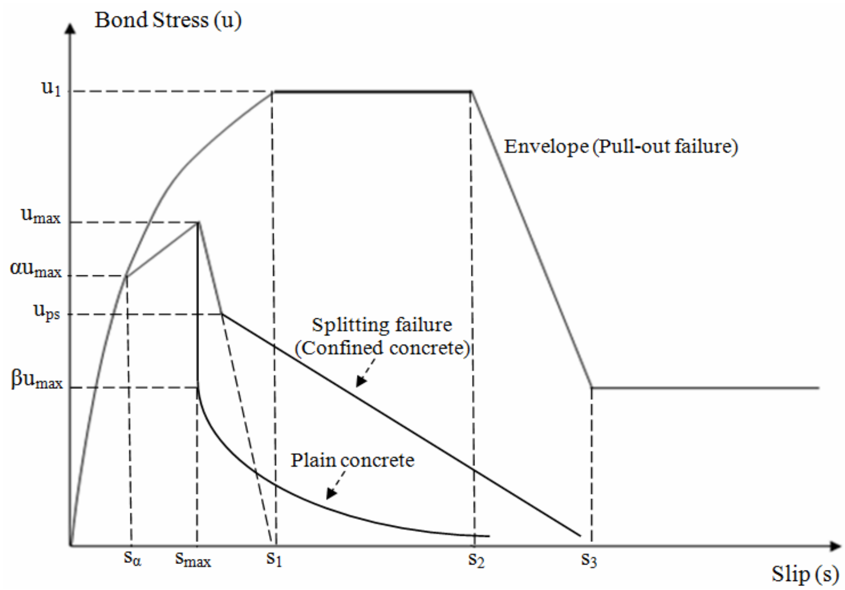



**Figure 2.7 Bond stress versus slip (Harajli, Hamad and Rteil, 2004).**

### 2.2.1 Bond Test Specimens

Two types of tests are conducted to measure the bond strength of reinforcing bars: pullout tests (Figure 2.8a) and beam tests (Figure 2.8b, c, d), both of which give different values. Bond strength from beam tests is typically found to be lower than from pullout tests (ACI 408R-03). This is because in the pullout tests, the splitting of the concrete is avoided due to the absence of local bending on the bar, a higher thickness of the concrete cover and the confining action of the reaction plate on the concrete specimen (i.e. the concrete surrounding the reinforcing bars is in compression). Alternatively, in the beam tests, the concrete surrounding the reinforcing bars is in tension, which varies along the span length and leads to cracking under low stresses and reduction in the bond strength. Thus, the pullout tests give an unrealistic bond stress values which can be considered as an upper-bound value for the bond stress-slip performance of FRP bars. That is why beam tests are more realistic than the pullout tests in simulating the real behaviour of concrete members in flexure (Tighiouart et *al.*, 1998).

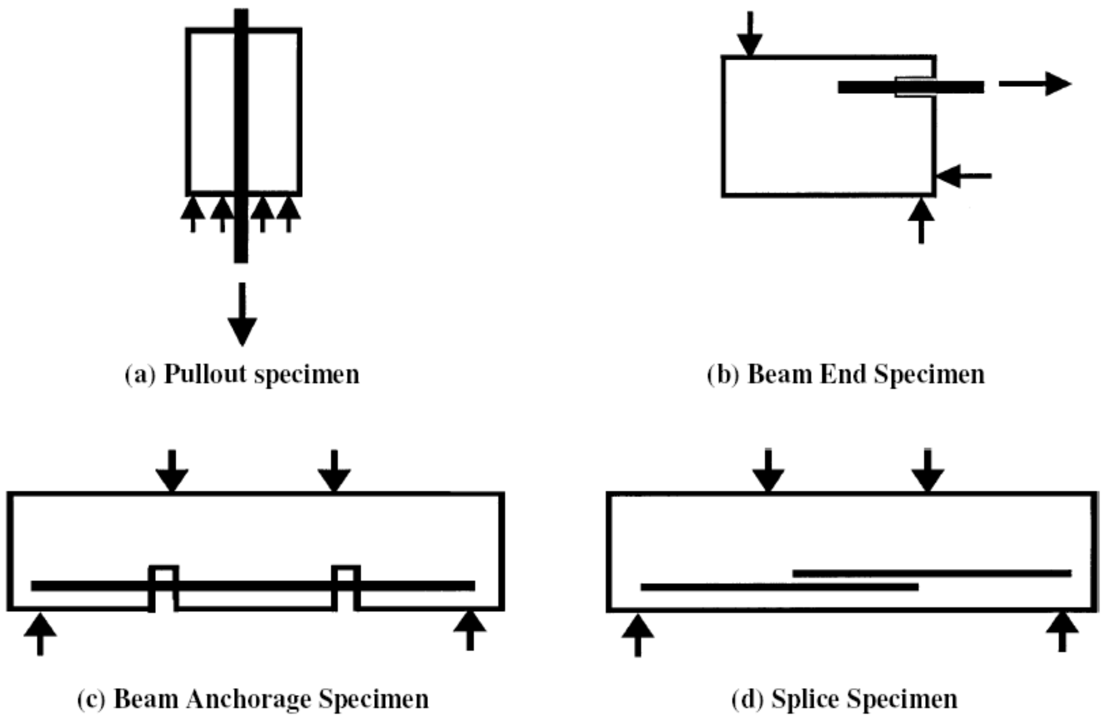



**Figure 2.8 Schematic of bond test specimens.**

### 2.2.2 Bond Behaviour of Steel Rebars

When the surface adhesion is lost, the steel reinforcing bar moves with respect to the surrounding concrete, while bearing forces on the ribs and friction forces on the ribs and the barrel of the bar are mobilized. It has been observed that after initial slip of the bar, most of the force is transferred by bearing. The compressive bearing forces on the ribs increase the value of the friction forces. As the slip increases, friction on the barrel of the reinforcing bar is reduced, leaving the forces at the contact faces between the ribs and the surrounding concrete as the principal mechanism of force transfer (ACI 408R-03). Friction, however, especially between the concrete and the bar ribs plays a significant role in the force transfer. Friction also plays an important role for plain bars (that is, with no ribs), with slip-induced friction resulting from transverse stresses at the bar surface caused by small variations in bar shape and minor, though significant, surface roughness.

### 2.2.3 Bond Behaviour of FRP Rebars

Bond behaviour of FRP bars with concrete is not the same as that of steel bars because of marked differences in force transfer and failure mechanisms of steel and FRP bars (Faza and GangaRao, 1990; Faza, 1991). This is attributed to the difference in the material properties and the interaction mechanisms of concrete and reinforcement (Chaallal and Benmokrane, 1993). The most fundamental difference is that steel is an isotropic, homogeneous, and elasto-plastic material, whereas FRP is anisotropic, non-homogeneous and linear elastic material. The anisotropy of the FRP bar results from the fact that its shear and transverse properties are dependent on both the resin and the fibre type and direction, even though the longitudinal properties are dominated by fibres (Cosenza *et al.*, 1997). Since material anisotropy leads to different physical and mechanical properties in both longitudinal and transverse directions, the anisotropic nature of the FRP materials need to be accounted for in the development of design equations and in the understanding of failure mechanisms (GangaRao *et al.*, 2001). The mechanical properties of the steel and the FRP reinforcing bars are qualitatively and quantitatively different from each other (JSCE, 1997). Also, FRP bars produced by different manufacturers are different in that they involve different manufacturing process for the outer surface and significant differences in material properties in the longitudinal and transverse directions. Moreover, the outer surface texture of the FRP rebars are created by using either epoxy, fibres or sand coating which make the rebars non-homogeneous and reduces the bond performance. Therefore, it has been observed that for FRP rebars, chemical adhesion and friction are the primary bond mechanisms (Daniali, 1992; Ehsani *et al.*, 1993; Larralde and Silva-Rodriguez, 1993; Benmokrane *et al.*, 1996). Figure 2.2 shows different types of commercially available FRP rebars along with a steel rebar.

## 2.3 Factors Affecting Bond Behaviour of FRP Rebar in Concrete

Considerable experimental research has been conducted to understand the bond behaviour of FRP rebars in concrete. This includes tests on beam and pullout specimens with different types and sizes of rebars (Daniali, 1990; Faza, 1991; Ehsani *et al.*, 1993, 1996; Kanakubo *et al.*, 1993; Makitani *et al.*, 1993; Benmokrane et *al.*, 1996; Cosenza *et al.*, 1996, 1997, 1999; Tepfers *et al.*, 1998; Tighiouart *et al.*, 1998, 1999; Shield *et al.*, 1997, 1999; Mosley, 2000; Pecce et *al.*, 2001; Defreese and Wollmann, 2002; Aly *et al.*, 2005, 2006, 2007; Okelo, 2007; Rafi *et al.*, 2007; Baena *et al.*, 2009). Research indicates that the bond behaviour of FRP rebars in concrete is influenced by several factors. Some of the important parameters that seem to affect the bond performance of FRP rebars in concrete are explained in the following sections.

### 2.3.1 Compressive Strength of Concrete

As discussed in section 2.2, both splitting and pullout mode of failures are dependent on the tensile and shear strength of the concrete, which in turn, is dependent on the compressive strength of concrete. It has been reported that the tensile strength of concrete is approximately proportional to the square root of the compressive strength of concrete ($\sqrt{f_c'}$) (ACI Committee 408, 1992). Hence, bond strength should be related to $\sqrt{f_c'}$. Regression analysis on different experimental results showed that for bond failure of FRP rebars in concrete, a better correlation exists between the bond strength and $\sqrt{f_c'}$ (Pleimannn, 1987, 1991; Faza and GangaRao, 1990; Ehsani *et al.*, 1996; Okelo and Yuan, 2005; ACI 440.1R-06; Okelo, 2007). Ehsani *et al.* (1995) performed investigation to determine the effect of concrete strength on the bond behaviour of FRP rebars in concrete. It was observed that with an increase in the concrete strength, the bond stress of FRP bars increased slightly. Also, the initial stiffness of the bond stress-slip curve increased and the slip decreased. Hattori *et al.* (1995) tested the bond performance of AFRP bars and noticed that the maximum bond stress is dependent on the compressive strength of concrete. Makitani *et al.* (1993), Benmokrane *et al.* (1996) and Tighiouart *et al.* (1998) investigated the effect of concrete strength on the bond behaviour of FRP rebars in concrete based on beam bond tests and it was concluded that the bond strength increase is proportional to the square root of the compressive strength of concrete.

Results from pullout tests also indicated that the mode of failure during bar pullout depends on the compressive strength of concrete. For concrete strength, $f_c' > 30$ MPa, bond strength of FRP rebars do not depend on the compressive strength of concrete, since in such cases the failure interface occurs at the surface of the FRP rebar. On the contrary, for low strength concrete (around 15 MPa), the compressive strength of the concrete directly influences the bond performance of FRP rebars, because in such cases the failure interface takes place in the concrete matrix (Karlsson, 1997; Tepfers *et al.*, 1998; Achillides and Pilakoutas, 2004; Baena *et al.*, 2009).

### 2.3.2 Concrete Cover

Concrete cover provides confinement to the rebars which increases the bond strength (Ehsani *et al.*, 1993; Kanakubo *et al.*, 1993; Defreese and Wollmann, 2002; Aly and Benmokrane, 2005). Therefore, the bond failure mechanism of FRP bars in concrete is influenced by the concrete cover around the reinforcing bar by virtue of its confining effect. ACI 440.1R-06 stated that bond failure occurs through splitting of the concrete when the member does not have adequate concrete cover. On the other hand, when sufficient concrete cover is provided, splitting failure is prevented or delayed. Then the system usually fails by shearing along a surface at the top of the ribs around the bars, resulting in a pullout failure. This indicates that the bond failure mode of a reinforced concrete member depends on the concrete cover. Ehsani *et al.* (1996) carried out an investigation on 48 beam specimens with GFRP rebars. It was observed that when the specimen had concrete cover of one bar diameter ($c = 1d_b$), splitting failure occurred, whereas pullout failure or rebar fracture occurred when the specimens had concrete cover of two bar diameters or more ($c > 2d_b$). It is worth mentioning here that the side concrete cover is more effective in increasing the bond strength than the bottom concrete cover and it is recommended not to increase the bottom concrete cover such that it exceeds the side concrete cover (Aly *et al.*, 2006). Aly *et al.* (2006) performed an investigation on six full-scale beams to study the effect of concrete cover on the bond strength of tensile lap splicing of GFRP rebars. In this study, the concrete cover was varied between one and four bar diameters ($d_b \leq c \leq 4d_b$) and it was observed that the bond strength increased by 27% as the concrete cover increased from one to four bar diameters. Moreover, it was noted that the effect of concrete cover on bond strength was nonlinear.

### 2.3.3 Bar Diameter

The effect of bar diameter on the bond resistance of FRP rebars in concrete have been investigated experimentally by Faza and GangaRao (1990), Larrard *et al.* (1993), Larralde and Silva-Rodriguez (1993), Nanni *et al.* (1995), Benmokrane *et al.* (1996), Tighiouart *et al.* (1998), Defreese and Wollmann (2002), Achillides and Pilakoutas (2004), Aly *et al.* (2006), Okelo

(2007) and Baena *et al.* (2009). The experimental investigations revealed the same results obtained for steel rebar i.e. the bond strength of FRP bars is increased with decrease in the bar diameter. It has been reported that larger diameter bars loose their adhesive bond earlier (Achillides and Pilakoutas, 2004). Tighiouart *et al.* (1998) and Hao *et al.* (2006) explained the cause of this decrease in bond strength with increased bar diameter. They stated that when the diameter of the bar is larger, more bleeding water is trapped beneath the rebar. As a result, there is a greater possibility of creating voids around the rebar which will eventually decrease the contact surface between the concrete and the rebar and thereby, reduces the bond strength.

### 2.3.4 Embedment Length

The effect of the embedment length on the maximum average bond stress of FRP bars in concrete was studied by Makitani *et al.* (1993), Nanni *et al.* (1995), Benmokrane *et al.* (1996), Shield *et al.* (1997), Tighiouart *et al.* (1998, 1999), Cosenza *et al.* (1999), Pecce *et al.* (2001) and Aly *et al.* (2006). It was reported that the maximum average bond stress value decreased with an increase in the embedment length. Steel bars showed the same results. This was explained due to the non-linear distribution of the bond stress along the length of the reinforcing bar. As the embedment length increases, the stress is distributed over a longer length and hence, the bond strength decreases. It was also noticed that the initial bond stiffness of the FRP bars was also influenced by the embedment length. Ehsani *et al.* (1995) reported that with an increase in the embedment length, there is an increase in the tensile load and the initial stiffness of the bond stress-slip curve. Moreover, it was found that the rate of bond stress increase is greater for smaller embedment lengths than for longer lengths and this was attributed to the non-linear distribution of bond stresses on the bar (Achillides and Pilakoutas, 2004). Okelo (2007) carried out an investigation on the bond behaviour of GFRP and CFRP bars and it was observed that the actual pullout of the rebar occurs when the embedment length is short, compressive strength of concrete is low and the rebar size is small. On the contrary, when the embedment length is long and compressive strength of concrete is high, the failure takes place by rebar fracture, concrete cover splitting or shear compression failure of the concrete.

### 2.3.5 Bar Cast Position

The effect of bar casting position on the bond behaviour of FRP rebars in concrete was investigated by Chaallal and Benmokrane (1993), Ehsani *et al.* (1993), Rossetti *et al.* (1995), Benmokrane and Masmoudi (1996), Tighiouart *et al.* (1998) and Wambeke (2003). It was observed that during the placement of concrete, air, water and fine particles migrate upward through the poured concrete and get trapped under the rebar. This phenomenon decreases the contact surface between concrete and rebar and thus causes a significant drop in the bond strength under the horizontal reinforcement placed near the top of the pour. Tests have shown that the bond strength of top cast bars is about 66% of that of the bottom cast bars (Ehsani *et al.*, 1993). A decrease in the bond strength will increase the required development length of the FRP bars and hence, a modification factor is needed for calculating the required development length for top rebars. Chaallal and Benmokrane (1993) proposed a modification factor of 1.1 for top bars from pullout tests. A modification factor of 1.3 was recommended by the ACI guide (ACI 440.1R-03) based on the recommendations of Tighiouart *et al.* (1999). However, this modification factor was refined with more experimental data by Wambeke and Shield (2006) and ACI 440.1R-06 recommended a top bar modification factor of 1.5. CSA S806-02 also recommended a top bar modification factor of 1.3.

### 2.3.6 Type of Fibres

Tighiouart *et al.* (1998) found that GFRP bars show less bond strength compared to the steel rebars and this is attributed to the difference in the surface deformations of the two types of bars. This was in agreement with the study of Benmokrane *et al.* (1996) who found that bond strength of GFRP reinforcing bars was 60-90% of that of the steel reinforcing bars depending on the bar diameter. Rafi *et al.* (2007) and Okelo (2007) carried out an investigation on CFRP bars by using beam bond specimens and found that bond strength of CFRP bars was about 85% of that of the deformed steel bars. Similar results were also obtained from pullout tests in normal strength concrete, where, the bond strengths of GFRP reinforcing bars varied from 73-96% of that of the steel reinforcing bars, depending on the bar diameter and the embedment length (Larralde and Silva-Rodriguez, 1993). This was also confirmed by Achillides and Pilakoutas (2004), who found that GFRP and CFRP bars developed 72% of the steel's bond strength. It was also observed from their experimental results that GFRP and CFRP bar exhibited the same bond strength. Wambeke and Shield (2006) gathered all the bond test data up to 2002 and after a comprehensive analysis of the database, it was concluded that the type of fibres does not seem to affect the bond strength of FRP rebars in concrete. According to CSA S806-02, CFRP and GFRP gives the same bond strength, but AFRP shows lower bond strength in comparison to CFRP and

GFRP. Based on that, CSA S806-02 specifies factors (1.0 for CFRP and GFRP; 1.25 for AFRP) to account for the effect of type of fibres during the calculation of the development length.

### 2.3.7 Type of Rebar Surface

FRP reinforcing bars are produced with different types of surface deformations such as sand coated, spiral wrapped, helical lugged/ribbed and indented (Figure 2.2). It was observed that deformed bars produce much better bond performance than plain bars due to the mechanical interlocking between the surface texture and the concrete (Faoro, 1992; Makitani *et al.*, 1993; Al-Zahrani, 1995; Nanni *et al.*, 1995; Rossetti *et al.*, 1995; Cosenza *et al.*, 1997). CSA S806-02 specifies different factors for different rebar surfaces for evaluating the development length of FRP rebars (1.0 for surface roughened or sand coated or braided surfaces; 1.05 for spiral pattern surfaces or ribbed surfaces; 1.8 for indented surfaces). However, Wambeke and Shield (2006) concluded based on the analysis of a database of 269 beam-type specimens, that rebar surface does not appear to affect the bond strength of FRP rebars in concrete. This was confirmed by Mosley *et al.* (2008), who performed investigation on the bond behaviour of AFRP and GFRP bars by using beam splice tests and concluded that the surface texture does not significantly affect the bond strength or crack width of the beams. However, Baena *et al.* (2009) carried out 88 pullout tests on FRP bars and concluded that when the failure is not occurring at the concrete matrix, rebar surface treatment has significant influence on the bond strength. From the above discussion, it can be concluded that no definite trend has been established for the effect of rebar surface on bond strength.

### 2.3.8 Transverse Reinforcement

Transverse reinforcements confine the concrete and thereby, should increase the bond strength of the reinforcing bars in concrete. Studies on bond behaviour of steel reinforcement have demonstrated that the presence of transverse reinforcement confines the developed and spliced bars by limiting the progression of splitting cracks and, thus, increasing the bond force required to cause failure (Tepfers, 1973; Orangun *et al.*, 1977; Darwin and Graham, 1993a, b). An additional increase in the transverse reinforcement results in an increase in the bond force that eventually converts a splitting failure to a pullout failure. Additional transverse reinforcement, above that needed to cause the transition from a splitting to a pullout failure, becomes progressively less effective, eventually providing no increase in the bond strength (Orangun *et* *al.*, 1977). However, little research has been done so far, on the effect of confinement for the transverse reinforcements on the bond behaviour of FRP rebars in concrete. In Wambeke and Shield's (2006) study, only 19 beam-type specimens (out of 269 specimens) had transverse reinforcements and the analysis of the database showed that the transverse reinforcement does not affect the bond strength of FRP rebars in concrete. Darwin *et al.* (1996) found that confining steel bars with a high relative rib area had more of a beneficial increase in the bond force over the same-size steel bars with moderate relative rib area. The counterargument was proposed in Wambeke and Shield's (2006) study. The GFRP bars have a very low relative rib area and, therefore, the presence of confinement may not increase the average bond stress. However, it was recommended to investigate the effect of confinement on bond strength of FRP rebar in concrete upon availability of more data.

## 2.4 Evaluation of Bond Strength

Bond strength is defined as the maximum local horizontal shear force per unit area of the bar perimeter. For a rebar embedded in concrete with a length $l_{embed}$, equilibrium condition can be established. Assuming a uniform distribution of stress, the force on the rebar is resisted by an average bond stress, $\tau_f$, acting on the surface of the rebar (Figure 2.9). Hence, the following relationship can be derived:

$$\tau_f \pi d_b l_{embed} + A_{f,barf} f_F = A_{f,bar}\left(f_F + \Delta f_F\right) \qquad \text{Equation 2.1}$$

where, $\tau_f$ = average bond stress (MPa); $d_b$ = diameter of the rebar (mm); $l_{embed}$ = embedment length of the rebar (mm); $f_F$ = tensile stress of the rebar (MPa); $A_{f,bar}$ = area of one rebar (mm$^2$). From Equation 2.1, the bond strength can be expressed as

$$\tau_f = \frac{A_{f,bar}\Delta f_F}{\pi d_b l_{embed}} = \frac{d_b \Delta f_F}{4 l_{embed}} \qquad \text{Equation 2.2}$$

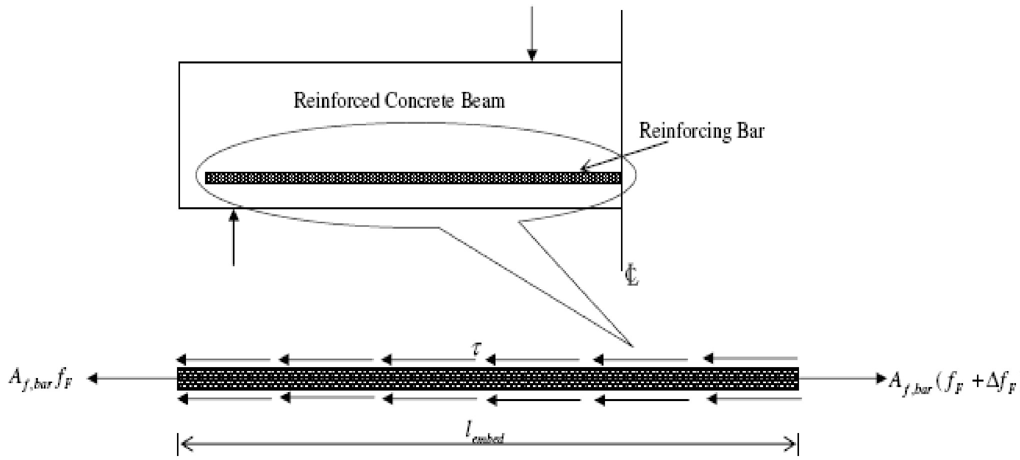



**Figure 2.9 Transfer of force through bond.**

## 2.5 Bond Strength and Development Length Equations in Design Codes

The embedment length required to prevent bond failure is referred to as the development length of the reinforcing bars. Design codes always specify the development length required to develop the design stress in the rebar because it is easier to implement by engineers. However, development length can be related to the bond strength by using Equation 2.2.

### 2.5.1 CSA S806-02

Canadian Standards Association (CSA S806-02) recommends the use of the following equation to determine the development length for the FRP rebars

$$l_d = 1.15 \frac{K_1 K_2 K_3 K_4 K_5}{d_{cs}} \frac{f_F}{\sqrt{f_c'}} A_{f,bar} \qquad \text{Equation 2.3}$$

where, $l_d$ = development length of FRP bar (mm); $A_{f,bar}$ = rebar cross-sectional area (mm$^2$); $d_{cs}$ = smallest of the distance from the closest concrete surface to the center of the bar being developed or two-thirds the c-c spacing of the bars being developed (mm) $d_{cs} \leq 2.5 d_b$ ; $f_F$ = required tensile stress in the rebar (MPa); $f_c'$ = compressive strength of concrete (MPa); $K_1$ = bar location factor (1.3 for horizontal reinforcement placed so that more than 300 mm of fresh concrete is cast below the bar; 1.0 for all other cases); $K_2$ = concrete density factor (1.3 for structural low-density concrete; 1.2 for structural semi-low-density concrete; 1.0 for normal density concrete); $K_3$ = bar size factor (0.8 for $A_b \leq 300\,\text{mm}^2$; 1.0 for $A_b > 300\ \text{mm}^2$); $K_4$ = bar fibre factor (1.0 for CFRP and GFRP; 1.25 for AFRP); $K_5$ = bar surface profile factor (1.0 for surface roughened or sand coated or braided surfaces; 1.05 for spiral pattern surfaces or ribbed surfaces; 1.8 for indented surfaces).

Substitution of Equation 2.3 into Equation 2.2 yields the following expression for the average bond strength

$$\tau_f = \frac{d_{cs}\sqrt{f_c'}}{1.15(K_1K_2K_3K_4K_5)\pi d_b} \qquad \text{Equation 2.4}$$

From Equation 2.4, it is seen that according to CSA S806 (2002), bond strength is a function of the concrete cover, the concrete strength, the bar diameter, the bar surface profile, the fibre type, bar location and concrete density.

### 2.5.2 CSA S6-06

According to the Canadian Highway Bridge Design Code (CSA S6-06), the expression for the development length of steel rebar was modified for FRP rebar and it is expressed as follows:

$$l_d = 0.45\frac{k_1k_4}{\left[d_{cs} + K_{tr}\dfrac{E_{FRP}}{E_s}\right]}\left[\frac{f_F}{f_{cr}}\right]A_{f,bar} \qquad \text{Equation 2.5}$$

where, $l_d$ = development length of FRP bar (mm); $A_{f,bar}$ = rebar cross-sectional area ($\text{mm}^2$); $d_{cs}$ = smallest of the distance from the closest concrete surface to the center of the bar being developed or two-thirds the c-c spacing of the bars being developed (mm); $k_1$ = bar location factor; $k_4$ = bar surface factor; $K_{tr}$ = transverse reinforcement index (mm) = $\frac{A_{tr}f_y}{10.5sn}$; $A_{tr}$ = area of transverse reinforcement normal to the plane of splitting through the bars (mm²); $f_y$ = yield strength of transverse reinforcement (MPa); $s$ = center to center spacing of the transverse reinforcement (mm); $n$ = number of bars being developed along the plane of splitting; $E_{FRP}$ = modulus of elasticity of FRP bar (MPa); $E_s$ = modulus of elasticity of steel (MPa); $f_F$ = specified tensile strength of FRP bar (MPa); $f_{cr}$ = cracking strength of concrete (MPa).

Substitution of Equation 2.5 into Equation 2.2 gives expression for average bond strength as

$$\tau_f = \frac{f_{cr}\left(d_{cs} + K_{tr}\frac{E_{FRP}}{E_s}\right)}{0.45\pi d_b k_1 k_4} \qquad \text{Equation 2.6}$$

Thus, in CSA S6-06, the equation to determine the development length for FRP bars has been obtained by simply multiplying the transverse reinforcement index for steel bars ($K_{tr}$) with the modular ratio $\left(\frac{E_{FRP}}{E_s}\right)$. However, Equation 2.6 shows that CSA S6-06 considered bond strength as a function of the concrete strength, the concrete cover, the concrete confinement provided by transverse reinforcement, the bar surface and the bar diameter.

### 2.5.3 JSCE Recommendation

The Japanese Design Code (JSCE, 1997) modified the expression for the development length of steel rebar and recommended the following equation for evaluating the required development length ($l_d$) of FRP rebars in concrete for splitting mode of failure, provided that $l_d$ can not be less than $20d_b$.

$$l_d = \alpha_1 \kappa \frac{f_d}{4 f_{bod}} d_b \qquad \text{Equation 2.7}$$

where, $f_d$ is the design tensile strength of the reinforcement; $\kappa$ is a top bar modification factor that takes a value of 1 if there is less than 300 mm (12 in.) of concrete cast below the bar; $d_b$ is the bar diameter (mm); and $f_{bod}$ is the design bond strength of concrete which is given by the following expression

$$f_{bod} = \frac{0.28\alpha_2 f_c'^{2/3}}{1.3} \leq 3.2\ \text{N/mm}^2 \qquad \text{Equation 2.8}$$

where, $f_c'$ is the compressive strength of concrete (MPa); and $\alpha_2$ is the modification factor for bond strength ($\alpha_2$ = 1 when the bond strength is equal to or greater than that of deformed steel bar, otherwise $\alpha_2$ shall be reduced according to the test results). The factor $\alpha_1$ is a confinement modification factor determined as follows:

$\alpha_1 = 1.0$ (where $k_c \le 1.0$);

$\alpha_1 = 0.9$ (where $1.0 < k_c \le 1.5$);

$\alpha_1 = 0.8$ (where $1.5 < k_c \le 2.0$);

$\alpha_1 = 0.7$ (where $2.0 < k_c \le 2.5$);

$\alpha_1 = 0.6$ (where $k_c > 2.5$);

where

$$k_c = \frac{c}{d_b} + \frac{15A_t}{sd_b} \cdot \frac{E_t}{E_s} \qquad \text{Equation 2.9}$$

where, $c$ is the smaller of the bottom clear cover of main reinforcement or half of the clear space between reinforcement being developed; $A_t$ is the area of transverse reinforcement; $s$ is the spacing of transverse reinforcement; $E_t$ is the Young's modulus of elasticity for the transverse reinforcement; and $E_s$ is the Young's modulus of elasticity for steel.

It can be observed that according to the Japanese design recommendation, the design bond strength or development length of the FRP rebar in concrete is a function of the concrete strength, the concrete cover, the bar location and the concrete confinement provided by the transverse reinforcement.

### 2.5.4 ACI 440.1R-06

The bond strength equation of FRP rebars to concrete available in ACI 440.1R-06 is as follows (in SI units):

$$\frac{\tau}{\sqrt{f_c'}} = 0.33 + 0.025\frac{c}{d_b} + 8.3\frac{d_b}{l_{embed}} \qquad \text{Equation 2.10}$$

where, $\tau$ is the FRP rebar-concrete bond strength; $f_c'$ is the compressive strength of concrete; $c$ is the lesser of the cover to the center of the bar or one-half of the center-to-center spacing of the bars being developed; $d_b$ is the bar diameter; and $l_{embed}$ is the embedment length of the bar in concrete. This equation was developed from the study by Wambeke and Shield (2006) in which a consolidated database of 269 beam bond tests was created from the published literature up to 2002. The database was limited to beam end tests, notch-beam tests, and splice tests with the majority of the bars represented in the database composed of GFRP (240 out of 269). Three types of rebar surfaces were considered-sand coated, spiral wrap of fibres and helical lug pattern. The diameter of the bars ranged between 13 mm to 29 mm. The compressive strength of concrete ranged from 28 to 45 MPa. Of the 240 beam bond specimens with GFRP bars, 75 failed by splitting of concrete, 94 by rebar pullout and 71 had tensile failure (rebar fracture). For developing Equation 2.10, only splitting failure mode was considered. All of the bond tests, resulting in splitting failures (48 unconfined and 19 confined bottom bars, 8 unconfined top bars) were performed using a clear cover of between one and three bar diameters ($d_b \le c \le 3d_b$).

As a result of the lack of effect of transverse reinforcement on average bond stress, the full set of data for splitting failures were considered and a linear regression was performed following the same approach as was done by Orangun *et al.* (1975) to develop Equation 2.10. The relation of Equation 2.10 was then used to determine an expression for the required development length to avoid splitting failure which resulted in (SI units)

$$l_{d,splitting} = \frac{d_b\left(\dfrac{f_{fu}}{0.28\sqrt{f_c'}} - 100\right)}{4.0 + 0.3\dfrac{c}{d_b}} \ge \frac{d_b f_{fu}}{2.54\sqrt{f_c'}} \qquad \text{Equation 2.11}$$

The term $\dfrac{d_b f_{fu}}{2.54\sqrt{f_c'}}$ is the required development length to avoid pullout failure and it was proposed after the analysis of 81 beam tests that resulted in pullout failures in Wambeke and Shield's (2006) database. Based on their data, Wambeke and Shield (2006) proposed a bar location modification factor of 1.5 for bars with more than 300 mm (12 in) of concrete cast below.

The equation of ACI 440.1R-06 was developed almost based on GFRP rebars. Also, there were very few bond test specimens in which transverse reinforcement was present. In the last decade, a large number of experimental studies were reported in the literature on the bond behaviour of FRP rebars. Therefore, it is necessary to re-evaluate the ACI reported equations with different types of fibres and with the presence of transverse reinforcement.

## 2.6 Bond Stress-Slip Relations

Bond is a critical design parameter for reinforced concrete structures which controls the performance of structural members both at serviceability limit state (crack width and deflection) and ultimate limit state (strength). To prevent bond failure in reinforced concrete members and to ensure complete transfer of forces between the reinforcement and the concrete, the reinforcement should be adequately anchored in the concrete. To determine the required anchorage length of the rebar, bond stress-slip ($\tau - s$) law is needed. Although many formulations for bond stress-slip law were proposed for steel rebars, for FRP rebars an extensive research effort is still needed. Moreover, the formulations of bond stress-slip relationship proposed so far for FRP rebars have to be validated by experimental investigation and curve fitting of the experimental data. Therefore, a generalized bond stress-slip law, which can be applied to different types of FRP rebars has not been established (Cosenza *et al.*, 1997). The following discussion will present an overview of the available bond stress-slip relationship of the FRP rebar in concrete in the literature.

Malvar (1994) proposed the first bond stress-slip ($\tau - s$) relationship for GFRP rebars. Malvar (1994) performed an extensive experimental investigation of the bond behaviour of GFRP rebars in concrete with different types of rebar surfaces and different confinement pressures. Based on the experimental results, Malvar (1994) proposed a model to predict the bond stress-slip law for FRP rebars in concrete, represented by the following relationship:

$$\frac{\tau}{\tau_m} = \frac{F\left(\frac{s}{s_m}\right) + (G-1)\left(\frac{s}{s_m}\right)^2}{1 + (F-2)\left(\frac{s}{s_m}\right) + G\left(\frac{s}{s_m}\right)^2}$$

Equation 2.12

where, $\tau_m$ = peak bond stress; $s_m$ = slip at peak bond stress; and *F*, *G* = empirical constants determined by curve fitting of the experimental data for each bar type. Malvar (1994) also provided two other relationships to predict bond stress-slip for a given value of confinement pressure which are expressed as follows:

$$\frac{\tau_m}{f_t} = A + B\left[1 - \exp\left(-\frac{C\sigma}{f_t}\right)\right] \quad \text{Equation 2.13}$$

$$s_m = D + E\sigma \quad \text{Equation 2.14}$$

where, $\sigma$ = confining axisymmetric radial pressure; $f_t$ = tensile concrete strength; and *A*, *B*, *C*, *D*, *E* = empirical constants determined for each type of rebar.

The well known bond stress-slip law, known as BEP model, for deformed steel bars failing by rebar pullout was proposed by Eligehausen *et al.* (1983). According to this model, the bond stress-slip of steel rebars shows four distinct branches (Figure 2.10): initial ascending branch up to the peak bond stress ($\tau_1$) for $s \le s_1$, a second branch with constant bond ($\tau = \tau_1$) up to slip $s = s_2$, a linearly descending branch from ($s_2, \tau_1$) to ($s_3, \tau_3$) and a horizontal branch for $s > s_3$, with a value of $\tau$ due to the development of friction ($\tau = \tau_3$).

The BEP model expresses the ascending branch of bond-slip relationship as follows:

$$\frac{\tau}{\tau_1} = \left(\frac{s}{s_1}\right)^{\alpha} \quad \text{Equation 2.15}$$

where, $\tau_1$ = maximum bond strength; and $s_1$ = slip corresponding to maximum bond strength. Values of $s_2$, $s_3$ and $\tau_3$ have to be calibrated based on the experimental results. In Equation 2.15, $\alpha$ is a curve-fitting parameter that must not be greater than 1, to be physically meaningful. The value of $\alpha$ proposed by Eligehausen *et al.* (1983) in the case of steel bars is equal to 0.4.

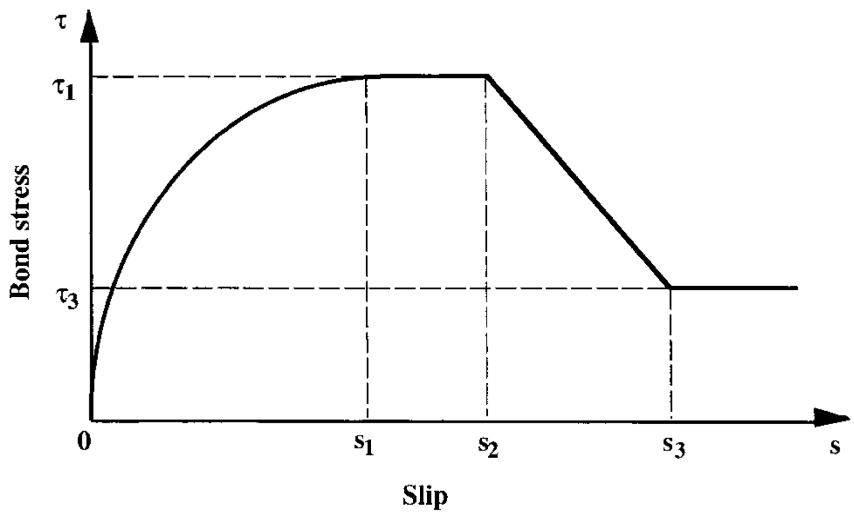



**Figure 2.10 BEP model for pullout failures of steel rebars (Eligehausen *et al.*, 1983).**

The BEP model was applied to FRP rebars by Faoro (1992), Alunno Rossetti (1995), Focacci *et al.* (2000), Pecce *et al.* (2001). When the BEP model was applied to FRP rebars, it was observed that there were some differences between the experimental curves and the curves obtained by applying the BEP model. Cosenza *et al.* (1996) investigated the bond stress-slip behaviour of GFRP rebars in concrete and based on the results, it was concluded that the bond stress-slip curves for GFRP rebars lack the second branch with constant bond as was found in the BEP model and hence, it was recommended not to consider this second branch in case of GFRP rebars (Figure 2.11). Based on their experimental results, Cosenza *et al.* (1996) modified the BEP model and proposed an alternative bond stress-slip relationship for GFRP rebars. According to the modified BEP model, the bond stress-slip curves have three distinct branches (Figure 2.11): initial ascending branch up to the peak bond stress ($\tau_1$) for $s \le s_1$ which is the same as was used in Equation 2.15, a softening branch, having slope $p\dfrac{\tau_1}{s_1}$ from ($s_1, \tau_1$) to ($s_3, \tau_3$) given by

$$\frac{\tau}{\tau_1} = 1 - p\left(\frac{s}{s_1} - 1\right) \qquad \text{Equation 2.16}$$

where, $p$ is an empirical parameter that needs to be determined based on the curve fitting of the experimental results; and a horizontal branch for $s > s_3$, with a value of $\tau$ due to the development of friction ($\tau = \tau_3$).

It has been observed that a refined model of the bond stress-slip is needed for the ascending branch only, since most structural problems are to be dealt with at this stress level. As a result, Cosenza *et al.* (1997) refined the BEP model and proposed another model for the ascending branch of the bond stress-slip curve up to the peak bond stress. This relationship is also known as CMR model and is defined by the following expression:

$$\frac{\tau}{\tau_m} = \left(1 - e^{-\frac{s}{s_r}}\right)^{\beta} \qquad \text{Equation 2.17}$$

where, $\tau_m$ = peak bond stress; and $s_r$ and $\beta$ = parameters based on curve-fitting of the actual data.

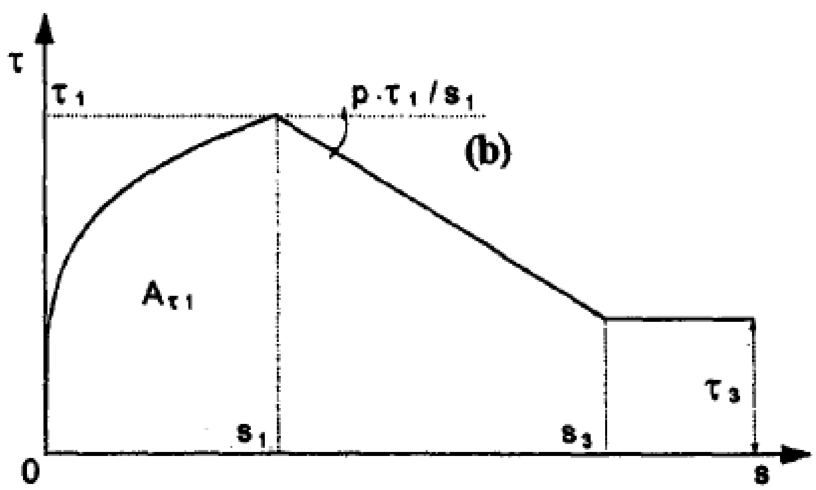



**Figure 2.11 Modified BEP model (Cosenza *et al.*, 1997).**

Tighiouart *et al.* (1998) performed experimental investigation on the bond behaviour of GFRP rebars in concrete by varying the bar diameter and the embedment length. Based on the experimental results, Tighiouart *et al.* (1998) suggested values for $s_r$ and $\beta$ of the CMR model ($S_r = -\frac{1}{4}$ and $\beta = 0.5$).

A numerical method was proposed by Focacci *et al.* (2000) to calibrate the parameters of a given local bond stress-slip relationship using experimental results of pullout tests. The proposed method aimed to determine the parameters of a given bond stress-slip relationship in such a way that it can predict the results of a pullout test in terms of the applied pullout force and the consequent slip at the loaded end and the slip at the free end. The BEP and the CMR bond stress-slip models were selected for the application of the proposed method. However, the proposed method could be applied to any analytical expression. The expressions for the BEP and the CMR models proposed by Focacci *et al.* (2000) are presented in Equations 2.18 and 2.19.

$$\tau(s) = \tau_m \left(\frac{s}{s_m}\right)^{\alpha} \left(1 - \frac{s}{\bar{s}}\right) \qquad \text{Equation 2.18}$$

$$\tau(s) = \frac{\tau_m s^{\beta}}{s_r^{\ \beta}} \left(1 - \frac{\beta s}{2 s_r}\right) \qquad \text{Equation 2.19}$$

where, $\tau_m$ = peak bond stress, $s_m$ = slip corresponding to peak bond stress, and $\alpha$, $\bar{s}$, $\beta$, $s_r$ are curve fitting parameters.

Baena *et al.* (2009) calibrated the modified BEP (Equation 2.15 and 2.16) and the CMR model (Equation 2.17) of the bond stress-slip relationship based on the results of 88 pullout tests specimens. From the experimental results, it was noted that the bar diameter should be incorporated into the bond stress-slip relationship for high strength concrete. Therefore, based on the experimental data, the following expressions were proposed for predicting the parameters of modified BEP and CMR model substituting $\tau_m$ for $\tau_1$ and $s_m$ for $s_1$:

For BEP model:
$$\begin{aligned} \tau_m &= \tau_0 + \tau_1 d_b \\ s_m &= m_0 e^{(m_1 d_b)} \\ \alpha &= \alpha_0 d_b^{\ \alpha_1} \end{aligned} \qquad \text{Equation 2.20}$$

where, $\tau_0$, $\tau_1$, $m_0$, $m_1$ and $\alpha_0$, $\alpha_1$ are curve fitting parameters.

For CMR model:
$$\begin{aligned} \beta &= \beta_0 e^{(\beta_1 d_b)} \\ s_r &= r_0 e^{(r_1 d_b)} \end{aligned} \qquad \text{Equation 2.21}$$

where, $\beta_0$, $\beta_1$ and $r_0$, $r_1$ are curve fitting parameters.

From the bond stress-slip relationships presented in Equations 2.12 to 2.21, it became evident that no specific formulations (proposed so far) for bond stress-slip relationship can predict the bond behaviour of different types of FRP rebars. Moreover, all of the proposed formulations need to be validated by comparison with the experimental investigation. In addition, these equations were developed from pullout test specimens (with only GFRP rebars), which do not represent the realistic behaviour of structural members. Therefore, it is necessary to develop a generalized bond stress-slip relationship from beam-type specimens which can be applied to different types of FRP rebars and be able to capture the real bond stress-slip behaviour.

## 2.7 Research Needs

From the presented literature, it is evident that there are some gaps in the available literature on the bond behaviour of FRP rebars in concrete. The research needs that are identified from the previous discussion are presented below:

- There is a need to re-evaluate the effect of different parameters, especially the effect of transverse reinforcement, on the bond behaviour of FRP rebars in concrete due to an increase in the experimental data produced during the last decade.

- Based on the new data, a new design equation should be proposed for determining the development length of FRP rebars in concrete.

- A general bond stress-slip law needs to be derived for pullout and splitting mode of failure. This relationship should be able to predict the bond behaviour of different types of FRP rebar with different surface textures. Moreover, the proposed relationship should take into account all the parameters that affect the bond performance of FRP rebars i.e. type of fibres, rebar surface, concrete strength, bar diameter, concrete cover, embedment length and concrete confinement.

## 2.8 Research Objectives

This study presents investigation on the bond behaviour of the FRP reinforcing bars in concrete environment and thereby, proposes design guidelines to alleviate the design of reinforced concrete structures using FRP reinforcing bars. The objectives set for the study are summarized below:

- Develop a consolidated database on the bond behaviour of FRP rebars in concrete by accumulating all the beam-type bond test data from the available literature up to 2009.
- Perform an analysis to evaluate the effect of different parameters on the bond behaviour of FRP rebars in concrete.
- Propose equations to predict the peak bond stress and the corresponding slip of FRP rebars in concrete, and derive a design equation to determine the development length of the FRP rebars that incorporates all the influential bond parameters.
- Establish a generalized bond stress-slip relationship for FRP rebars in concrete, which can be applied to any type of FRP rebar with any type of surface texture by taking into consideration all the parameters that influence the bond behaviour of FRP rebars in concrete i.e. fibre type, rebar surface, bar diameter, concrete strength, concrete cover, embedment length and confinement provided by the transverse reinforcement.
- Validate the proposed bond stress-slip relationship and the effect of transverse reinforcement on the bond behaviour of FRP rebars in concrete by using finite element analysis.

# Chapter 3: Description of the Database

## 3.1 General

The first step of the present study was to create a database of different bond tests available in the literature up to 2009. The bond tests were usually categorized into two major groups-pullout tests and beam tests. In pullout tests, the concrete surrounding the reinforcement is in compression and hence, it does not represent the actual behaviour of reinforced concrete members, where the concrete and the reinforcement are in tension. On the contrary, in beam tests, the concrete surrounding the reinforcement is in tension and therefore, it represents a more realistic behaviour of reinforced concrete members. In this study, only beam bond tests were considered and a database of 541 beam-type specimen consisted of beam end specimens, beam anchorage specimens, and splice specimens was created from the available literature (Daniali, 1990; Faza and GangaRao, 1990; Faza, 1991; Ehsani *et al.*, 1993, 1996; Kanakubo *et al.*, 1993; Makitani *et al.*, 1993; Benmokrane et *al.*, 1996; Shield *et al.*, 1997, 1999; Tepfers *et al.*, 1998; Tighiouart *et al.*, 1998, 1999; Cosenza *et al.*, 1997, 1999; Mosley, 2000; Pecce *et al.*, 2001; DeFreese and Wollmann, 2002; Wambeke, 2003; Aly and Benmokrane, 2005; Maji and Orozco, 2005; Aly *et al.*, 2006; Wambeke and Shield, 2006; Aly, 2007; Okelo, 2007; Rafi *et al.*, 2007; Thamrin and Kaku, 2007; Mosley *et al.*, 2008). The detail of the database is presented in Appendix A. The beam-type specimens of the database had different concrete strengths, concrete covers, embedment lengths and confinements. In addition, the failure mode was different for different specimens. The following sections describe the parameters considered in the database.

## 3.2 Failure Modes

The beam-type specimens considered in the study failed by four different modes: flexural failure, shear failure, bond splitting failure and bond pullout failure. Of the 541 specimens, 161 had flexural or shear failure. These specimens were excluded from the analysis as the bars achieved their ultimate strength, i.e. they did not fail through bond. Of the remaining 380 specimens, 177 had bond failure through splitting of concrete cover and 203 had bond failure through rebar pullout. These will be used to analyze the bond behaviour of FRP rebars in concrete.

### 3.3 Type of Fibre

The available equations for predicting maximum bond stress and bond stress-slip relationship were based on only glass FRP rebars (GFRP). The objective of this study was to derive design equations for FRP rebars which will hold for different types of FRP. Hence, all types of FRP rebars – glass, aramid and carbon- were considered in this study. Of the 380 beam-type specimens of the database that failed in bond, 275 had glass FRP rebars (72%), 90 had carbon FRP rebars (24%) and 15 had aramid FRP rebars (4%). It is observed that the number of specimens with AFRP was very small in comparison to specimens with GFRP and CFRP. However, since AFRP bars are rarely used in the construction of reinforced concrete structures, the data can be thought to be sufficient for representing bond behaviour of FRP rebars in concrete made from different fibres.

### 3.4 Type of Rebar Surface

The bond test specimens considered in the database consisted of three types of rebar surface – sand coated, spiral wrapped and helical lugged/ribbed. In few of the specimens, sand coating and spiral wrapping were applied simultaneously. Of the 380 beam-type specimens which failed in bond, 155 specimens had spiral wrapped FRP bars (41%), 163 had helical lugged FRP bars (43%) and 62 had sand coated FRP bars (16%). Of the 62 sand coated bars, 22 were GFRP, 37 were CFRP and 3 were AFRP. Of the 155 spiral wrapped bars, 113 were GFRP, 33 were CFRP and 9 were AFRP. Of the 163 helical lugged bars, 140 were GFRP, 20 were CFRP and 3 were AFRP. Figure 3.1 shows the breakdown of the database with respect to different types of fibre and their surface geometries.

### 3.5 Bar Cast Position

Bar cast position has significant effect on the bond behaviour of FRP rebars in concrete as described in section 2.3.5. It has been observed that the top reinforcing bars usually have lower bond strength than the bottom bars. Therefore, in this study the database was splitted based on the bar cast positions. Of the 380 beam-type specimens which failed in bond, 332 specimens tested were cast as bottom bars and 48 were cast as top bars, which indicate that about 87% of specimens were tested with bottom bars. For evaluating bond behaviour of FRP rebars in concrete, only the bottom bar specimens were considered and the top bar specimens were used to develop a modification factor for top bar cast positions.

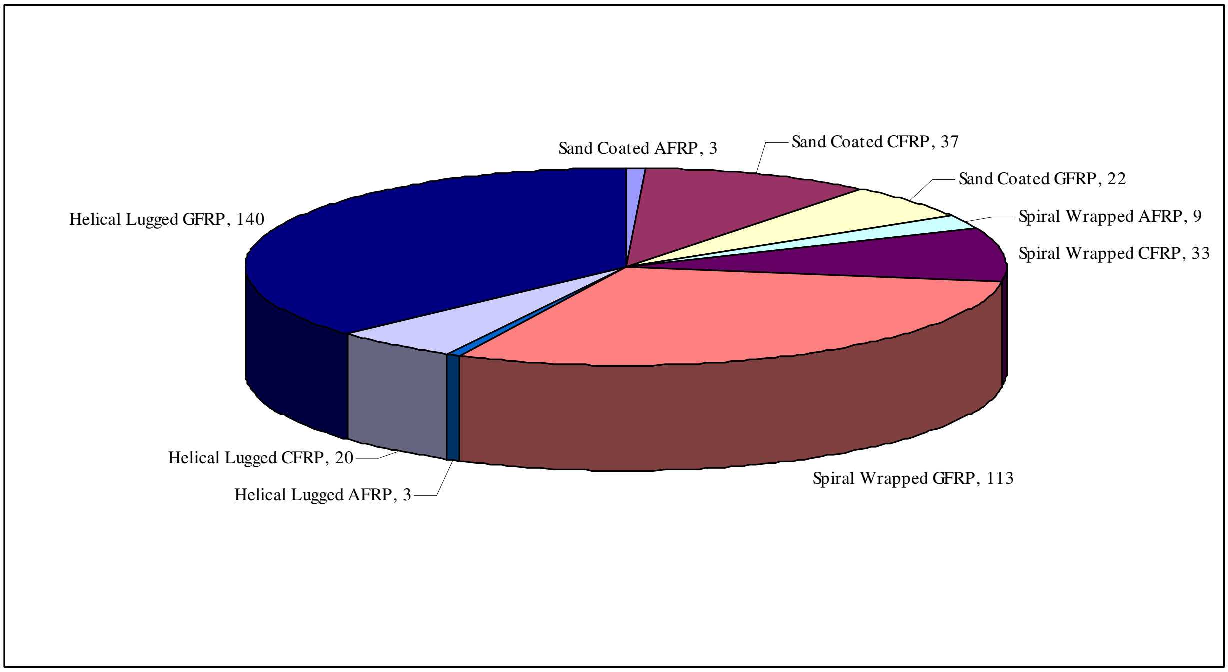



**Figure 3.1 Classification of the specimens with respect to type of fibre and rebar surface.**

## 3.6 Transverse Reinforcement

Transverse reinforcement confines concrete and thereby, increases the bond performance of reinforcing bars in concrete. For FRP rebars, there is still no evidence of the effect of transverse reinforcement on the bond behaviour due to the limited availability of the experimental data in the literature. Therefore, in this study, all the experimental data on the confined and the unconfined beam-type specimens were considered to assess the effect of concrete confinement provided by the transverse reinforcement on the bond performance of FRP rebars in concrete. There were 105 beam tests which resulted in a splitting failure that contained transverse reinforcement. For all the specimens, the transverse reinforcements were made of steel. The nominal diameter of the steel stirrups used in the specimens varied between 8 mm (0.32 in) to 11.3 mm (0.44 in) with a spacing of between 78 mm (3.1 in) and 150 mm (5.9 in) and all of the tests were performed on bottom bars. There were 127 beam tests that resulted in a pullout failure and contained transverse reinforcement. In all of these tests, the nominal diameter of the steel stirrups was 10 mm (0.4 in) with a spacing of between 50 mm (2 in) and 153 mm (6 in) and all of these tests were performed on bottom bars. Figure 3.2 shows the breakdown of the database with respect to failure modes, bar cast positions and confinement.

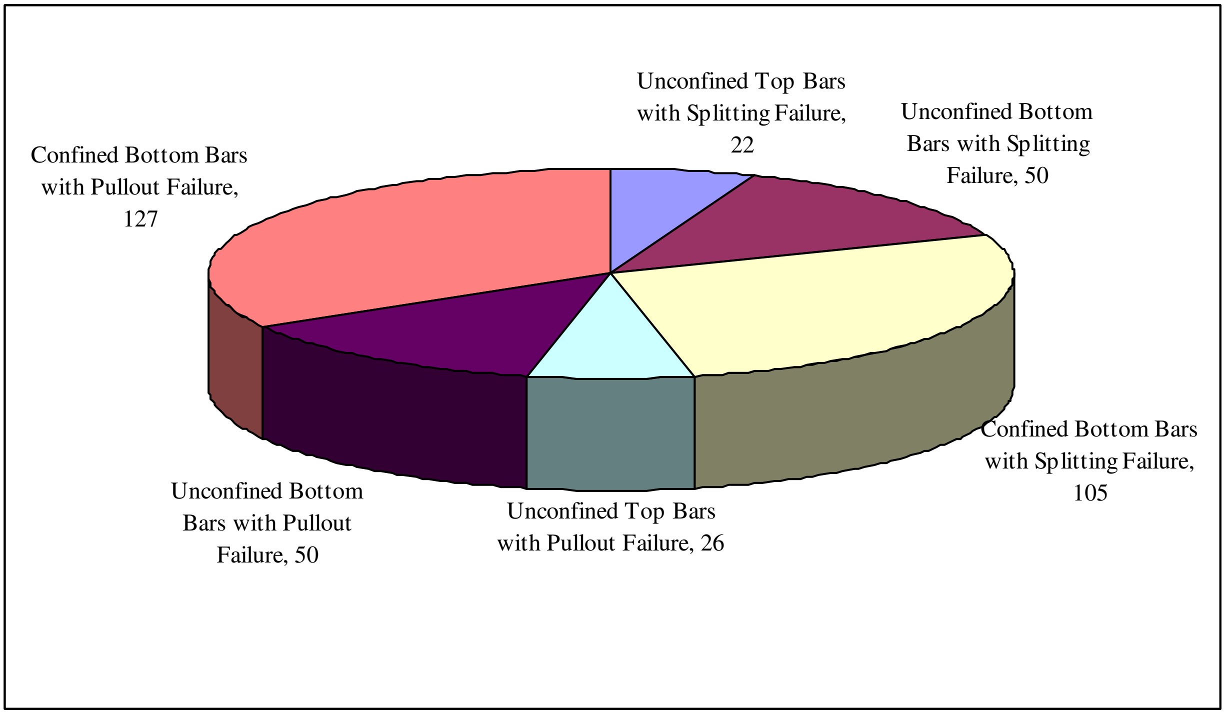



**Figure 3.2 Classification of the specimens with respect to concrete confinement, bar location and failure mode.**

## 3.7 Bar Diameter

In the database, the bar diameter of the FRP rebars varied widely. Bar diameter of the specimens having splitting mode of failure varied from 8 mm to 28.58 mm, whereas the bar diameter varied from 6.35 mm to 28.58 mm for specimens having pullout mode of failure. For sand coated bars, the bar diameter varied between 8 mm to 19.1 mm irrespective of the mode of failure. On the other hand, the diameters of the spiral wrapped bars and helical lugged bars ranged between 6.35 mm to 27.4 mm and 8 mm to 28.58 mm respectively. Figure 3.3 shows the variation of the bar diameters considered in the database of all the specimens which failed by rebar pullout and concrete splitting. It can be observed that the number of specimens with small diameter FRP bars were very diminutive.

## 3.8 Compressive Strength of Concrete

The database contained a fairly wide range of compressive strength of concrete. The compressive strength of concrete, for the specimens which failed by splitting of concrete, varied between 27 MPa and 49 MPa.

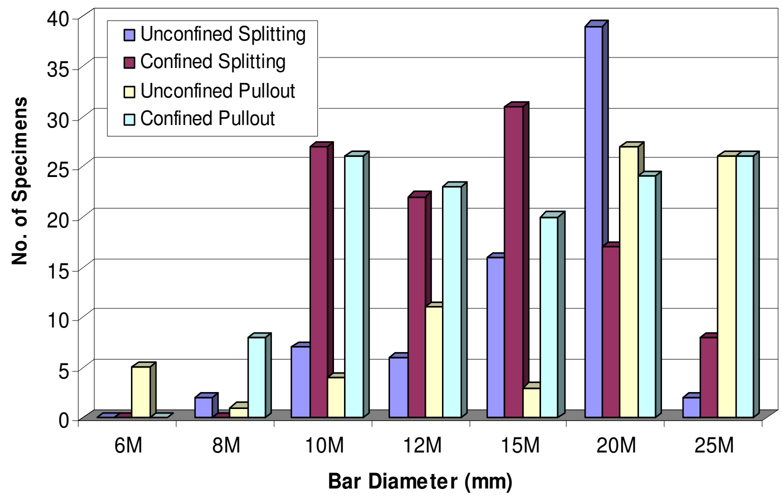



**Figure 3.3 Variation of bar diameter for all specimens failing by concrete splitting and rebar pullout.**

Only two specimens were tested with 65 MPa concrete strength. On the other hand, most of the specimens which failed by rebar pullout had compressive strength of concrete between 23 MPa and 47 MPa. Only four specimens were tested with concrete strength greater than 50 MPa- two of them had 51 MPa concrete strengths and the other two had 65 MPa. Figure 3.4 shows the variation of compressive strengths of concrete in all the specimens failing by rebar pullout and splitting of concrete. It can be observed that about 51% of all the specimens had normal strength concrete ( $f_c'$ = 20-35 MPa), 48% had medium high strength concrete ( $f_c'$ = 35-50 MPa) and only 1% had high strength concrete ( $f_c'$ >50 MPa). Therefore, it is concluded that the findings of this study is only limited for $f_c' < 50$ MPa. More tests are required with $f_c' > 50$ to arrive at definite conclusion about the bond behaviour of FRP rebars in high strength concrete.

## 3.9 Concrete Cover

In the database, concrete cover also varied between wide ranges. Figure 3.5 shows the variation of concrete cover normalized by bar diameter ( $\frac{c}{d_b}$ ) for all the specimens which failed by concrete splitting and rebar pullout. It was observed that most of the specimens which failed by splitting of the concrete cover had a concrete cover to bar diameter ratio between 1 and 3

($d_b \leq c \leq 3d_b$), whereas most of the specimens which failed by rebar pullout had a concrete cover to bar diameter ratio greater than 3 ($c \geq 3d_b$).

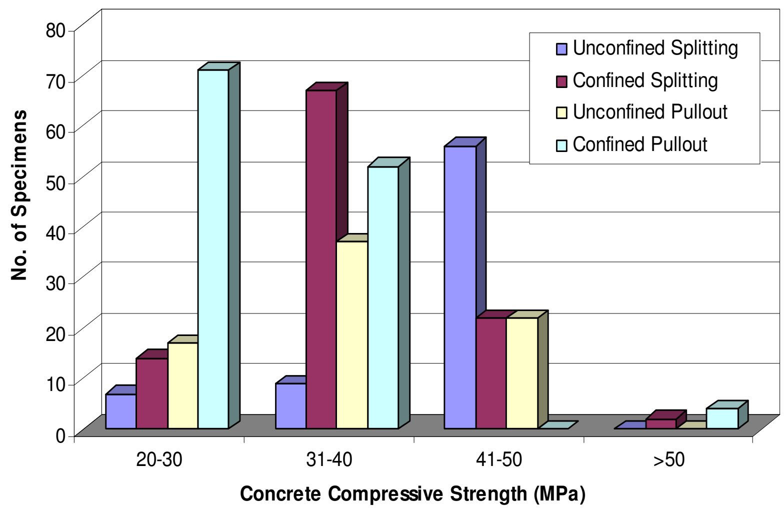



**Figure 3.4 Compressive strength of concrete for all the specimens failing by concrete splitting and rebar pullout.**

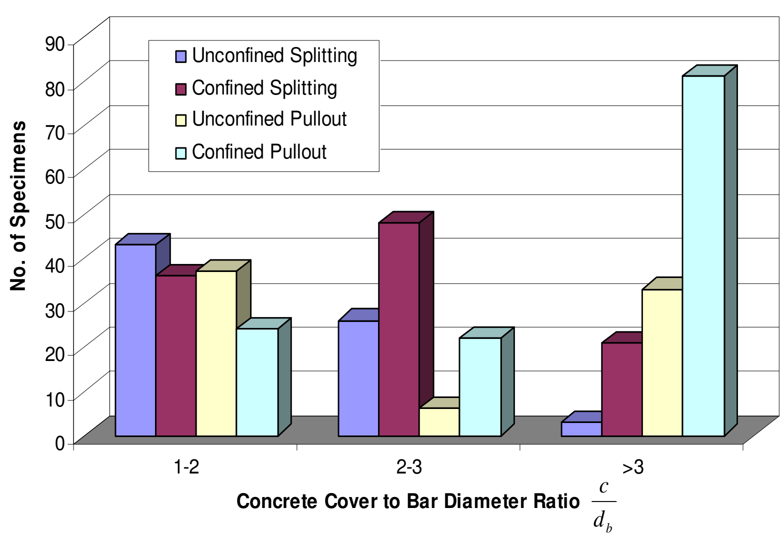



**Figure 3.5 Concrete cover to bar diameter ratio for all the specimens failing by concrete splitting and rebar pullout.**

It was observed that of the 177 specimens which failed by splitting of concrete, 45% and 42% had concrete cover to bar diameter ratio between 1-2 and 2-3 respectively. This includes both top and bottom bar specimens. If only bottom bar specimens were considered, 93% of the specimens failing by concrete splitting had concrete cover to bar diameter ratio of less than 3. Of the 203 specimens which failed by rebar pullout, 57% had concrete cover to bar diameter ratio greater than 3. This includes both top and bottom bar specimens. If top bar specimens were excluded, about 70% of the specimens failing by rebar pullout had concrete cover to bar diameter ratio of greater than 3 and the remaining 30% had concrete cover to bar diameter ratio of between 1 and 3.

## 3.10 Embedment Length

Embedment length may be defined as the anchorage length of the reinforcement (or the length of a splice in a splice test) to the concrete. In the database, there was a significant variation in the embedment lengths of the FRP rebars. Figure 3.6 shows the variation of the embedment length normalized by the bar diameter ($\frac{l_{embed}}{d_b}$) of FRP rebars for all the specimens failing by splitting of concrete and rebar pullout.

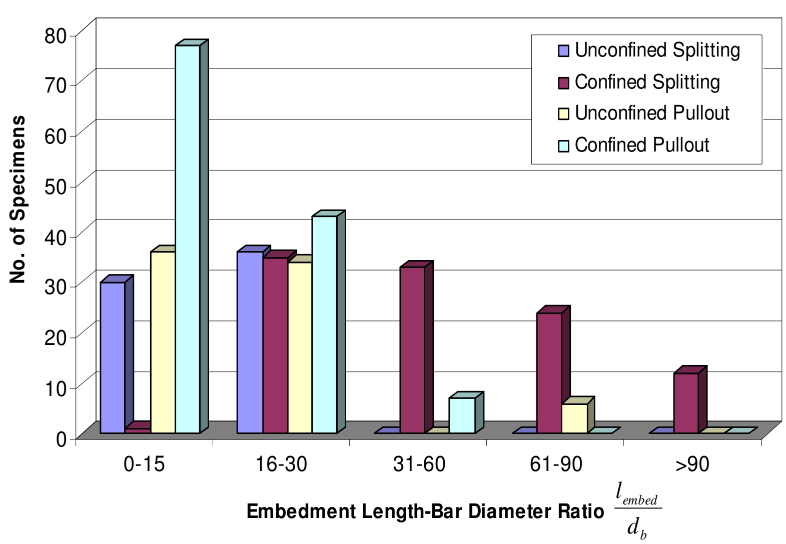



**Figure 3.6 Embedment length-bar diameter ratio for all the specimens failing by concrete splitting and rebar pullout.**

The embedment length of the specimens which failed by concrete splitting were much longer than those of the specimens which failed by rebar pullout. The embedment length of the specimens which failed by concrete splitting, ranged between 4 to 116 bar diameters ($4d_b \leq l_{embed} \leq 116d_b$). On the contrary, the embedment length of specimens having pullout failure ranged between 3 to 60 bar diameters ($3d_b \leq l_{embed} \leq 60d_b$). Of the specimens which failed by splitting of the concrete, over 56% had embedment length of less than or equal to 30 bar diameters ($l_{embed} \leq 30d_b$) and 44% had embedment length greater than 30 bar diameters ($l_{embed} > 30d_b$). On the other hand, 94% of the specimens which failed by rebar pullout had embedment length of less than or equal to 30 bar diameters and only 6% had embedment length greater than 30 bar diameters ($l_{embed} > 30d_b$).

### 3.11 Database for Slip at Peak Bond Stress and Bond Stress-Slip Relationship

The 380 beam bond tests (failed in bond) considered in this study reported the peak bond stress of the specimens, but bond stress-slip curves and the slip corresponding to the peak bond stress were not reported for each of the 380 beam tests. Therefore, for developing bond stress-slip relationship and an equation for determining the slip corresponding to the peak bond stress, only bond tests where these values were reported were considered. The database used for developing bond stress-slip relationship and slip corresponding peak stress is presented in Appendix B and Appendix C respectively.

There were 97 specimens for which slip corresponding to peak bond stress was reported. Of the 97 specimens, 40 failed by concrete splitting and 57 failed by rebar pullout. The 97 specimens consisted of 7 AFRP bars, 31 CFRP bars and 59 GFRP bars. Of the 97 specimens, 61 had helical lugged bars, 5 had sand coated bars and 31 had spiral wrapped bars.

There were 91 beam-type specimens in the database for which bond stress-slip data were reported along with the bond stress-slip curves. Of these 91 specimens, 23 specimens failed by concrete splitting and 68 specimens failed by rebar pullout. Of the 23 beam-type specimens that failed by splitting of concrete, 11 had helical lugged FRP rebars and 12 had spiral wrapped FRP rebars. There was no reported specimen with sand coated rebars which failed by concrete splitting. All of bars were cast as bottom bars. Of the 23 beam specimens, 6 were unconfined and

17 were confined. The 23 specimens consisted of 7 AFRP rebars, 11 CFRP rebars and 5 GFRP rebars. On the other hand, of the 68 beam-type specimens that failed by rebar pullout, 40 had helical lugged FRP rebars, 26 had spiral wrapped FRP rebars and 2 had sand coated FRP rebars. All of bars were cast as bottom bars. Of the 68 beam-type specimens, 6 were unconfined and 62 were confined. The 68 specimens consisted of 9 AFRP rebars, 22 CFRP rebars and 37 GFRP rebars.

## 3.12 Summary

The database contains adequate information about all the parameters that appear to influence the bond behaviour of FRP rebars in concrete and it takes into account a wide range of values for all the parameters. Further analysis using MS Excel and a statistical analysis program, JMP8, revealed that only 5% correlation exists between the individual parameters. Hence, it was concluded that there was no correlation between any two independent parameters. Therefore, the data can be thought to be sufficient to perform statistical analysis to evaluate the effects of different parameters that seem to affect the bond performance of FRP rebars in concrete. The next chapters concentrate on the statistical and the numerical analysis of the database.

# Chapter 4: Analysis of Data and Derivation of Development Length

## 4.1 General

In this chapter, a statistical analysis of the database will be performed to identify the parameters that influence the bond stress of FRP rebars and the corresponding slip. Based on the results of the analysis these parameters will be incorporated in the equations that will be derived to predict the peak bond stress (bond strength) and the corresponding slip. Also, an equation will be proposed to determine the required development length of FRP rebars.

## 4.2 Data Analysis

The database was analysed based on the two types of failure modes-splitting failure and pullout failure. For analysing the data, the bond stress was normalized by the square root of the compressive strength of concrete to reduce the variability of the bond stress data with respect to the compressive strength of concrete. Moreover, the embedment length and concrete cover were normalized by the bar diameter to reduce the variability with respect to bar diameter. The following sections discuss the effects of different parameters on the bond stress of FRP rebars in concrete.

### 4.2.1 Type of Fibres

The 380 specimens of the database, which failed in bond, included 275 glass FRP rebars, 90 carbon FRP rebars and 15 aramid FRP rebars which indicates that the number of specimens with GFRP rebars is much higher compared to the specimens with CFRP and AFRP rebars. Data analysis was performed for different types of fibres by splitting the database with respect to the concrete cover to bar diameter ratio (Figure 4.1). It was observed that irrespective of the failure mode and $\frac{c}{d_b}$ ratio, the type of fibre does not have any noticeable effect on the bond behaviour of FRP rebars to concrete. This is in agreement with CSA S806-02 which recommended the same modification factor for CFRP and GFRP when calculating the required development length of FRP rebars in concrete. However, it should be mentioned here that there was no correlation between any two individual parameters as discussed in section 3.12.

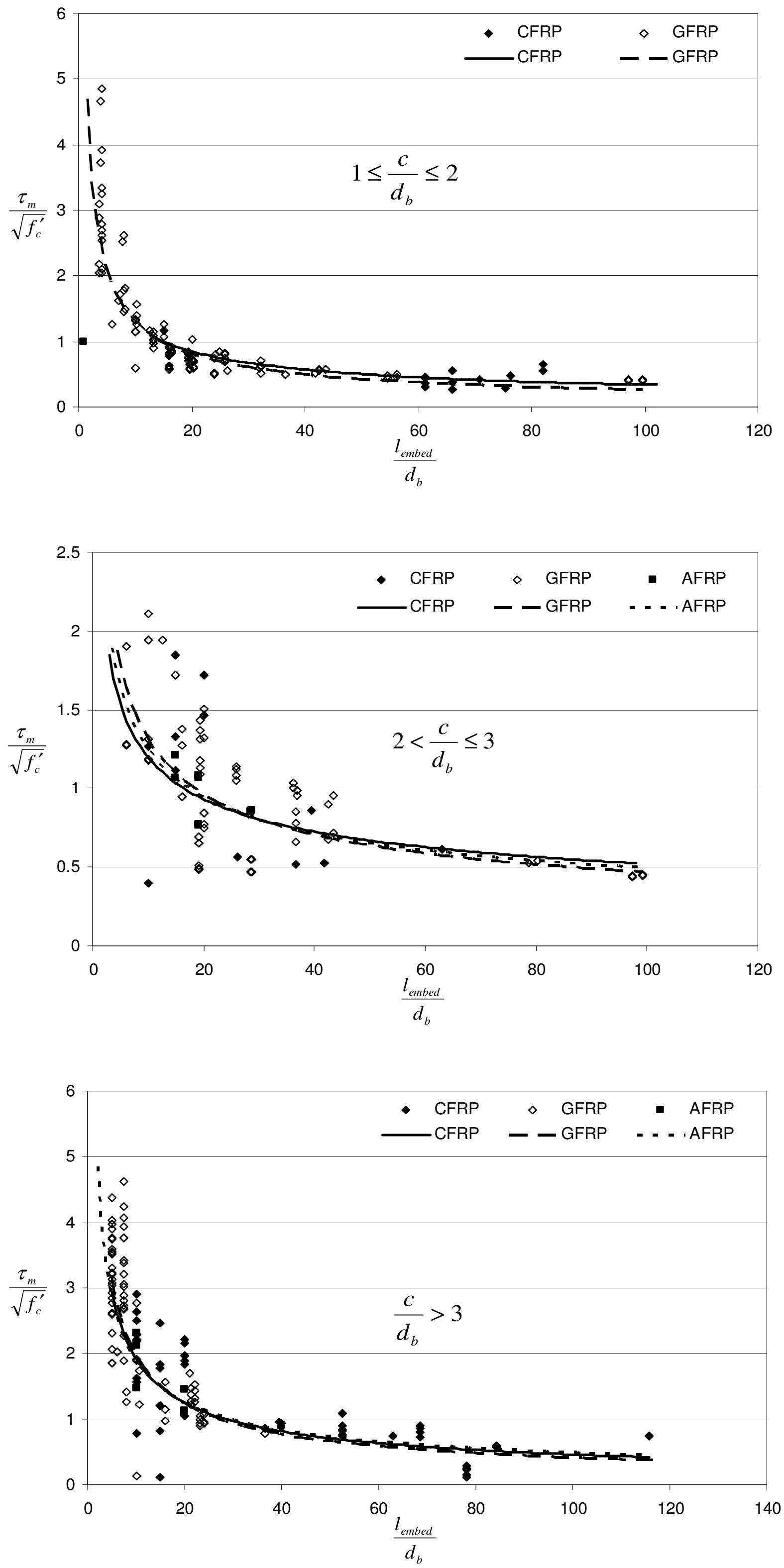
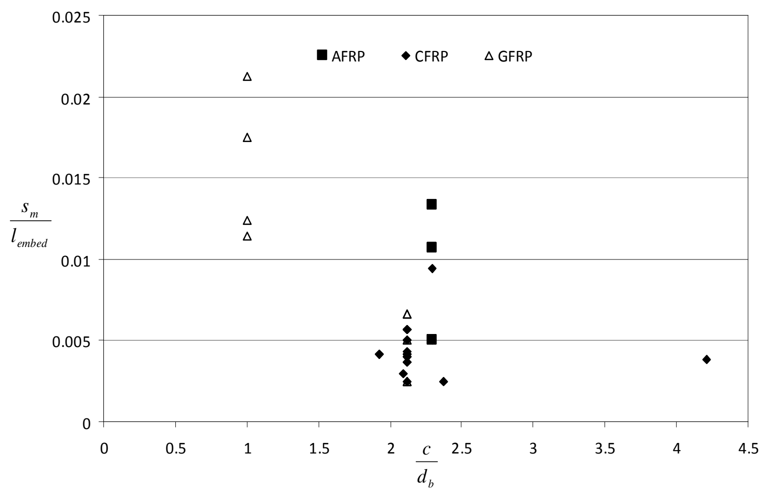
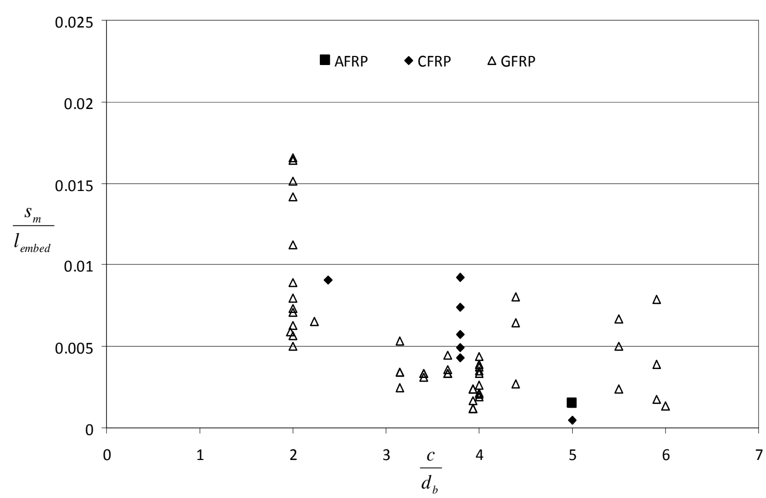



**Figure 4.1 Normalized average bond stress of the specimens for different types of FRP with different concrete cover to bar diameter ratio.**

There were 97 specimens for which slip corresponding to peak bond stress was reported. Of the 97 specimens, 40 failed by concrete splitting and 57 failed by rebar pullout. On the other hand, of the 97 specimens, 7 had AFRP bars, 31 had CFRP bars and 59 had GFRP bars. Figure 4.2 shows the variation of the normalized slip ($\frac{s_m}{l_{embed}}$) corresponding to peak bond stress ($\tau_m$) with respect to the normalized cover for splitting and pullout modes of failure.




(a) Splitting Failure




(b) Pullout Failure

**Figure 4.2 Normalized slip corresponding to peak bond stress plotted against normalized cover for different types of FRP.**

It was observed that for a splitting mode of failure, no definite trend was found for the variation of the normalized $s_m$ with the type of the FRP due to lack of enough data. On the contrary, for pullout failure mode, CFRP bars tend to show higher normalized $s_m$ values than GFRP and AFRP bars. Still any definite conclusion could not be made since the number of CFRP specimens was very small compared to the GFRP specimens for pullout mode of failure. Therefore, it is recommended that more tests are required to arrive at a definite conclusion about the effect of the type of fibres on the normalized $s_m$. In this study, it will be assumed that type of fibre does not have any effect on the bond performance of FRP rebars in concrete.

### 4.2.2 Type of Rebar Surface

Three types of bar surfaces were observed during the analysis of the data and they are: helical lugged/ribbed, sand coated and spiral wrapped bars (Figure 4.3). Of the 380 beam-type specimens which failed in bond, 155 specimens had spiral wrapped FRP bars, 163 had helical lugged FRP bars and 62 had sand coated FRP bars.


**Figure 4.3 Types of FRP rebars considered in the analysis.**

Figure 4.4 shows the normalized average bond stresses ($\frac{\tau_m}{\sqrt{f_c'}}$) of the specimens plotted against the normalized embedment lengths ($\frac{l_{embed}}{d_b}$) for different cover to bar diameter ($\frac{c}{d_b}$) ratios. The following observations were made from Figure 4.4.

- $1 \le \frac{c}{d_b} \le 2$: For small embedment lengths ($l_d \le 15d_b$), bars with spiral wraps had larger bond strength than the bars with helical lugs/sand coating, but for large embedment lengths ($l_d > 15d_b$), bars with helical lugs had larger bond strength than the other two.

- $2 \le \frac{c}{d_b} \le 3$: For small embedment lengths ($l_d \le 15d_b$), bars with sand coating had the largest bond strength compared to bars with helical lugs/spiral wraps and helical lugged bars had greater bond strength than spiral wrapped bars. On the other hand, for large embedment lengths ($l_d > 15d_b$), bars with spiral wraps and sand coating had almost similar bond strength which is larger than the helical lugged bars.

- $\frac{c}{d_b} > 3$: For small embedment lengths ($l_d \le 15d_b$), all the bars have similar bond strength, but for large embedment lengths ($l_d > 15d_b$), bars with sand coating have larger bond strength than the other two and helical lugged and spiral wrapped bars have almost the same bond strength.

From the above discussion, it is clear that the effect of rebar surface has no definite trend on the bond strength irrespective of the failure mode and hence, it is recommended that more tests to be performed to arrive at any definite conclusion about the effect of rebar surface on bond strength of FRP bar with concrete. It should be mentioned here that CSA S806-02 proposed the same bar surface modification factors for spiral wrapped, helical lugged and sand coated FRP rebars.

Of the 97 specimens, for which $s_m$ was reported, 61 had helical lugged bars, 5 had sand coated bars and 31 had spiral wrapped bars. Of the 61 specimens with helical lugged bars, 46 failed by rebar pullout and 15 failed by concrete splitting. On the other hand, of the 31 specimens with spiral wrapped bars, 9 failed by rebar pullout and 22 failed by concrete splitting. For the 5 specimens with sand coated bars, 2 failed by rebar pullout and 3 failed by concrete splitting.

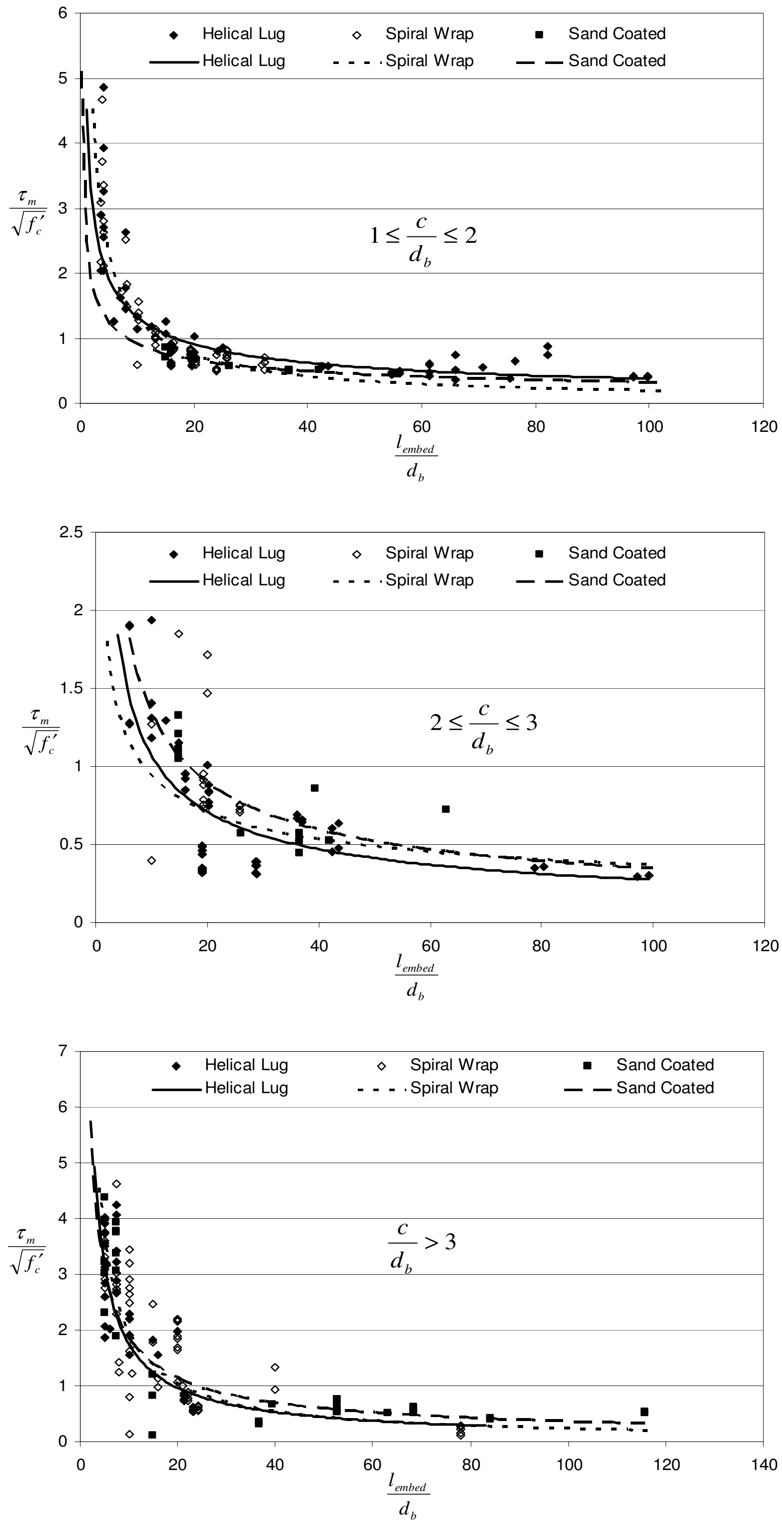
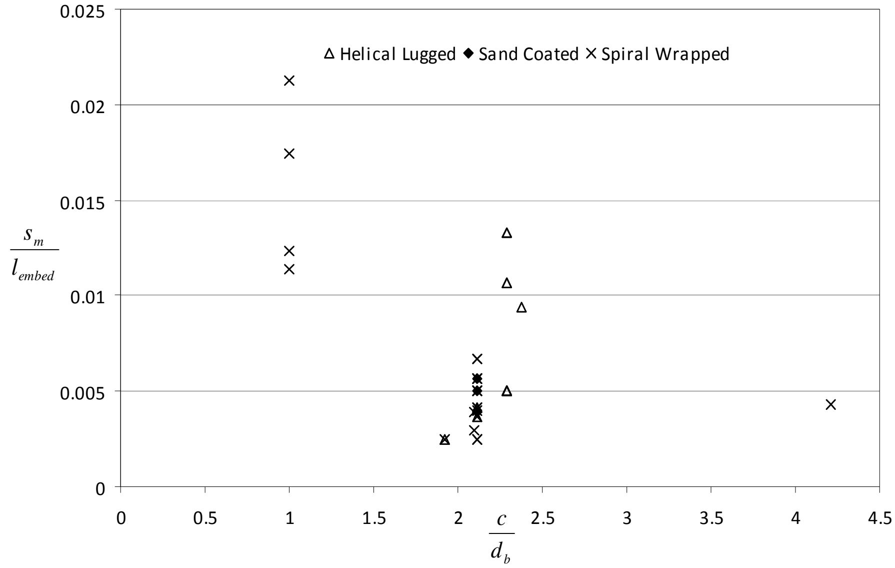
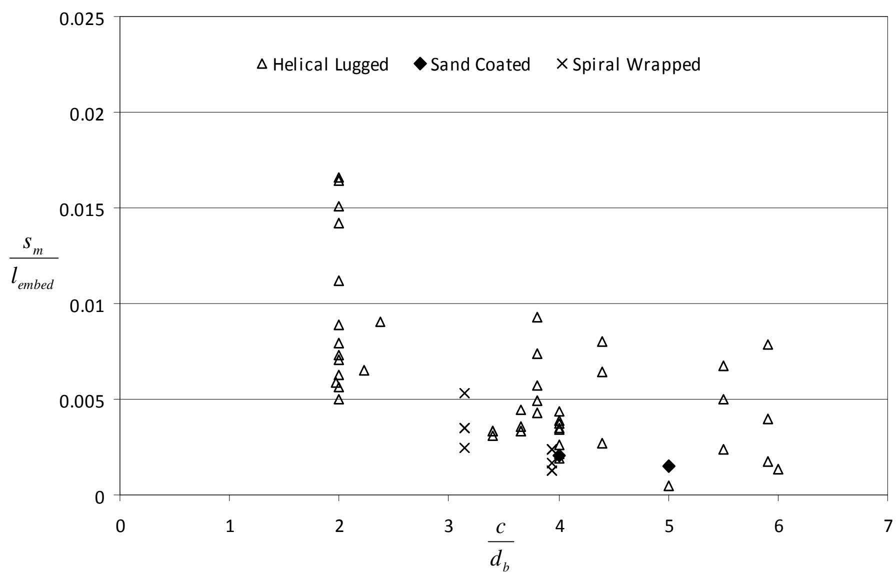



**Figure 4.4 Normalized average bond stress of the specimens for different surface texture of the rebars with different concrete cover to bar diameter ratio.**




(a) Splitting Failure




(b) Pullout Failure

**Figure 4.5 Normalized slip at peak bond stress of the specimens with different rebar surface.**

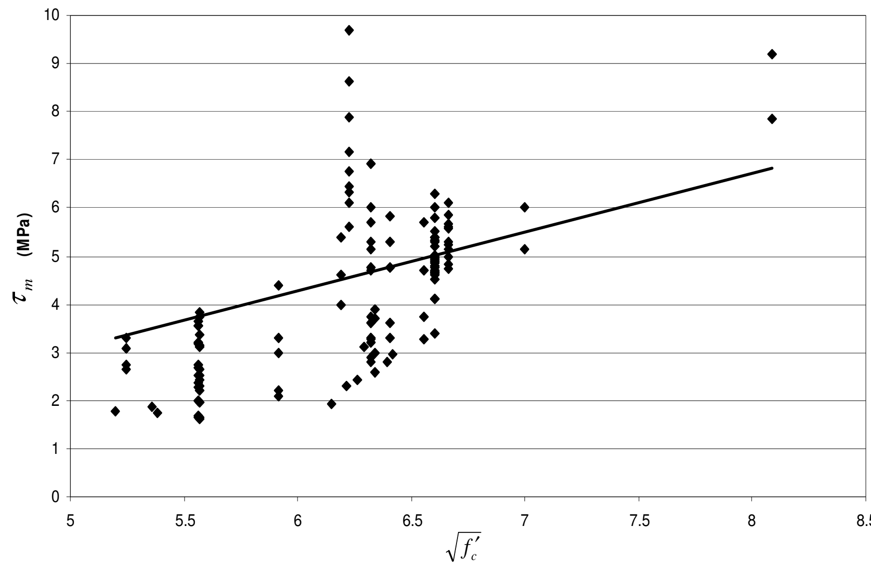
Figure 4.5 clearly shows that helical lugged bars had higher values of the normalized slip corresponding to peak bond stress than sand coated and spiral wrapped bars for both type of failure modes. Sand coated and spiral wrapped bars showed almost the same normalized $s_m$ values. Based on the results, it was concluded that rebar surface affects the slip corresponding to the peak bond stress and it should be taken into consideration when developing an equation for slip corresponding to peak bond stress.

### 4.2.3 Compressive Strength of Concrete

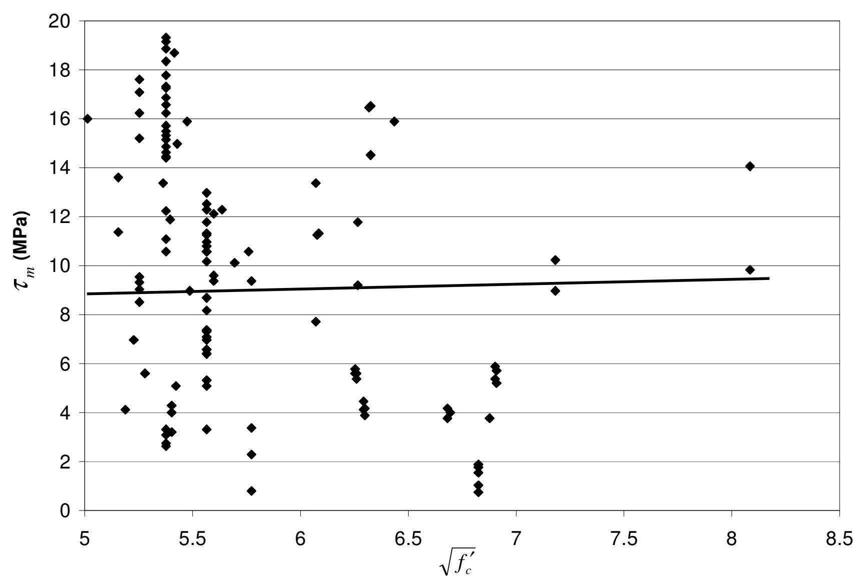
From the reported literature, it was observed that the average bond stress of FRP rebars in concrete is a function of square root of concrete strength (Faza and GangaRao, 1990; Pleiman, 1991; Ehsani *et al.*, 1996; Esfahani *et al.*, 2005; Okelo and Yuan, 2005). Therefore, the peak bond stresses of the 380 beam-type specimens which failed in bond were plotted against the square root of the corresponding concrete strength ($\sqrt{f_c'}$). Figure 4.6(a) and Figure 4.6(b) show the peak bond stresses of the specimens of the database with respect to square root of concrete strength for splitting and pullout mode of failures respectively.

It was observed that for splitting mode of failure, peak bond stress increased with an increase in the square root of concrete strength (Figure 4.6a). A higher concrete strength provided a higher confinement to the embedded reinforcement (FRP rebar) and hence, a larger force is needed to crack the concrete cover. Therefore, the bond strength increased. On the other hand, Figure 4.6b indicates that the pullout bond strength is not affected by the compressive strength of the concrete. This could be explained by the fact that pullout failure occurs when there is enough confinement provided to the concrete and hence, there is no splitting crack in the concrete. In such case, the rebar surface and the concrete surrounding the rebar surface shears off due to friction and the rebar starts to slip. Therefore, the failure mode is not dependent on the strength of concrete.

Figure 4.7 shows the variation of the normalized slip corresponding to peak bond stress with the square root of concrete strength for both splitting and pullout modes of failure. It was observed that the slip corresponding to peak bond stress decreased with the increase in concrete strength for both types of failure mode. Therefore, it is evident that the compressive strength of concrete affects the bond behaviour of FRP rebars in concrete and hence, it must be taken into account while determining a bond stress-slip relationship.




(a) Splitting Failure




(b) Pullout Failure

**Figure 4.6 Variation of peak bond stress with square root of concrete strength.**

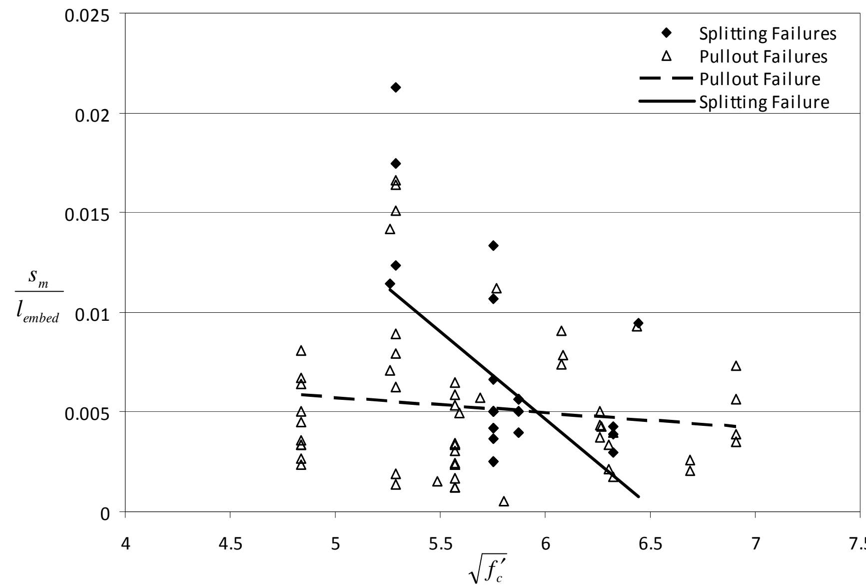
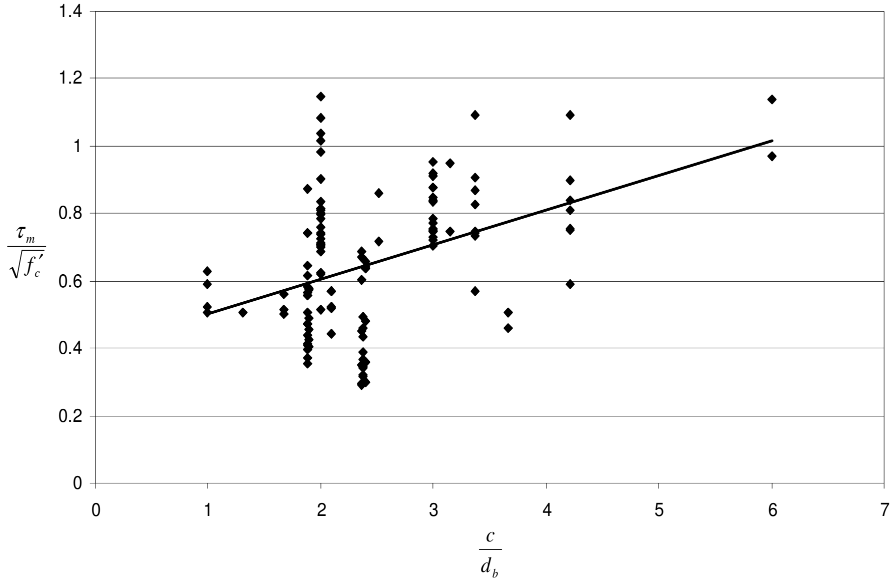



**Figure 4.7 Variation of normalized slip corresponding to peak bond stress with square root of concrete strength for different types of failure.**

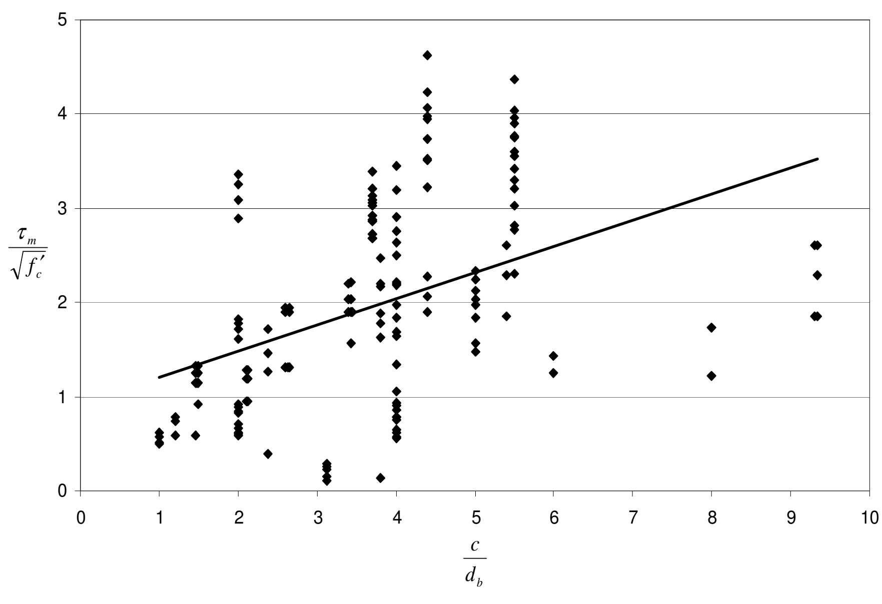
### 4.2.4 Concrete Cover

The more the concrete cover, the more the concrete is confined which will increase the bond strength of the reinforcing bars. Figure 4.8(a) and Figure 4.8(b) shows the variation of the normalized average bond stress for different concrete cover to bar diameter ratios for the beam-type specimens of the database for splitting and pullout modes of failure respectively. It is quite evident from these figures that the bond strength increases with an increase in the concrete cover due to the increased confining effect and that the bond strength for pullout mode of failure is higher than that for splitting mode of failure for same $\frac{c}{d_b}$.

Figure 4.9 shows the variation of the normalized slip ($\frac{s_m}{l_{embed}}$) corresponding to the peak bond stress for different concrete cover to bar diameter ratio for both splitting and pullout modes of failure. It was observed that the normalized slip decreased with an increase in the concrete cover. This was attributed to the confining action of the concrete cover which resulted in the peak bond stress to occur at a relatively smaller slip.




(a) Splitting Failure




(b) Pullout Failure

**Figure 4.8 Variation of normalized average bond stress with concrete cover to bar diameter ratio.**

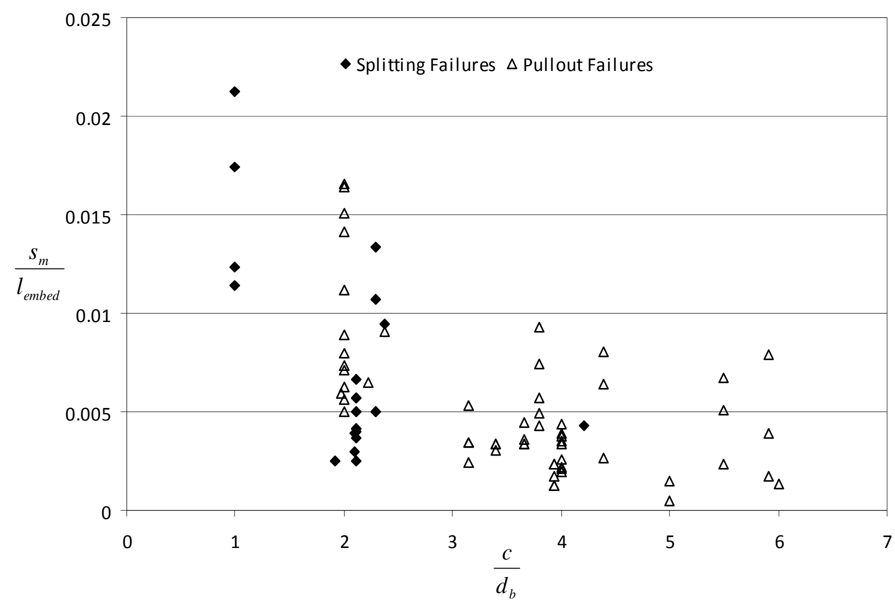
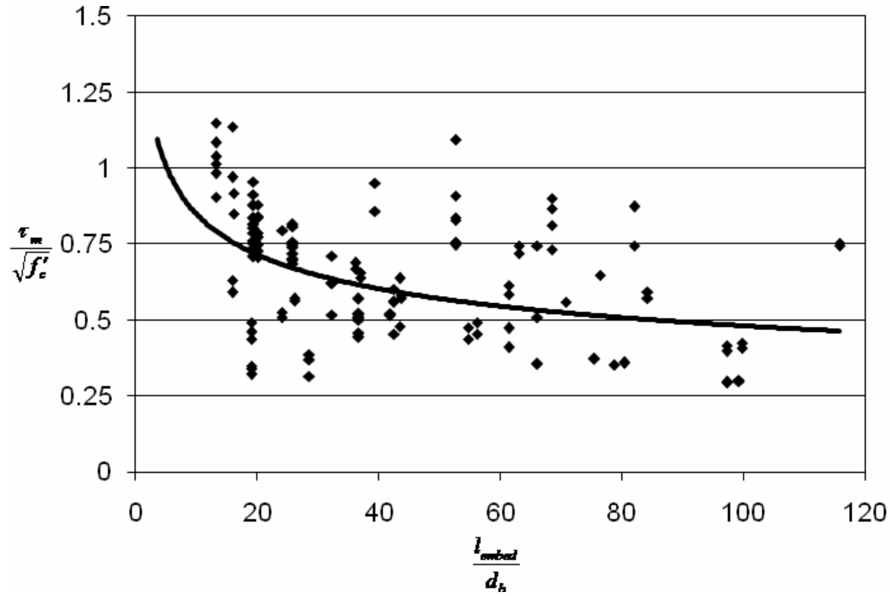



**Figure 4.9 Variation of normalized slip corresponding to peak bond stress with different concrete cover to bar diameter ratio for different types of failure.**

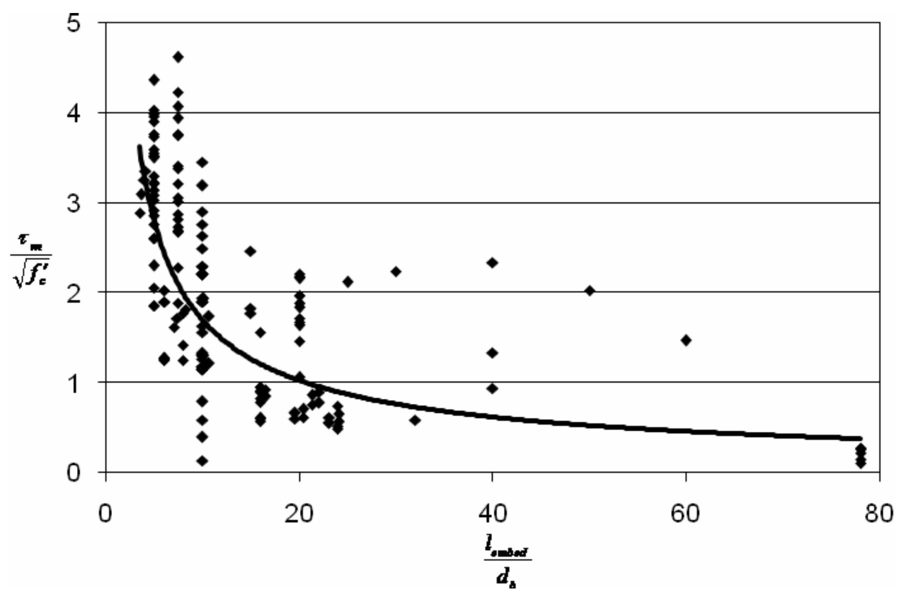
### 4.2.5 Embedment Length

From the reported literature, it was shown that the embedment length of FRP rebars is inversely proportional to its bond strength (Achillides and Pilakoutas, 2004; Aly *et al.*, 2006). Figure 4.10 shows the variation of the normalized average bond stress plotted against the normalized embedment length for splitting and pullout failures. It was observed that the bond strength decreased with an increase in the embedment length of the FRP rebars. This was attributed to the nonlinear distribution of the bond stress on the bar. In general, the tensile stress in the rebar attenuates rapidly from the loaded end (high tensile stress in the rebar) towards the free end (low tensile stress in the rebar) referring to a nonlinear distribution of the bond stress. As the embedment length increased, the applied load approached the tensile strength of the rebar and the average bond strength diminishes and hence, specimens with shorter development length develop higher bond strength.

Figure 4.11 shows the variation of the slip corresponding to the peak bond stress with respect to the embedment length for both pullout and splitting failures. With an increase in the embedment length of the bar, the slip corresponding to the peak bond stress increased. This was attributed to the nonlinear distribution of the bond stress on the bar. As the embedment length increases, the stress is distributed over a longer length and hence, bond failure occurs at a relatively higher slip.




(a) Splitting Failure




(c) Pullout Failure

**Figure 4.10 Variation of normalized average bond stress with normalized embedment length for bottom bar specimens.**

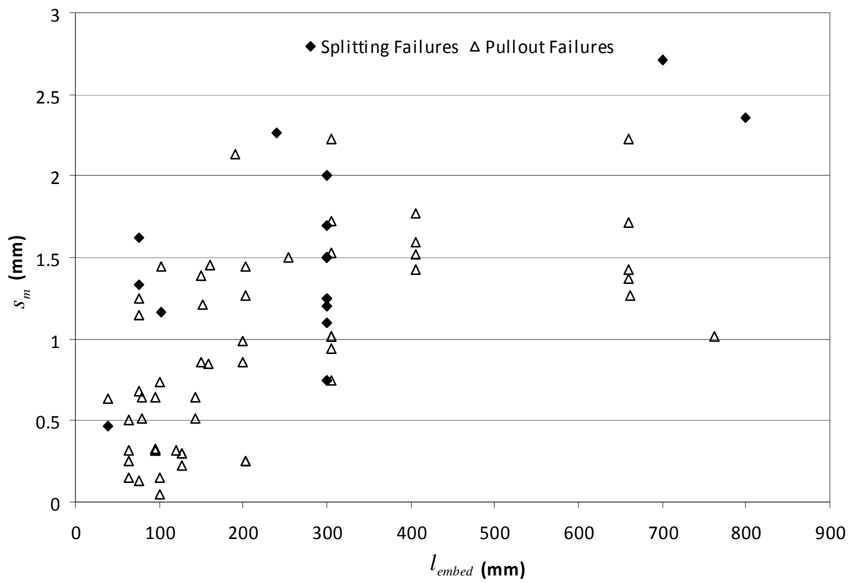



**Figure 4.11 Slip corresponding to peak bond stress plotted against embedment length of the specimens for pullout and splitting failures.**

### 4.2.6 Effect of Confinement

In theory, the presence of transverse reinforcement should confine the concrete and thereby, limit the progression of splitting cracks, thus, increasing the bond strength. However, due to the limited availability of experimental data in the literature, the theory has not been proven in case of FRP rebars in concrete. In the database, there were 177 and 203 specimens which failed by concrete splitting and rebar pullout respectively. Of the 177 specimens that failed by concrete splitting, 105 had transverse reinforcement and of the 203 specimens that failed by rebar pullout, 127 had transverse reinforcement.

Figure 4.12(a) and Figure 4.12(b) present the normalized bond strength of the unconfined and confined bottom bar specimens which failed by concrete splitting and rebar pullout respectively. It was observed that for both types of failure modes, confined specimens had higher bond strength than the unconfined specimens which signifies that confinement affects the bond behaviour of FRP rebars in concrete.

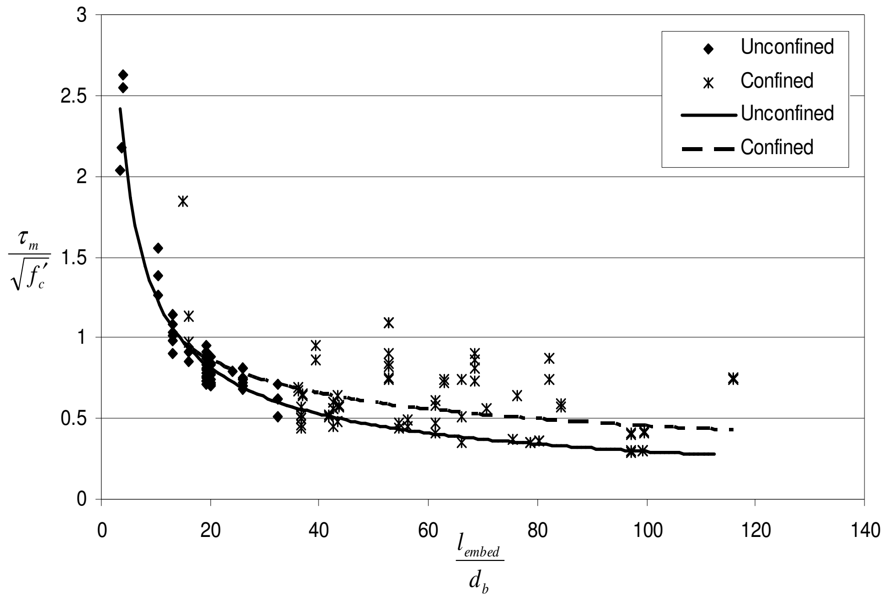
Figure 4.13 shows the effect of transverse reinforcement on the bond strength of FRP rebars in concrete for both splitting and pullout modes of failure. The parameter that was selected to represent the effect of transverse reinforcement was $\frac{A_{tr}}{snd_b}$, where, $A_{tr}$ is the area of transverse reinforcement normal to the plane of splitting through the bars, $s$ is the center to center spacing of the transverse reinforcement, $n$ is the number of bars being developed along the plane of splitting and $d_b$ is the bar diameter. This parameter was selected as it has been observed that for steel rebars, the effectiveness of a transverse reinforcement is proportional to the area of transverse reinforcement and inversely proportional to the spacing of the transverse reinforcement, the rebar diameter and the number of bars being developed (Orangun *et al.*, 1975). It was found from Figure 4.13(a) that for splitting mode of failure, as $\frac{A_{tr}}{snd_b}$ increased by 10%, the normalized average bond stress increased by10%-15% on an average. On the other hand, for pullout mode of failure (Figure 4.13b), there was no increase in the normalized average bond stress with increase in $\frac{A_{tr}}{snd_b}$. This was expected, as for pullout failure there is enough confinement provided to the concrete and failure takes place through shearing off the rebar surface and the concrete surrounding the rebar surface due to friction and there is no splitting crack in the concrete. Hence, increasing concrete confinement by providing transverse reinforcement does not increase the average bond stress.

Figure 4.14 shows the effect of transverse reinforcement on the normalized slip corresponding to the peak bond stress for both splitting and pullout modes of failure. It was observed that with an increase in the amount of the transverse reinforcement, the normalized slip values decreased due to the confining action provided by the transverse reinforcements. Therefore, the presence of transverse reinforcement should be taken into consideration when developing an equation for slip corresponding to peak bond stress.

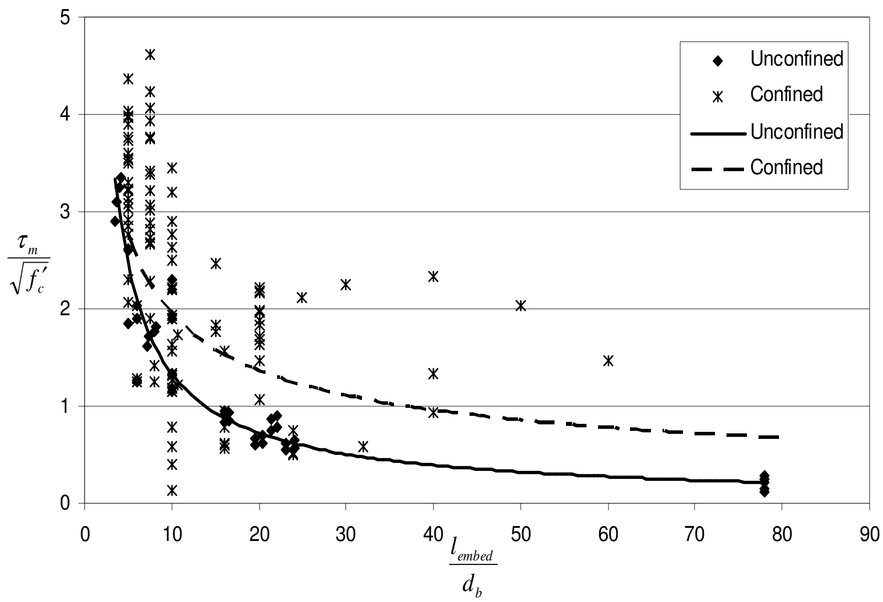
## 4.3 Derivation of Equations for the Peak Bond Stress and the Corresponding Slip

### 4.3.1 Peak Bond Stress

Peak bond stress values were reported for all 380 beam-type specimens of the database which failed in bond. Of these 380 beam-type specimens, 177 failed by concrete splitting. These 177 data were used to generate an equation to predict the peak bond stress of FRP rebars in concrete.

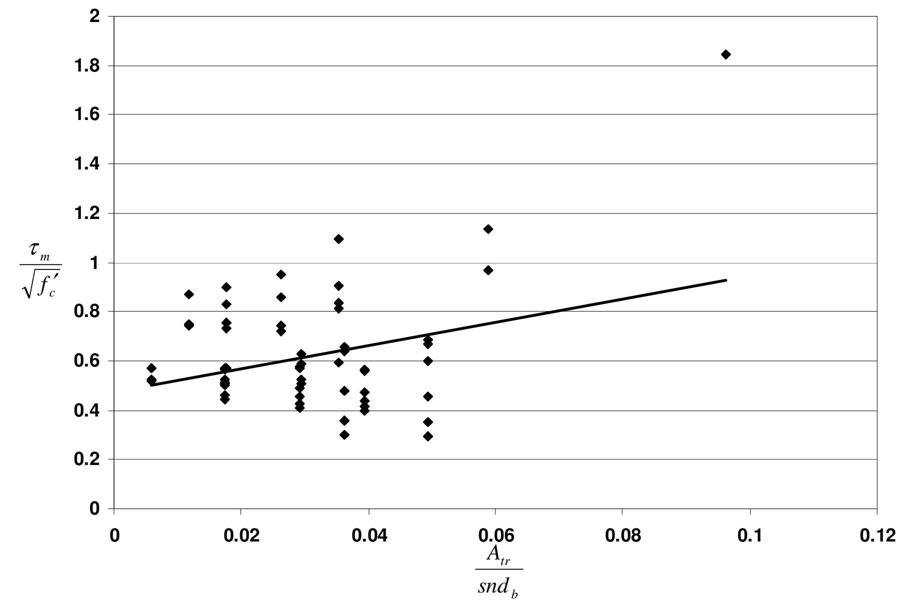



(a) Splitting Failure

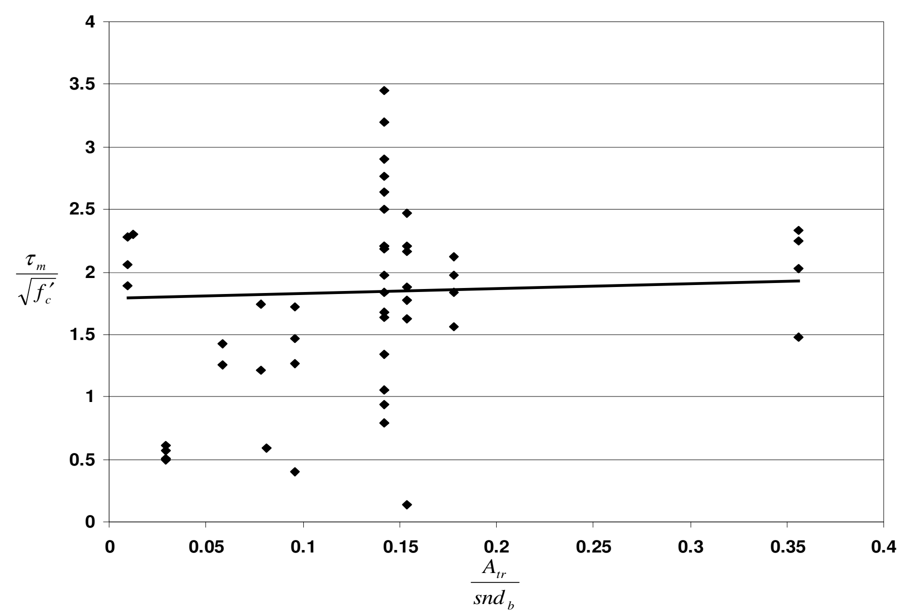



(b) Pullout Failure

**Figure 4.12 Normalized average bond stress plotted against normalized embedment length for bottom bar specimens.**




(a) Splitting Failure




(b) Pullout Failure

**Figure 4.13 Effect of transverse reinforcement on the normalized average bond stress of bottom bar specimens.**

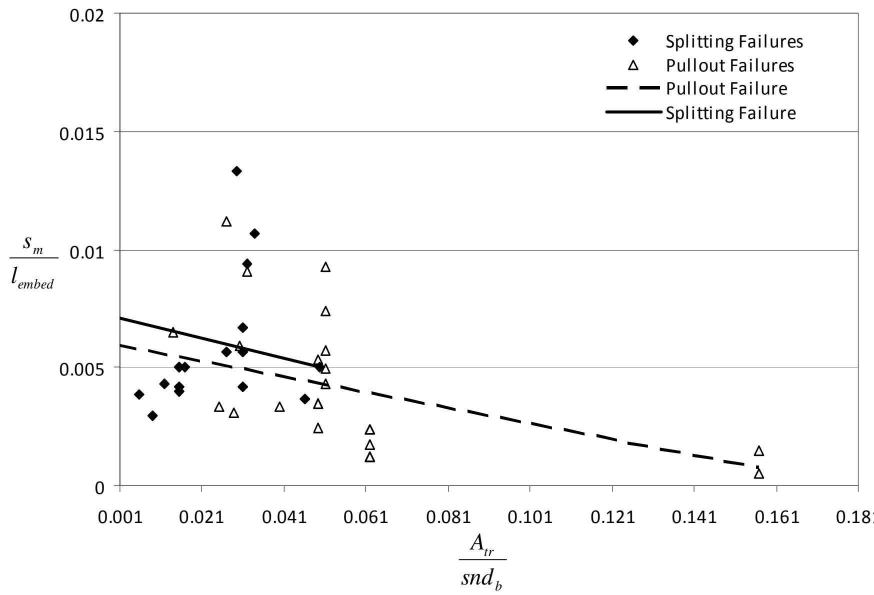



**Figure 4.14 Effect of transverse reinforcement on the normalized slip corresponding to peak bond stress for the bottom bar specimens.**

However, from sections 4.2.1 and 4.2.2, it was evident that the type of fibre and the rebar surface do not affect the peak bond stress of FRP rebars in concrete. On the other hand, from section 4.2.6, it was observed that the presence of transverse reinforcement affects the peak bond stress. Therefore, the 177 data points were divided based on whether the bond region was confined with transverse reinforcement or not (72 unconfined, 105 confined). In addition, the 203 specimens which failed by rebar pullout were used to set a limit for the development length to avoid pullout failure.

### Peak Bond Stress Based on Unconfined Beam Tests with Splitting Failure

There were 72 unconfined beam tests that failed by splitting of the concrete. Of these 72 tests, 22 tests were performed on specimens where the bars were cast as top bars. These 22 tests were not used to develop the peak bond stress equation. The normalized average bond stresses ($\frac{\tau_c}{\sqrt{f_c'}}$) of the remaining 50 beam tests were plotted against the normalized embedment lengths ($\frac{l_{embed}}{d_b}$) in Figure 4.15.

It was observed that as the normalized embedment length increased, the peak bond stress decreased because the stress was distributed over a longer length. Using the same approach as Orangun *et al.* (1975), a linear regression analysis on the normalized cover (cover to the center of the bar divided by the nominal bar diameter) and the inverse of the normalized embedment length was used to develop Equation 4.1 in SI units.

$$\frac{\tau_c}{\sqrt{f_c'}} = 0.03 + 0.14\frac{c}{d_b} + 9.0\frac{d_b}{l_{embed}} \qquad \text{Equation 4.1}$$

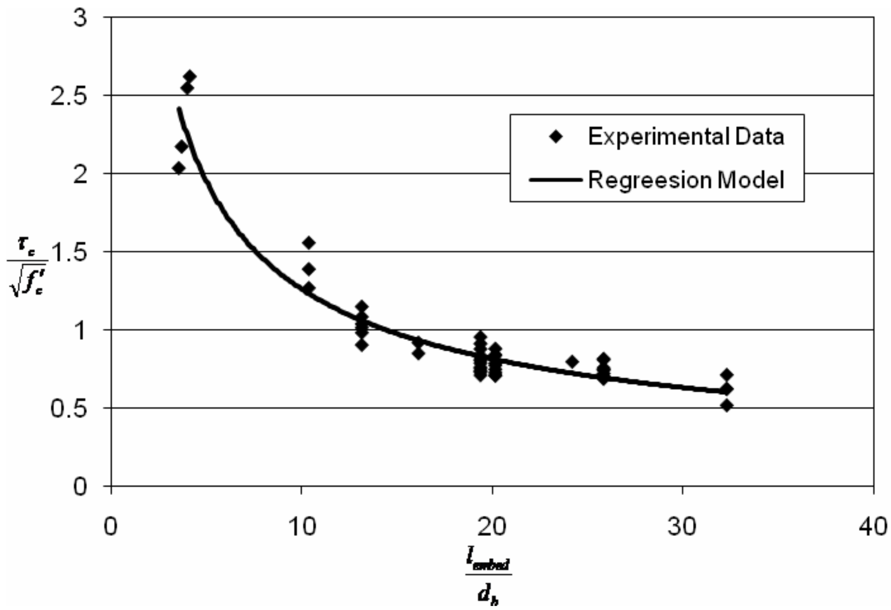



**Figure 4.15 Normalized average bond stress plotted against normalized embedment length for unconfined bottom bar specimens failed by concrete splitting.**

where, $\tau_c$ is the peak bond stress of unconfined FRP rebar to concrete (i.e. due to concrete cover only). The standard errors for each of the coefficients of Equation 4.1 are presented in Table 4.1. The regression statistics of the linear regression performed to develop Equation 4.1 showed that the proposed equation presented a high adjusted determination coefficient (adjusted R square) value of 0.903 explaining 90.3% of the variability of the response and standard error of 0.142 (Table 4.2). This indicates a good correlation of the proposed equation with the experimental data. The statistical significance of the model (Equation 4.1) has been evaluated by the F-test analysis of variance (ANOVA) which has revealed that this regression is statistically significant (Table 4.3).

**Table 4.1Standard errors for the coefficients of Equation 4.1**

| | Coefficients | Standard Error |
|---|---|---|
| Intercept | 0.03 | 0.0477 |
| $\frac{c}{d_b}$ | 0.14 | 0.0173 |
| $\frac{d_b}{l_{embed}}$ | 9.0 | 0.4172 |

**Table 4.2 Regression statistics for Equation 4.1**

| Regression Statistics | |
|---|---|
| Multiple R | 0.952405 |
| R Square | 0.907075 |
| Adjusted R Square | 0.903121 |
| Standard Error | 0.142632 |
| Observations | 50 |

**Table 4.3 ANOVA of the 50 unconfined bottom bar specimens having splitting failure**

| | Degrees of Freedom | Sum of Squares | Mean Squares | F | Significance F |
|---|---|---|---|---|---|
| Regression | 2 | 9.333487 | 4.666743 | 229.3922 | 5.63784E-25 |
| Residual | 47 | 0.956166 | 0.020344 | | |
| Total | 49 | 10.28965 | | | |

When the predicted values from Equation 4.1 were plotted against the experimental values and the values obtained from the ACI 440.1R-06 equation (Figure 4.16), it was found that the bond strength values obtained from the proposed equation are very close to the actual test results and the values predicted by the ACI 440.1R-06 equation. The average of the ratio of the experimental to the predicted values using Equation 4.1 was found to be 0.998 with a standard deviation of 0.123. This indicates that any significant parameter was not left out from the proposed equation. Thus, Equation 4.1 can provide an adequate estimate of the peak bond stress of the FRP rebars to concrete when failure is initiated by concrete splitting.

### Peak Bond Stress Based on Confined Beam Tests with Splitting Failure

In this study, there were 105 beam-type specimens which had transverse reinforcement and failed by concrete splitting. From the analysis of the database, it was evident that the presence of the transverse reinforcement increased the overall bond strength of the FRP rebars to concrete and hence, the presence of transverse reinforcement should be taken into consideration when calculating the peak bond stress and the development length of the FRP rebars (section 4.2.6). The peak bond stress of a confined rebar can be regarded as the linear addition of the strength of an unconfined rebar and the strength contributed by the transverse reinforcement (Orangun *et al.* 1975).

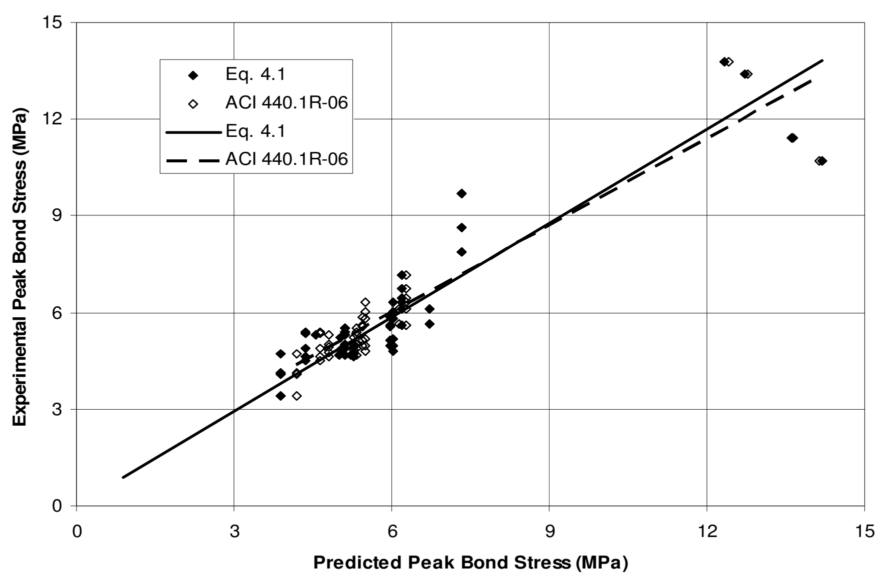



**Figure 4.16 Comparison of the proposed equation with the ACI 440.1R-06 equation for unconfined bottom bar specimens having splitting failure.**

The transverse reinforcement contribution to bond stress ( $\tau_{tr}$ ) was calculated by subtracting $\tau_c$ , as determined from Equation 4.1, from the total bond stress achieved in a confined beam test, $\tau_{confined}$ i.e. $\tau_{tr} = \tau_{confined} - \tau_c$ . The value of $\frac{\tau_{tr}}{\sqrt{f'_c}}$ was plotted against $\frac{A_{tr}}{snd_b}$ for the bars considered in Figure 4.17. The straight line fit proposed led to the following equation:

$$\frac{\tau_{tr}}{\sqrt{f_c'}} = 2.9 \frac{A_{tr}}{snd_b}$$ Equation 4.2

Therefore, the peak bond stress of an FRP bar with transverse reinforcement was determined by combining Equations 4.1 and 4.2 as follows:

$$\frac{\tau_m}{\sqrt{f_c'}} = \frac{\tau_c}{\sqrt{f_c'}} + \frac{\tau_{tr}}{\sqrt{f_c'}} = 0.03 + 0.14 \frac{c}{d_b} + 9.0 \frac{d_b}{l_{embed}} + 2.9 \frac{A_{tr}}{snd_b}$$ Equation 4.3

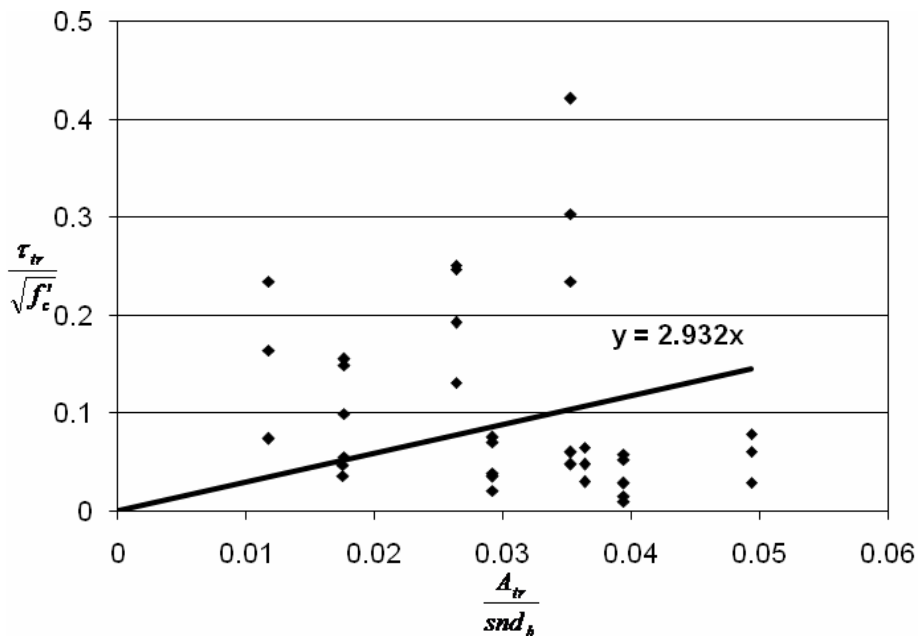



**Figure 4.17 Effect of transverse reinforcement for confined tests with splitting failures.**

Equation 4.3 provides the peak bond stress values for FRP rebars to concrete for splitting mode of failure. The regression statistics of Equation 4.3 showed that the proposed equation presented a moderate adjusted determination coefficient (adjusted R square) value of 0.671 explaining 67.1% of the variability of the response and standard error of 0.116 (Table 4.4). This indicates a reasonable correlation of the proposed equation with the experimental data. The statistical significance of the model (Equation 4.3) has been evaluated by the F-test analysis of variance (ANOVA) which has revealed that this regression is statistically significant (Table 4.5).

Figure 4.18 shows the comparison of the normalized average bond stress for the proposed equation (Equation 4.3) against the experimental data and ACI 440.1R-06 equation respectively.

**Table 4.4 Regression statistics for Equation 4.3**

| Regression Statistics | |
|---|---|
| Multiple R | 0.824899 |
| R Square | 0.680458 |
| Adjusted R Square | 0.670967 |
| Standard Error | 0.116191 |
| Observations | 105 |

**Table 4.5 ANOVA of the 105 confined bottom bar specimens having splitting failure**

| | Degrees of Freedom | Sum of Squares | Mean Squares | F | Significance F |
|---|---|---|---|---|---|
| Regression | 3 | 2.903607 | 0.967869 | 71.6926 | 6.37242E-25 |
| Residual | 101 | 1.363526 | 0.0135 | | |
| Total | 104 | 4.267133 | | | |

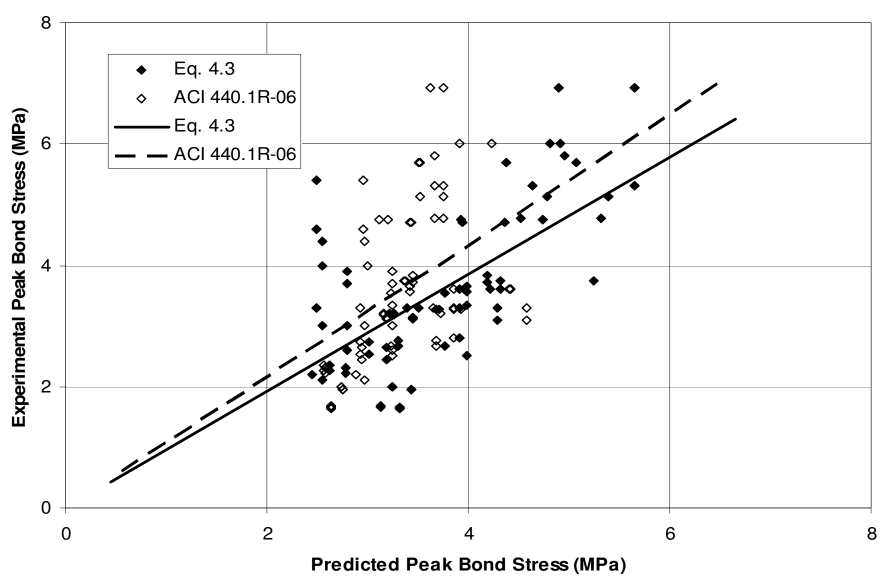



**Figure 4.18 Comparison of the proposed equation with the ACI 440.1R-06 equation for confined bottom bar specimens having splitting failure.**

It can be observed that the ACI equation underestimates the bond strength in presence of transverse reinforcement. This manifests the inadequacy of ACI equation in calculating the bond strength of FRP rebars to concrete in presence of transverse reinforcement. On the other hand, the proposed equation takes into account the effect of the presence of transverse reinforcement and it shows good agreement with the test results. The average of the ratio of experimental to predicted values using Equation 4.3 was found to be 0.94 with a standard deviation of 0.21, while the average of the ratio of the experimental to the predicted values using ACI equation was found to be 1.05 with a standard deviation of 0.33. It can be observed that the ACI equation underestimated the bond strength by 5%, whereas the proposed equation overestimated the bond strength by 6%. Although the ACI equation is showing conservativeness over the experimental results, it is missing one of the important parameters i.e. the effect of the transverse reinforcement. But the proposed equation was able to capture all the important parameters although it overestimated the bond strength by 6%. However, the proposed equation will result in shorter development length than the ACI equation because it takes advantage of the presence of confinement provided by the transverse reinforcement.

### 4.3.2 Slip Corresponding to Peak Bond Stress

From section 4.2.2, it was observed that the normalized slip corresponding to the peak bond stress ($\frac{s_m}{l_{embed}}$) is influenced by the type of the rebar surface and so, all the data were splitted based on the type of the rebar surface. Of the 97 specimens, for which $s_m$ was reported, 61 had helical lugged bars, 5 had sand coated bars and 31 had spiral wrapped bars. Moreover, from sections 4.2.3 to 4.2.6, it was noted that the normalized $s_m$ is affected by the concrete strength, the concrete cover, the embedment length and the confinement. Therefore, these parameters were considered when developing a model for $s_m$. Linear regression was performed to develop an equation to predict the slip corresponding to the peak bond stress. The response parameter was chosen as the slip corresponding to the peak bond stress normalized by embedment length ($\frac{s_m}{l_{embed}}$) and the variable parameters were chosen as the square root of the concrete strength ($\sqrt{f'_c}$), the concrete cover to bar diameter ratio ($\frac{c}{d_b}$) and $\frac{A_{tr}}{snd_b}$. Linear regression analysis was performed on the data of the specimens having helical lugged bars and bar surface modification factor was proposed based on the data of specimens having sand coated and spiral wrapped bars. The helical lugged bars were chosen for regression because it had the highest number of specimens in the database.

There were 61 specimens that had helical lugged FRP rebars. Of the 61 specimens, 6 had AFRP bars, 11 had CFRP bars and the remaining 44 had GFRP bars. However, it was found from section 4.2.1 that the type of FRP does not affect $\frac{s_m}{l_{embed}}$ and hence, all types of FRP data were combined for the analysis. The 61 specimens had compressive strength of the concrete ranging between 23 to 48 MPa, the concrete cover ranging between 1 to 6 bar diameters ( $d_b \le c \le 6d_b$ ) and the embedment length ranging between 3 to 28 bar diameters ($3d_b \le l_{embed} \le 28d_b$). Figure 4.7, Figure 4.9 and Figure 4.14 show the plot of the normalized slip corresponding to the peak bond stress with respect to the different parameters for the specimens for different types of FRP rebars. It was observed that with an increase in the compressive strength of concrete, the concrete cover and the transverse reinforcement, the normalized slip decreased due to their confining action. The regression resulted in the following equation in SI units.

$$\frac{s_m}{l_{embed}} = \frac{1}{1000}\left(20.8 - 1.3\sqrt{f_c'} - 2.1\frac{c}{d_b} - 3.8\frac{A_{tr}}{snd_b}\right) \qquad \text{Equation 4.4}$$

Equation 4.4 provides the slip corresponding to the peak bond stress for helical lugged FRP bars. Table 4.6 shows the standard errors for the coefficients of Equation 4.4. The regression statistics of the linear regression performed to develop Equation 4.4 showed that the proposed equation presented an adjusted determination coefficient value of 0.428 explaining 42.8% of the variability of the response (Table 4.7). The statistical significance of the model predicted in Equation 4.4 has been evaluated by the F-test analysis of variance (ANOVA) which has revealed that this regression is statistically significant (Table 4.8). It was found that the average normalized slip ($\frac{s_m}{l_{embed}}$) of the sand coated and spiral wrapped bars were less than the values obtained from the Equation 4.4 by 50%-60% (Figure 4.19). Therefore, rebar surface modification factor should be proposed for Equation 4.4 based on the available data.

**Table 4.6 Standard errors for the coefficients of Equation 4.4**

| | Coefficients | Standard Error |
|---|---|---|
| Intercept | 0.0208 | 0.0043 |
| $\sqrt{f_c'}$ | 0.0013 | 0.0007 |
| $\frac{c}{d_b}$ | 0.0021 | 0.0003 |
| $\frac{A_{tr}}{snd_b}$ | 0.0038 | 0.0258 |

**Table 4.7 Regression statistics for Equation 4.4**

| Regression Statistics | |
|---|---|
| Multiple R | 0.65427 |
| R Square | 0.42806 |
| Adjusted R Square | 0.39796 |
| Standard Error | 0.00346 |
| Observations | 61 |

**Table 4.8 ANOVA of 61 specimens having helical lugged FRP rebars**

| | Degrees of Freedom | Sum of Squares | Mean Squares | F | Significance F |
|---|---|---|---|---|---|
| Regression | 3 | 0.000512 | 0.000171 | 14.2205 | 4.95683E-07 |
| Residual | 57 | 0.000684 | 1.2E-05 | | |
| Total | 60 | 0.001195 | | | |

The average ratio of test/predicted normalized slip ($\frac{s_m}{l_{embed}}$) for helical lugged and spiral wrapped specimens was 1.08 and 0.46 respectively. A modification factor of 0.43 was recommended based on the ratio of the spiral wrapped FRP bar specimens to that of the helical lugged FRP bar specimens. Similarly, the average ratio of test/predicted normalized slip ($\frac{s_m}{l_{embed}}$) for helical lugged and sand coated specimens was 1.08 and 0.41 respectively. A modification factor of 0.38 was recommended based on the ratio of the sand coated FRP bar specimens to that of the helical lugged FRP bar specimens. Therefore, by incorporating the bar surface modification factor, Equation 4.4 can be rewritten as

$$\frac{s_m}{l_{embed}} = \frac{\eta}{1000}\left(20.8 - 1.3\sqrt{f_c'} - 2.1\frac{c}{d_b} - 3.8\frac{A_{tr}}{snd_b}\right) \qquad \text{Equation 4.5}$$

where, $\eta$ is the bar surface modification factor, which equals to 1 if the bar surface is helical lugged, 0.43 if it is spiral wrapped and 0.38 if it is sand coated. Figure 4.20 shows the comparison of the predicted normalized slip ($\frac{s_m}{l_{embed}}$) obtained by using Equation 4.5 with the experimental data.

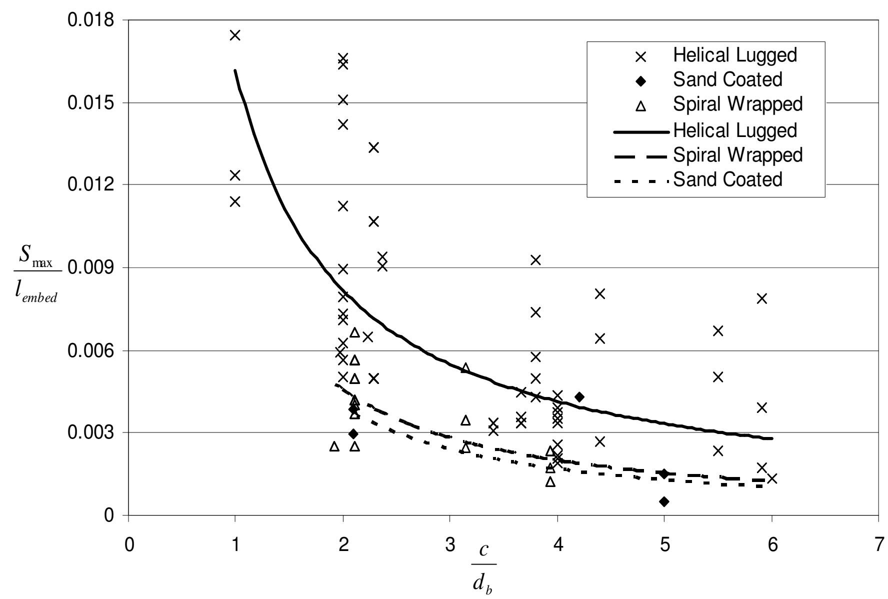



**Figure 4.19 Comparison of normalized slip corresponding to peak bond stress for FRP bars having different surface texture.**

It was observed that predicted values were reasonably close to the actual test results. The average of the ratio of the predicted to the experimental values for the normalized slip ($\frac{s_m}{l_{embed}}$) was 1.04 with a standard deviation of 0.18, which indicates a good correlation between the experimental and predicted values. Therefore, based on the analysis and the comparison with the experimental results, it can be concluded that the proposed equation (Equation 4.5) is adequate in predicting the slip corresponding to the peak bond stress for different types of FRP rebars with different rebar surface. However, due to lack of enough data, specimens having pullout and splitting failure were combined together for developing Equation 4.5. Therefore, more tests are required to split the data according to the mode of failure and thus, Equation 4.5 can be modified with availability of more experimental data.

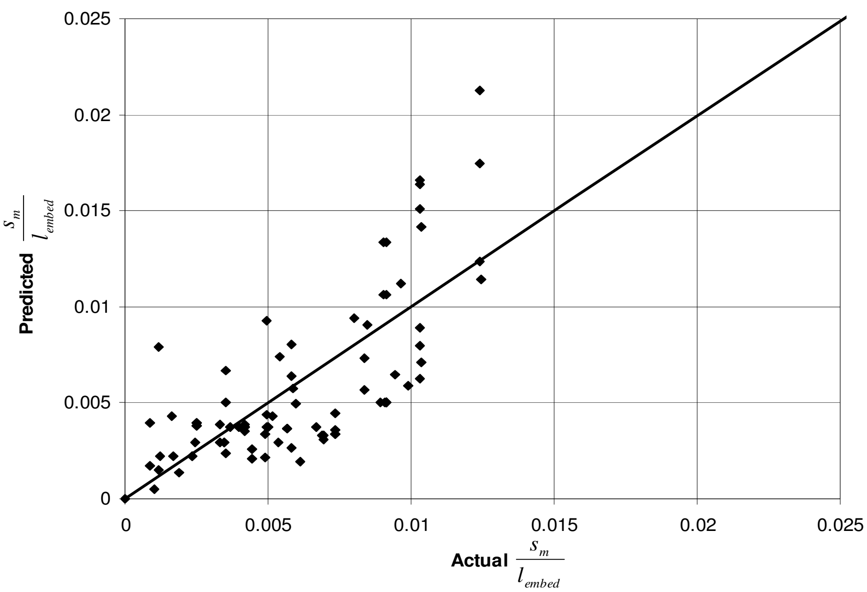



**Figure 4.20 Test vs. predicted normalized slip corresponding to peak bond stress for all specimens.**

## 4.4 Development Length

### 4.4.1 Beam Tests with Splitting Failures

Equation 4.3 can be used to generate an equation to determine the development length required to achieve the full tensile strength of the FRP rebar. The average bond stress $\tau$ can be written in terms of the stress in the reinforcing bar as:

$$\tau = \frac{f_F A_b}{\pi d_b l_{embed}} = \frac{f_F d_b}{4 l_{embed}} \qquad \text{Equation 4.6}$$

where, $f_F$ is the maximum stress in the FRP bar. By combining Equations 4.3 and 4.6 and re-arranging, a relationship between the embedment length required to achieve a stress $f_F$ in the rebar can be determined as follows:

$$l_d = \frac{d_b\left(\frac{f_f}{4\sqrt{f_c'}} - 9.0\right)}{0.03 + 0.14\frac{c}{d_b} + 2.9\frac{A_{tr}}{snd_b}} = \frac{d_b\left(\frac{f_f}{4\sqrt{f_c'}} - 9.0\right)}{0.03 + 0.14\left(\frac{c}{d_b} + 20.7\frac{A_{tr}}{snd_b}\right)} \qquad \text{Equation 4.7}$$

where, $l_d$ is the embedment length required to develop a tensile stress of $f_F$ in the rebar. The embedment length is the bonded length of the rebar provided in the member, whereas, the development length is the embedment length of the rebar required to achieve the desired tensile strength. Equation 4.7 gives an expression for the development length required to avoid splitting mode of failure. This equation will give shorter development length than that required by ACI 440.1R-06 and CSA S806-02 equations since the effect of confinement was taken into consideration. This can save a considerable amount of FRP materials and thereby, reduce the cost of construction. For example, for a beam reinforced with 2-16 mm GFRP bars ($f_{Fu} = 650$ MPa) with 10 mm diameter steel stirrups placed at 100 mm spacing, with a compressive strength of concrete, $f_c' = 30$ MPa, and $\frac{c}{d_b} = 1.5$, Equation 4.7 provides 995 mm development length. On the contrary, ACI 440.1R-06, CSA S806-02, CSA S6-06 and JSCE equations require 1310, 2500, 1465 and 1059 mm development length respectively, which are 32%, 152%, 47% and 7% higher than that required by the proposed equation (Equation 4.7).

### 4.4.2 Beam Tests with Pullout Failures

In the database, there were 203 beam tests that resulted in pullout failures; 26 of these had FRP bars cast as top bars. Of the remaining 177 beam tests, 127 tests were confined and 50 were unconfined. The normalized average bond stresses of all the specimens having pullout and splitting failures were plotted against $\left(\frac{c}{d_b} + 20.7\frac{A_{tr}}{snd_b}\right)$ in Figure 4.21.

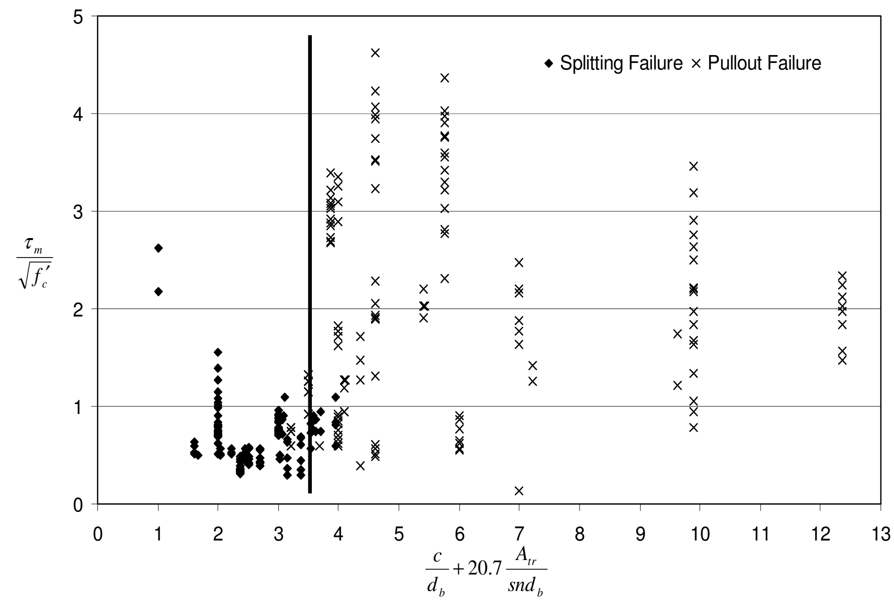



**Figure 4.21 Normalized average bond stresses of confined specimens for both pullout and splitting mode of failure.**

The term $\left(\frac{c}{d_b}+20.7\frac{A_{tr}}{snd_b}\right)$ was chosen because it indicates the total amount of confinement provided to the concrete. When $\left(\frac{c}{d_b}+20.7\frac{A_{tr}}{snd_b}\right)$ is large, there will be enough confinement provided to the concrete and hence, pullout failure will occur. On the contrary, when $\left(\frac{c}{d_b}+20.7\frac{A_{tr}}{snd_b}\right)$ is not sufficient enough, then the specimen will fail by splitting of concrete due to the lack of concrete confinement. From Figure 4.21, it was noticed that for $\left(\frac{c}{d_b}+20.7\frac{A_{tr}}{snd_b}\right)>3.5$, almost all the specimens failed by rebar pullout. This indicates that when $\left(\frac{c}{d_b}+20.7\frac{A_{tr}}{snd_b}\right)$ is greater than 3.5, there will be enough confinement to the concrete and the specimen will fail by rebar pullout. This sets an upper limit to avoid pullout mode of failure for $\left(\frac{c}{d_b}+20.7\frac{A_{tr}}{snd_b}\right)$ in Equation 4.7 as 3.5.

### 4.4.3 Effect of Bar Cast Position

The casting position has been shown to significantly influence the peak bond stress under monotonic static loading (Ehsani *et al.*, 1996). The Canadian and American design codes define top bar reinforcement as the horizontal reinforcement with more than 300 mm (12 in) of concrete below it at the time of casting. In cases of top bar reinforcement, air, water and fine particles migrate upward through the poured concrete during the placement of concrete, thus decreasing the contact area between the rebar and the concrete. This phenomenon can cause a significant drop in the peak bond stress. In the current ACI and CSA codes, the top bar effect is accounted for by multiplying the development length of FRP reinforcement by a top bar modification factor. ACI 440.1R-06 recommended the use of a bar location modification factor of 1.5 for top bars based on the study by Wambeke and Shield (2006), whereas CSA S806-02 recommended 1.3 as the top bar modification factor.

In the present study, there were 22 specimens with top bar which failed by concrete splitting. Figure 4.22 shows a comparison of the normalized average bond stress of unconfined top and bottom bar specimens which failed by concrete splitting. It was found that the average peak bond stress of the top bars was less than the values obtained from the bottom bars by 40-50%. Therefore, bar location modification factor should be proposed based on the available data. The average ratio of test/predicted normalized bond stress for bottom bar and top bar specimen was 0.92 and 0.65 respectively for splitting mode of failure. A modification factor of 1.5 was recommended based on the ratio of the bottom bar specimens to that of the top bar specimens which is the same as the one recommended by ACI 440.1R-06. Therefore, by incorporating the bar location modification factor, Equation 4.7 can be rewritten as

$$l_d = \frac{d_b\left(\dfrac{f_f}{4\sqrt{f_c'}} - 9.0\right)\chi}{0.03 + 0.14\left(\dfrac{c}{d_b} + 20.7\dfrac{A_{tr}}{snd_b}\right)} \qquad \text{Equation 4.8}$$

where $\chi$ is the bar location modification factor, which equals to 1.5 if there is more than 300 mm (12 in) of concrete cast below the bar, otherwise $\chi$ equals 1.

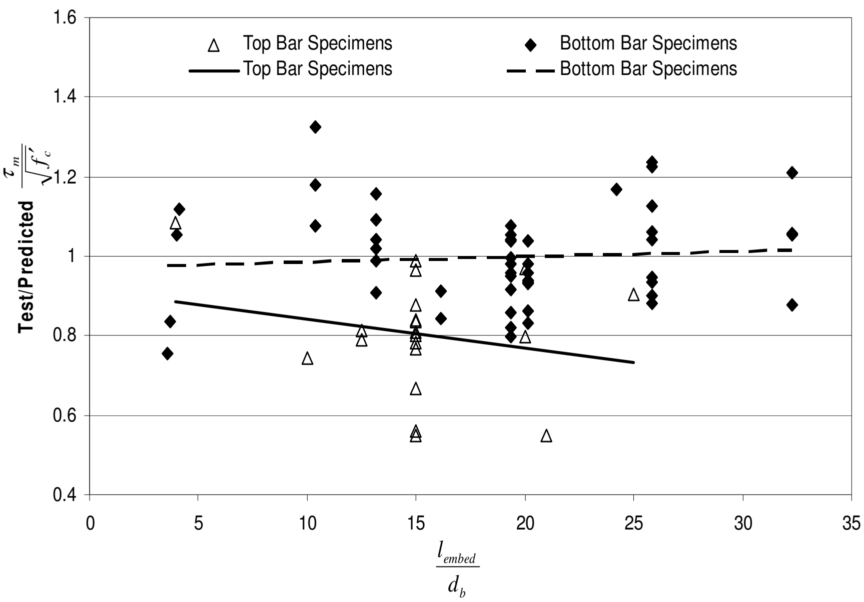



**Figure 4.22 Comparison of normalized average bond stress of unconfined top and bottom bar specimens having splitting failure.**

## 4.5 Summary

This chapter presented the analysis results of the accumulated database which identified the parameters that affect the bond behaviour of FRP rebars in concrete. Linear regression was performed to develop equations for predicting the peak bond stress and the corresponding slip by taking into account all the parameters that affect the bond behaviour of FRP rebars. Modification factors were proposed for rebar surface and bar cast position. It was found that the proposed equations were in good agreement with the experimental results. Based on the peak bond stress equation, design equation for determining the development length of FRP rebars in concrete was derived and a limit was recommended for avoiding a more brittle pullout mode of failure. The most significant contribution of this chapter is that it underlines the effect of confinement provided by the transverse reinforcement on the bond behaviour of FRP rebars in concrete which was either ignored in the formulations proposed for predicting the bond behaviour or modified from the equations available for steel rebars.

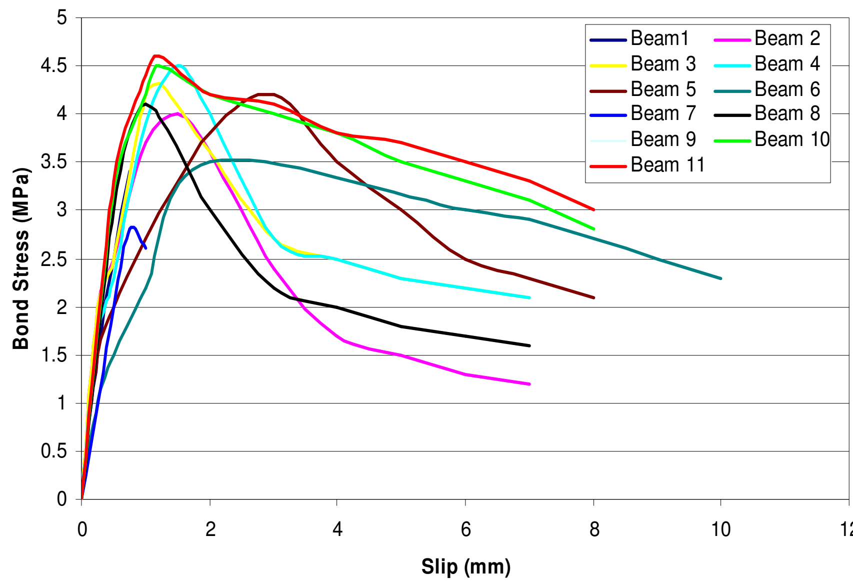
# Chapter 5: Modeling of Bond Stress-Slip Relationship and Finite Element Analysis

## 5.1 General

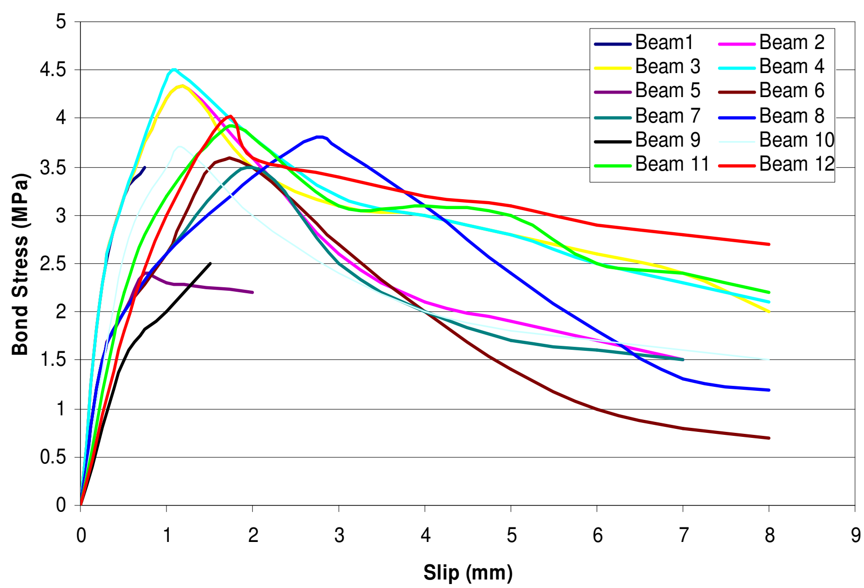
In the previous chapter, it has been observed that the confinement provided by the transverse reinforcement affects the peak bond stress of the FRP rebars in concrete and therefore, a design equation for the peak bond stress was proposed taking into account the effect of the transverse reinforcement. In this chapter, a generalized bond stress-slip relationship will be proposed based on the experimental data and by using the peak bond stress and the corresponding slip equations derived in Chapter 4. In addition, a finite element analysis (FEA) will be performed on the 105 beam-type specimens of the accumulated database, which had transverse reinforcements and failed by splitting of concrete. The purpose of the finite element analysis is to further investigate the effect of the transverse reinforcement on the peak bond stress of FRP rebar in concrete.

## 5.2 Derivation of Bond Stress-Slip Relationship

There were 91 beam-type specimens in the database for which bond stress-slip data were reported along with the bond stress-slip curves. Of these 91 specimens (all the bars were cast as bottom bars), 23 specimens failed by concrete splitting and 68 specimens failed by rebar pullout. Figure 5.1 and Figure 5.2 show typical bond stress-slip curves of the specimens which failed by splitting of concrete and rebar pullout respectively. It can be observed that for pullout mode of failure, the bond stress-slip curves consist of two distinct branches-one initial ascending branch up to the peak bond stress and the other one is a descending post-peak branch (Figure 5.2). On the contrary, for splitting mode of failure, bond stress-slip curves of FRP rebars consist of three distinct branches (Figure 5.1)-two ascending pre-peak branches and one descending post-peak branch. However, in this study, for simplicity and due to the lack of enough experimental data (only 23 specimens failed by splitting of concrete), only one pre-peak branch and one post-peak branch was considered for splitting mode of failure. Therefore, the bond stress-slip data were splitted into two parts-one for the ascending branch of the bond stress-slip curve up to the peak bond stress and the other one is for the descending post-peak branch of the bond stress-slip curve (Figure 5.3). In addition, the data were splitted based on the surface type of the FRP rebars (sand coated, spiral wrapped and helical lugged) which affected the slip corresponding to the peak bond stress.

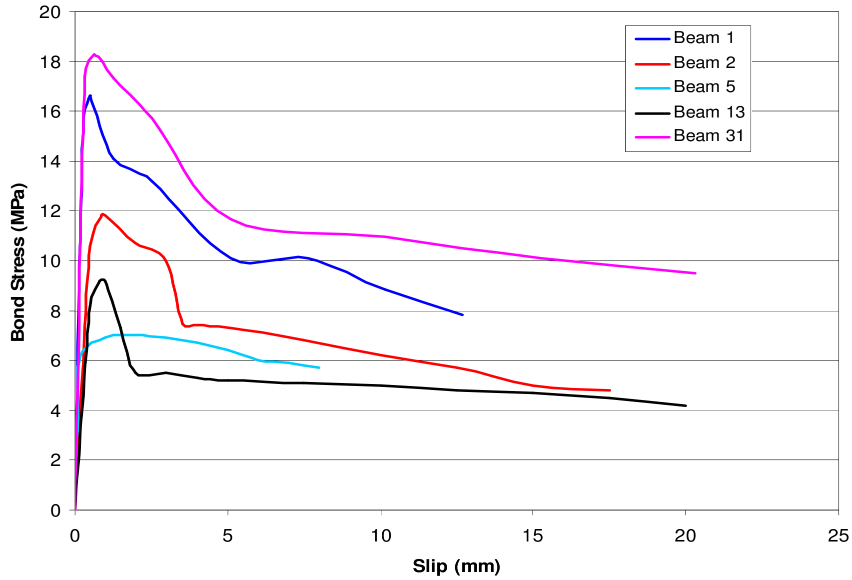



(a) Helical Lugged Bars

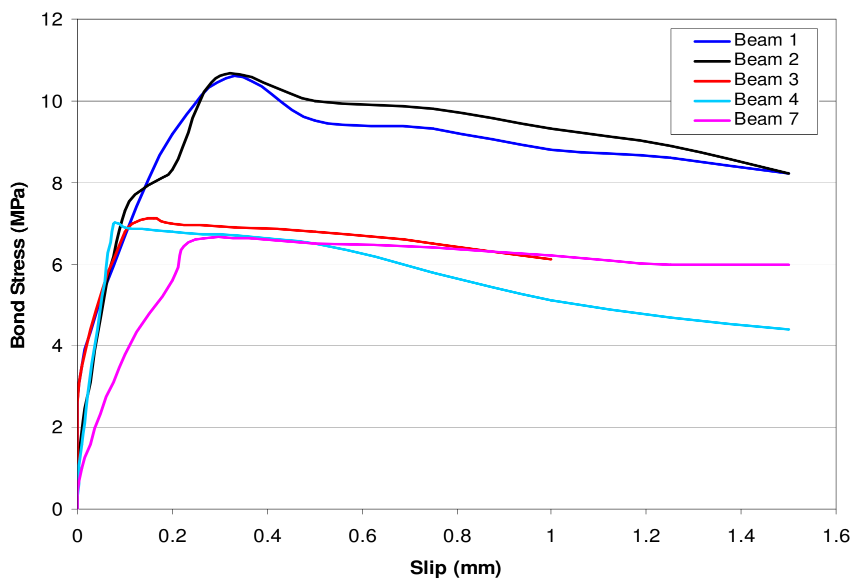



(b) Spiral Wrapped Bars

**Figure 5.1 Bond stress-slip curves for bottom bar specimens having splitting failures.**




(a) Helical Lugged Bars




(b) Spiral Wrapped Bars

**Figure 5.2 Bond stress-slip curves for bottom bar specimens having pullout failures.**

Nonlinear regression analysis was performed on the bond stress-slip data to develop two equations for the ascending and the descending branches of the bond stress-slip curve. It is noted from Figure 5.3 that to predict the bond stress-slip relationship of FRP rebar in concrete, it is necessary to know the peak bond stress ( $\tau_m$ ) and the corresponding slip ( $s_m$ ), because the ascending part ends at that point ( $s_m, \tau_m$ ) and the descending part starts from the same point. Therefore, in the derivation of the bond stress-slip, Equation 4.3 and Equation 4.5 were used to define the peak bond stress and the corresponding slip respectively.

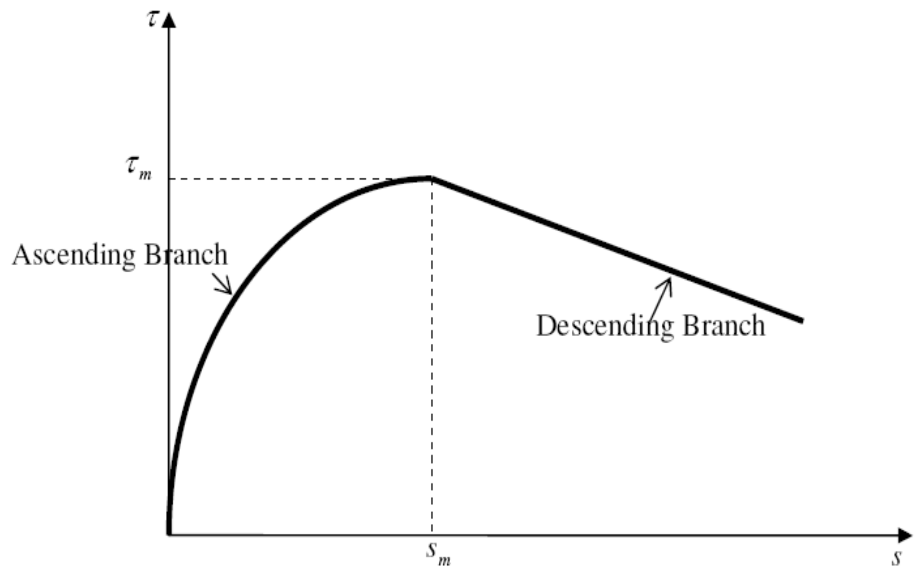



**Figure 5.3 A schematic of the proposed bond stress-slip relationship.**

### 5.2.1 Bond Stress-Slip Relationship Based on Splitting Mode of Failure

Of the 23 beam-type specimens that failed by splitting of concrete, 11 had helical lugged FRP rebars and 12 had spiral wrapped FRP rebars. There was no reported specimen with sand coated rebars which failed by concrete splitting. All of the bars were cast as bottom bars. The data was divided for the ascending part and the descending part of the curves for different surface of the rebar. Of the 23 beam specimens, 6 were unconfined and 17 were confined. However, the effect of confinement would be accounted for in the bond stress-slip relationship through the use of the peak bond stress and the corresponding slip equations. Of the 23 specimens, 7 had AFRP rebars, 11 had CFRP rebars and 5 had GFRP rebars. Since it was observed (section 4.2.1) that the type of FRP does not affect the bond stress-slip of FRP rebars in concrete, it was only important to split the data according to the type of the rebar surface and perform a statistical analysis to develop the bond stress-slip relation for FRP bars with different rebar surface.

Nonlinear regression analysis was performed on the normalized bond stress ($\frac{\tau}{\tau_m}$) and the normalized slip ($\frac{s}{s_m}$) to develop a generalized bond stress-slip relationship for the 23 beam-type specimens which failed by concrete splitting. Figure 5.4 and Figure 5.5 present the experimental data along with the nonlinear regression results for all specimens having helical lugged FRP bars and spiral wrapped FRP bars respectively.

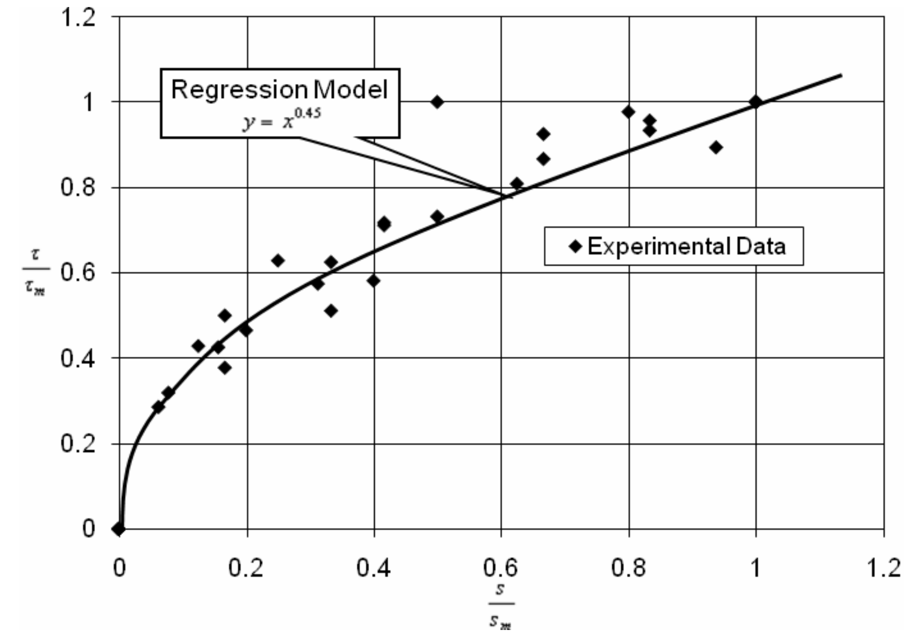
It was observed that the ascending part of the bond stress-slip curve, for both helical lugged and spiral wrapped FRP bars, showed the same behaviour and therefore, the following equation was proposed for the ascending part of the bond stress-slip relationship $(0 \leq s \leq s_m)$:

$$\left(\frac{\tau}{\tau_m}\right) = \left(\frac{s}{s_m}\right)^{0.45} \qquad \text{Equation 5.1}$$

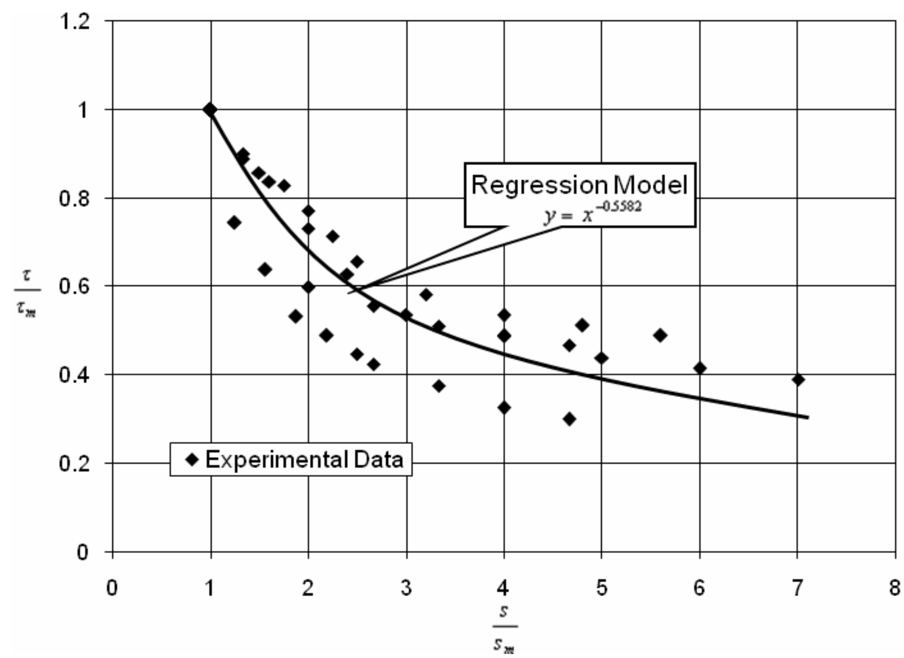
On the other hand, for the descending part of the bond stress-slip curves $(s > s_m)$, there was a slight difference in the behaviour of helical lugged and spiral wrapped FRP bars (Figure 5.4b and Figure 5.5b). It was also noted that the bond stress-slip behaviour of the FRP bars for the descending part of the bond stress-slip curve was nonlinear. Therefore, one generalized equation was proposed for the descending part of the bond stress-slip relationship based on a nonlinear regression analysis of the experimental data and it is expressed as:

$$\left(\frac{\tau}{\tau_m}\right) = \left(\frac{s}{s_m}\right)^{\alpha} \qquad \text{Equation 5.2}$$

where, $\alpha$ is dependent on the rebar surface (-0.56 for helical lugged FRP bars and -0.60 for spiral wrapped FRP bars). Therefore, based on the experimental data and the nonlinear regression results, the proposed generalized bond stress-slip relationship of FRP rebars in concrete is:

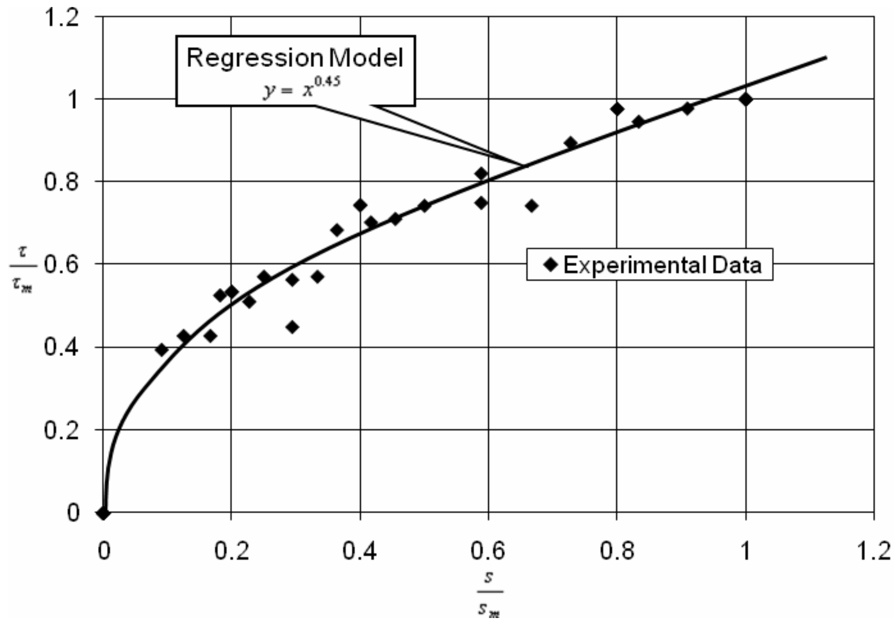



(a) Ascending Branch

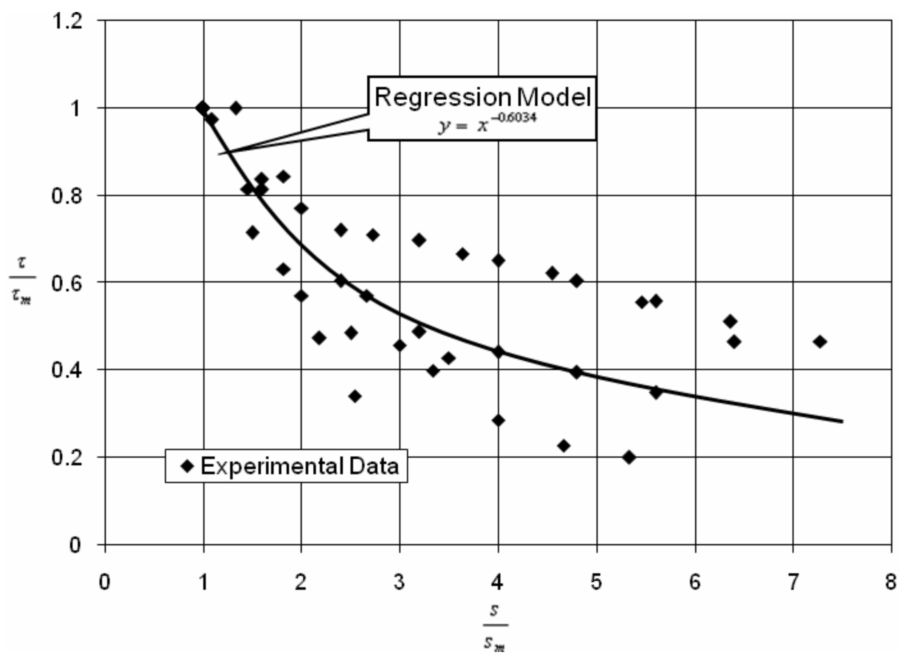



(b) Descending Branch

**Figure 5.4 Nonlinear regression of the experimental data of the bond stress-slip curves for specimens with helical lugged FRP rebars failed by splitting of concrete.**




(a) Ascending Branch




(b) Descending Branch

**Figure 5.5 Nonlinear regression of the experimental data of the bond stress-slip curves for specimens with spiral wrapped FRP rebars failed by splitting of concrete.**

$$\left(\frac{\tau}{\tau_m}\right) = \begin{cases} \left(\frac{s}{s_m}\right)^{0.45} & \text{When } 0 \le s \le s_m \\ \left(\frac{s}{s_m}\right)^{\alpha} & \text{When } s > s_m \end{cases}$$ Equation 5.3

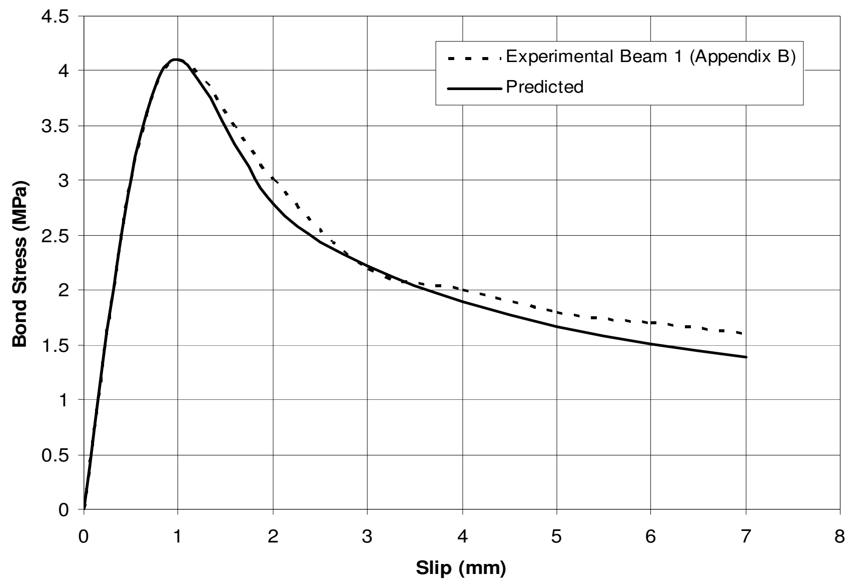
where, $\tau_m$ and $s_m$ are calculated from Equation 4.3 and 4.5 respectively, and

$$\alpha = \begin{cases} -0.56 & \text{for helical lugged/ribbed bars} \\ -0.60 & \text{for spiral wrapped bars} \end{cases}$$

Figure 5.6 and Figure 5.7 show a comparison of the predicted bond stress-slip curves with the experimental results for four beam-type specimens. The comparison of the predicted and the experimental bond stress-slip curves for all 23 specimens is presented in Appendix D (Figure D.1 and Figure D.2) and the reference of each of the experimental beam specimens are presented in Appendix B (Table B.1). It was observed that the predicted values showed good agreement with the experimental data, especially for the ascending part of the bond stress-slip curve up to the peak bond stress and the proposed relationship could capture the peak bond stress in each case. The proposed equation for the ascending part of the bond stress-slip relationship showed a high adjusted determination coefficient (adjusted R-square) value of 0.963 explaining 96.3% of the variability of the response. On the contrary, the proposed equation for the descending part of the bond stress-slip relation showed a moderate adjusted determination coefficient (adjusted R-square) value of 0.663 explaining 66.3% of the variability of the response. Therefore, it can be concluded based on the results of the analysis that the proposed generalized bond stress-slip relationship can give a good prediction of the bond stress-slip behaviour of FRP rebars in concrete when the failure is initiated by splitting of concrete.

## 5.3 Finite Element Analysis (FEA)

During the statistical analysis of the database, it was noted that the confinement provided by the transverse reinforcement increased the peak bond stress and hence, Equation 4.3 was proposed for predicting the peak bond stress of FRP rebars in concrete by taking into account the effect of transverse reinforcement. This conclusion was based on 105 confined beam specimens which failed by splitting of concrete. The data had large scatter and therefore, it was necessary to investigate more. In this section, finite element analysis will be performed to further investigate the effect of concrete confinement provided by the transverse reinforcement on the peak bond stress of FRP rebars in concrete.



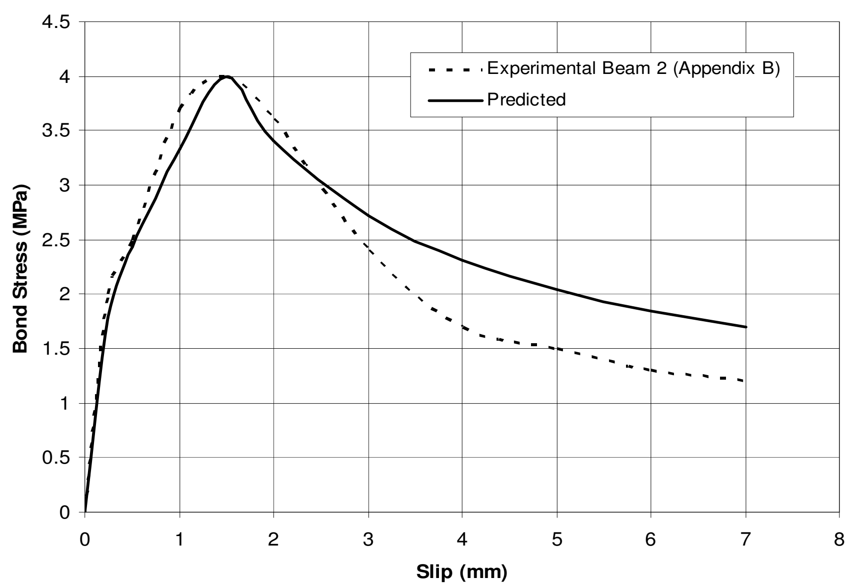




**Figure 5.6 Comparison of the predicted vs. the experimental results for specimens with helical lugged FRP bars having splitting failure.**

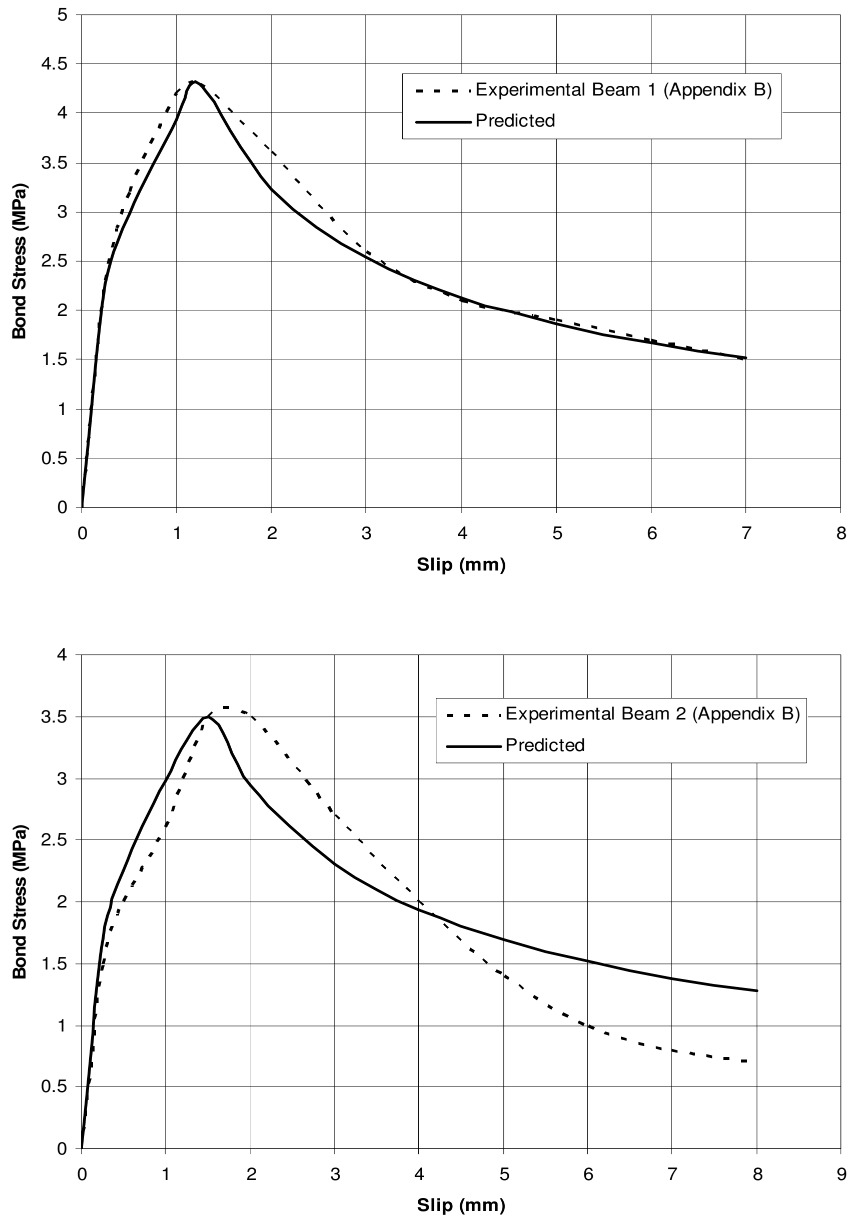
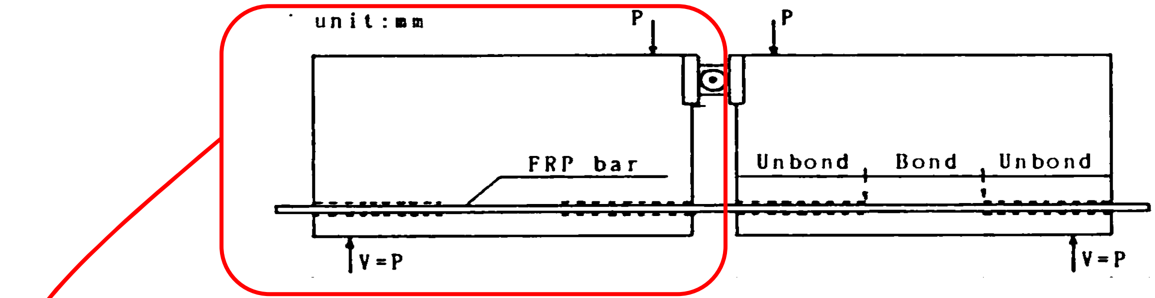


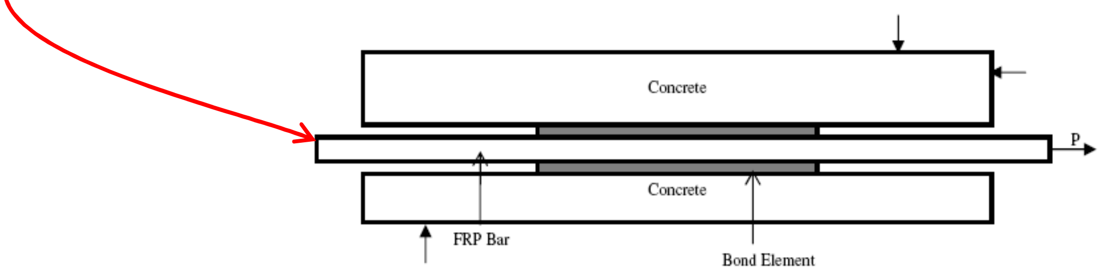

**Figure 5.7 Comparison of the predicted vs. the experimental results for specimens with spiral wrapped FRP bars having splitting failure.**

### 5.3.1 Finite Element Modeling

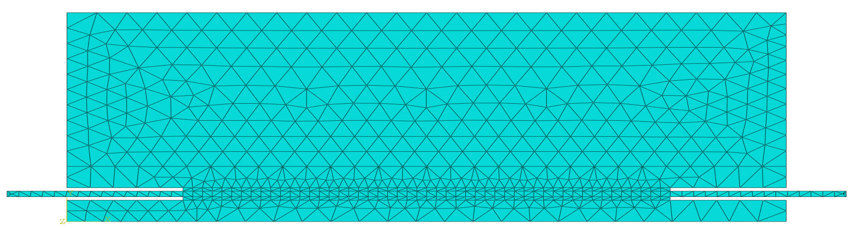
For the finite element analysis of the beam specimens, a commerical finite element package "ABAQUS" was used, since it provides the facility of modeling concrete as a smeared-crack material in 2-dimensional models. In addition, it is regarded as offering a better nonlinear solution procedure for approaching the initiation of cracking in the model. There were 105 confined beam-type specimens which failed by concrete splitting. These included hinged beam specimens and splice beam specimens and all of the specimens were confined with transverse reinforcement. In the FE modeling of the specimens, a half beam model was considered to simulate the hinged beam specimens and a full beam model was considered to simulate the splice beam specimens (Figure 5.8 and Figure 5.9).




(a) Experimental hinged beam specimen used by Makitani *et al.* (1993)

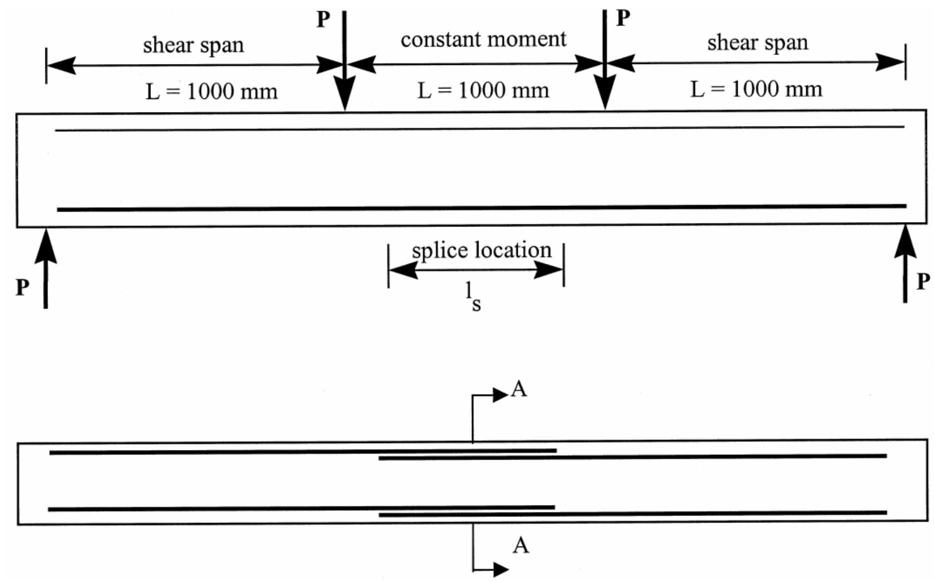



(b) Half beam model considered in the FE analysis

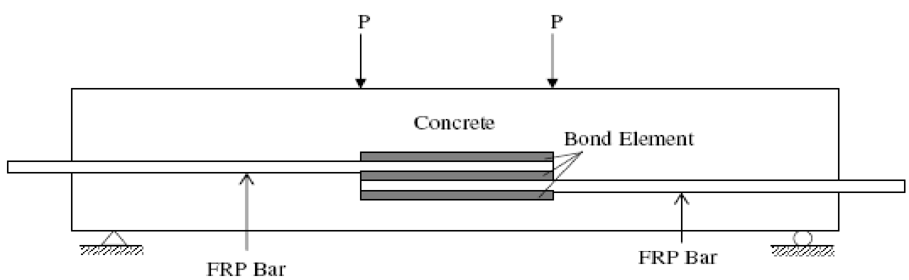


(c) Finite element mesh

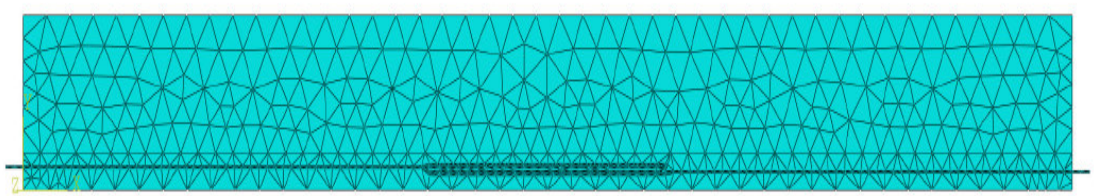
**Figure 5.8 Hinged beam specimen.**




(a) Experimental splice beam specimen used by Tighiouart *et al.* (1999)




(b) Full beam model considered in the FE analysis



(c) Finite element mesh

**Figure 5.9 Splice beam specimen.**

Modeling the Interaction between Concrete and FRP Rebar

Shell elements were used to establish connection between the concrete and the FRP bar. These connecting elements are referred to as "bond element". The main role of the bond elements in this model was to simulate the bond interaction between the bar and the surrounding concrete. The required input data that defined the behaviour of the bond element was the bond stress-slip properties of the bar and the surrounding concrete. In order to define the input bond stress-slip curve, the proposed bond stress-slip relationship for splitting mode of failure was used (Equation 5.3). The values of the peak bond stress ($\tau_m$) and the corresponding slip ($s_m$) in Equation 5.3 was determined by using the following equations that were derived in Chapter 4.

$$\frac{\tau_m}{\sqrt{f_c'}} = 0.03 + 0.14\frac{c}{d_b} + 9.0\frac{d_b}{l_{embed}} + 2.9\frac{A_{tr}}{snd_b} \qquad \text{Equation 4.3}$$

$$s_m = \frac{\eta l_{embed}}{1000}\left(20.8 - 1.3\sqrt{f_c'} - 2.1\frac{c}{d_b} - 3.8\frac{A_{tr}}{snd_b}\right) \qquad \text{Equation 4.5}$$

where, $f_c'$ is the compressive strength of concrete; $c$ is the lesser of the cover to the center of the bar or one-half of the center-to-center spacing of the bars being developed; $d_b$ is the bar diameter; $l_{embed}$ is the embedment length of the bar in concrete; $A_{tr}$ is the area of the transverse reinforcement normal to the plane of splitting through the bars; $s$ is the center to center spacing of the transverse reinforcement; $n$ is the number of bars being developed along the plane of splitting; and $\eta$ is a surface dependent factor, which equals to 1 if the bar surface is helical lugged, 0.43 if it is spiral wrapped and 0.38 if it is sand coated. It can be noted that the bond elements are not continued all through the length of the beam to simulate the experimental set up.

### Materials Model

The following sections will describe the material models that have been used to represent the behaviour of the concrete and the FRP bars in this study.

#### Concrete

Concrete was modeled by using shell element. Since the concrete is mostly used to resist compressive stresses, the behaviour of concrete in compression is of prime importance. In this study, a constitutive model for the concrete in compression suggested by Popovics (1973) and later modified by Thorenfeldth (1987), has been used to describe the compressive behaviour of concrete in the direction of the principal compressive strain. The uniaxial stress-strain relation is expressed by Equation 5.4.

$$\frac{\sigma}{f'_c} = \frac{\varepsilon}{\varepsilon_0} \times \frac{n}{\left[ n - 1 + \left( \frac{\varepsilon}{\varepsilon_0} \right)^{nk} \right]} \quad \text{Equation 5.4}$$

where, $n$ is the curve fitting parameter and $k$ is the post-peak decay term and is taken as 1 for $\frac{\varepsilon}{\varepsilon_0} < 1$. Collins and Mitchell (1991) suggested expressions for $n$ and $k$, which are given in Equation 5.5. It is to be noted that $f'_c$ is taken in the metric system of units in Equation 5.5. A typical stress-strain relation according to Equation 5.4 is shown Figure 5.10.

$$n = 0.8 + \frac{f'_c}{17} \qquad k = 0.67 + \frac{f'_c}{62} \quad \text{Equation 5.5}$$

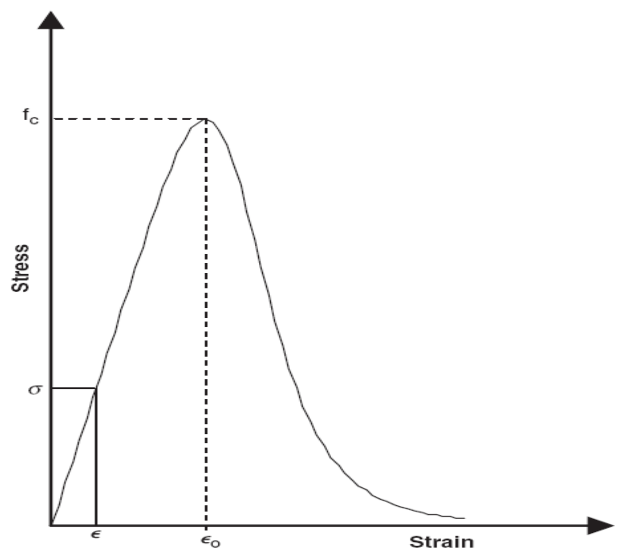



**Figure 5.10 Concrete compressive stress-strain model (Thorenfeldt *et al.* 1987).**

Concrete is a weak material in tension and its tensile strength is of very little significance in any direct application. However, it plays a key role in the development of cracks in the concrete, which can influence its behaviour at the structure level and also in bond. In this study, the stress-strain relation for the uncracked concrete in the direction of the maximum principal tensile strain has been assumed linear up to the tensile strength ( $f_{ct}$ ) and its post-peak behaviour comprise of a tension softening branch as shown in Figure 5.11. Equations 5.4 and 5.5 were used to calculate the stress and the plastic strain for concrete and these were used as material properties for concrete.

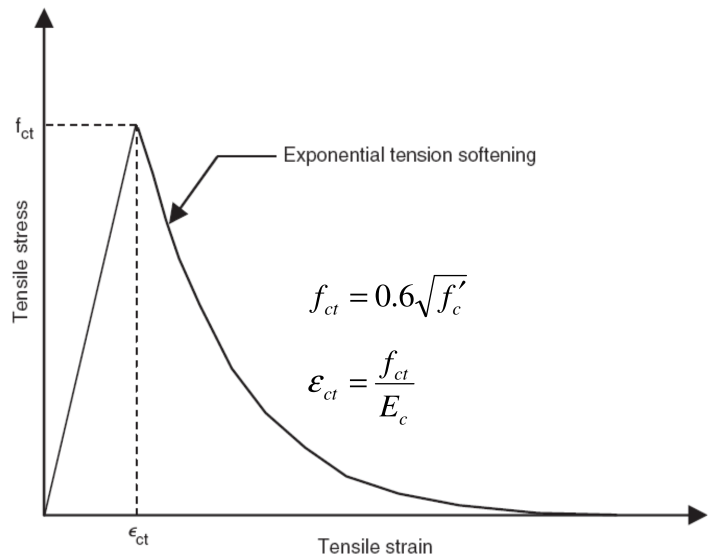



**Figure 5.11 Behaviour of concrete under tension.**

FRP Reinforcement

Shell element was used to model the FRP rebar. FRP reinforcements were modeled as a linear elastic material with a brittle fracture in tension (Figure 5.12). The ultimate tensile strength of the material is represented by $f_{Fu}$ , while the corresponding strain at failure is $\varepsilon_{Fu}$ .

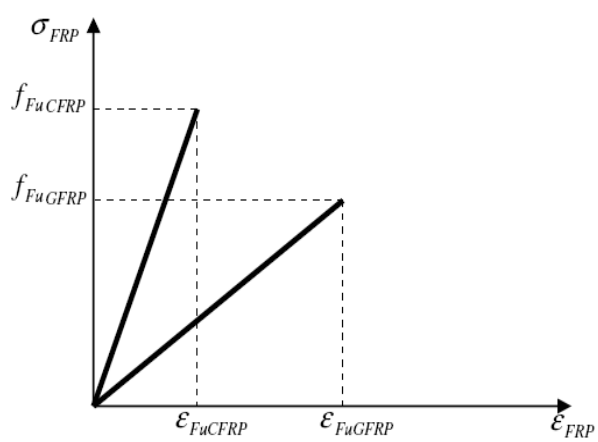



**Figure 5.12 Constitutive relations for FRP reinforcements.**

### Finite Element Mesh

The different parts of the beam was meshed by using the module "mesh" in ABAQUS/CAE. The top down meshing technique (free meshing), a more flexible method, was used in this study. A 3-node linear plane strain triangle element (CPE3) was defined for the concrete, the FRP reinforcing bar, and the bond element. Finer meshing was used near the bond element. Figure 5.8(c) and Figure 5.9(c) show the finite element mesh for the half beam and the full beam specimens considered in the study respectively. The models of the beam specimens were run with different mesh densities and it was observed that the modeling procedure used was insensitive to the mesh size.

### 5.3.2 FEA Results and Discussion

The objective of the finite element analysis was to model the experimental beams of the database and investigate whether the presence of transverse reinforcement affects the peak bond stress of the FRP rebars in concrete. The proposed equation to predict the peak bond stress obtained from the experimental data can be expressed as follows

$$\frac{\tau_m}{\sqrt{f_c'}} = 0.03 + 0.14\frac{c}{d_b} + 9.0\frac{d_b}{l_{embed}} + C_t\frac{A_{tr}}{snd_b} \qquad \text{Equation 5.6}$$

where, $C_t$ is a constant that was determined from the experimental statistical analysis as 2.9.

The approach for the finite element analysis was to model each of the 105 confined beam specimens of the database that failed by concrete splitting and the bond stress-slip relationship for each of the specimens was assigned as the input parameter on the bond element. The bond stress-slip relationship for each of the specimens was obtained by using Equation 5.3. The peak bond stress was determined from Equation 5.6 by using a different value for $C_t$. Static load was applied on the specimens until each of the specimens failed in bond. The failure loads obtained from the finite element analysis were then compared with the experimental failure loads. If the failure load obtained from the FE analysis was not equal or very close to the experimental failure load, the coefficient $C_t$ of the transverse reinforcement effect ( $\frac{A_{tr}}{snd_b}$ ) in peak bond stress equation (Equation 5.6) was modified and the model was executed again. Figure 5.13 shows a flow chart for the iterations performed during the finite element analysis. Thus, several iterations were performed on each beam specimen by changing the coefficient $C_t$. Hence, 105 values of the coefficient $C_t$ were obtained for each of the 105 confined beam specimens which are shown in Appendix E (Table E.1).

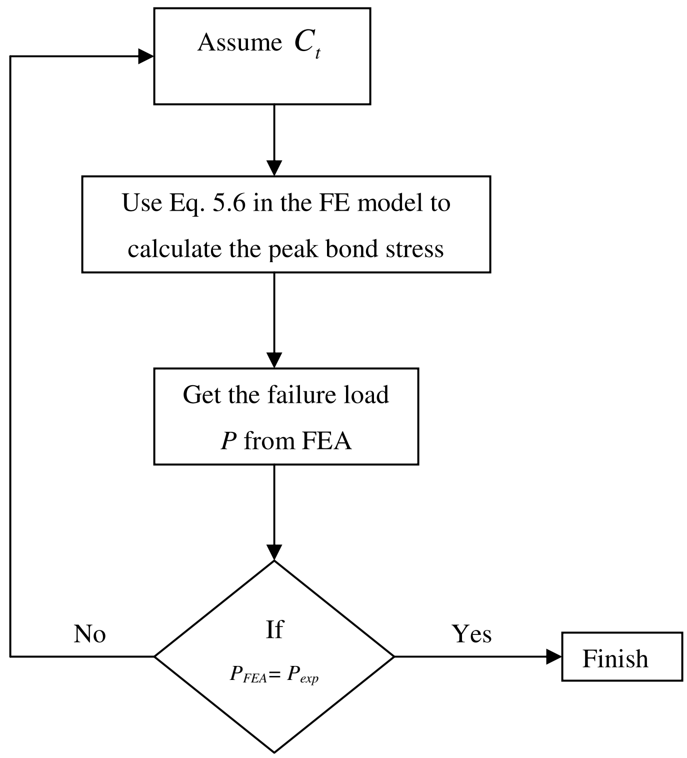



**Figure 5.13 Flow chart of the iterations performed in FEA.**

By using the 105 values of $C_t$, the peak bond stress of the 105 specimens were obtained. The contribution of the transverse reinforcement in the peak bond stress $(\tau_{tr})_{FEA}$ was calculated by deducting the peak bond stress of the unconfined specimen, $\tau_c$ calculated by using Equation 4.1, from the peak bond stress obtained from FEA i.e. $(\tau_{tr})_{FEA} = \tau_{FEA} - \tau_c$. Figure 5.14 shows the normalized peak bond stress contribution of the transverse reinforcement ( $\frac{\tau_{tr}}{\sqrt{f_c'}}$ ) plotted against $\frac{A_{tr}}{snd_b}$ from both the experimental and the finite element analysis results along with the regression line of the plotted values.

It was observed that the regression model of the plotted values obtained from the FE analysis gave the value of the coefficient $C_t$ as 2.45, whereas, from the experimental results it was obtained as 2.93. A positive value of the coefficient $C_t$ indicates that the confinement provided by the transverse reinforcement increased the peak bond stress and hence, the presence of transverse reinforcement should be considered in determining the peak bond stress. The results also indicated that the proposed equation (Equation 5.6) for predicting the peak bond stress may be unconservative in some cases.

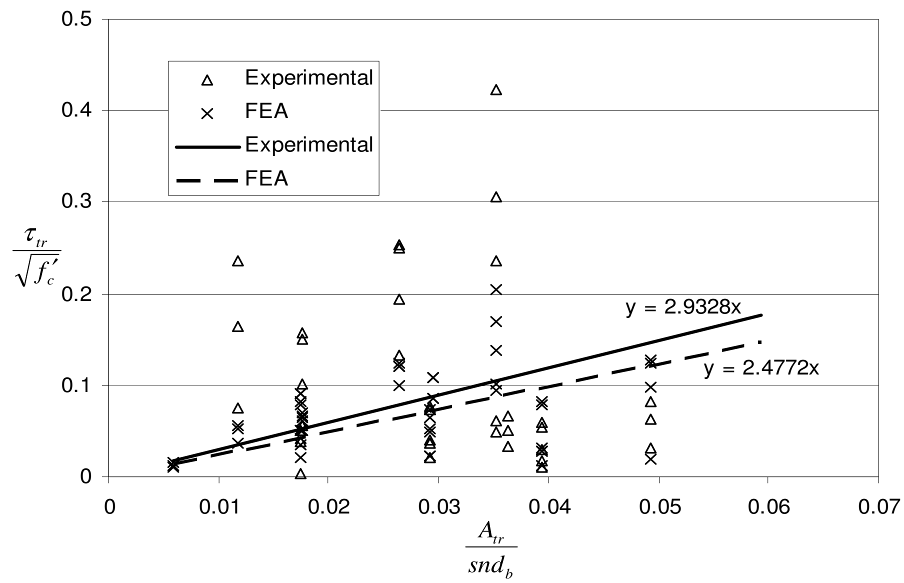



**Figure 5.14 Comparison of experimental and finite element analysis results.**

Therefore, based on the results of the finite element analysis, a value of 2.0 was recommended as the coefficient $C_t$ of the effect of transverse reinforcement ($\frac{A_{tr}}{snd_b}$) in Equation 5.6 to be on the conservative side. Then the equation for the peak bond stress takes the following form

$$\frac{\tau_m}{\sqrt{f_c'}} = 0.03 + 0.14\frac{c}{d_b} + 9.0\frac{d_b}{l_{embed}} + 2.0\frac{A_{tr}}{snd_b} \qquad \text{Equation 5.7}$$

Using Equation 5.7, the following development length equation was derived for FRP rebars in concrete

$$l_d = \frac{d_b\left(\frac{f_f}{4\sqrt{f_c'}} - 9.0\right)\chi}{0.03 + 0.14\left(\frac{c}{d_b} + 14.3\frac{A_{tr}}{snd_b}\right)}$$ Equation 5.8

## 5.4 Sensivity Analysis

Figure 5.15 shows the comparison of the required development length obtained from the proposed equation (Equation 5.8) against ACI 440.1R-06, CSA S806-02, CSA S6-06 and JSCE equations for different cover to bar diameter ($\frac{c}{d_b}$) ratio for a beam reinforced with 2-16 mm FRP bars with 10 mm diameter steel stirrups placed at 100 mm spacing. It was observed that for all cover to bar diameter ($\frac{c}{d_b}$) ratios, ACI 440.1R-06 and CSA S806-02 equations overestimate the development length required to achieve the full tensile strength of the rebar compared to the proposed equation (Equation 5.8). For $1 \le \frac{c}{d_b} \le 2$, the development length required by the ACI 440.1R-06 equation is 15%-20% higher than that required by the proposed equation, whereas the development length required by the CSA S806-02 equation is more than twice the length required by the proposed equation. For $2 \le \frac{c}{d_b} \le 3.5$, the development length required by the ACI 440.1R-06 equation is 50%-60% higher than that required by the proposed equation, whereas the development length required by the CSA S806-02 equation is still almost twice the length required by the proposed equation. It was observed that as the concrete strength is increased or the ultimate tensile strength of the bar is decreased, the proposed equation can save more of the development length compared to the ACI 440.1R-06 or the CSA S806-02 equations.

CSA S6-06 also overestimates the development length compared to the proposed equation. For FRP rebars with low ultimate tensile strength, the development length required by the CSA S6-06 equation is 20% (on an average) higher than that required by the proposed equation. On the other hand, for FRP rebars with high ultimate tensile strength and $\frac{c}{d_b} \le 2.5$, the development length required by the CSA S6-06 equation is 10% (on an average) higher than that required by

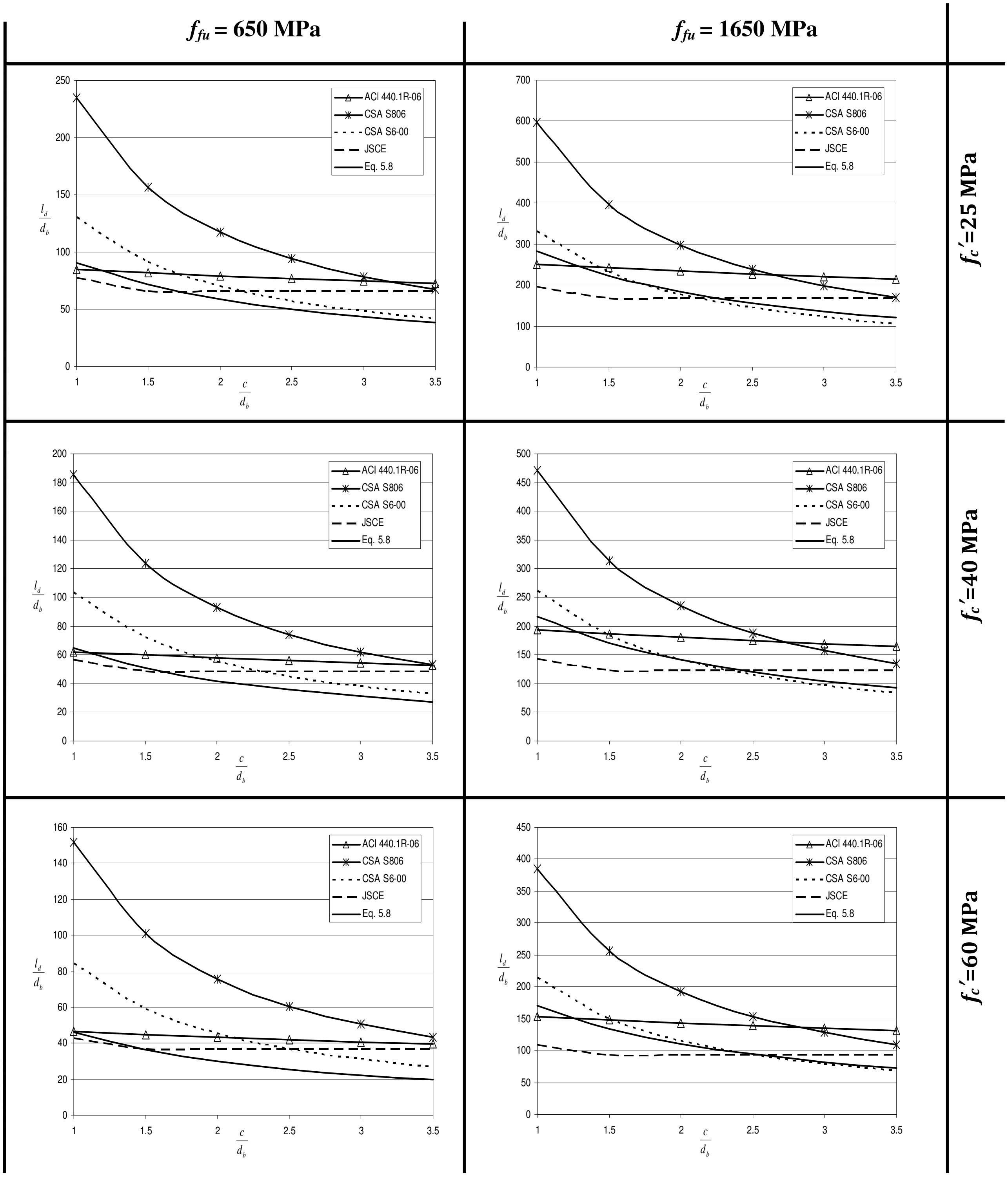



**Figure 5.15 Comparison of the required development length for different cover to bar diameter ratio**

the proposed equation, but for $\frac{c}{d_b} > 2.5$, CSA S6-06 and the proposed equation calculate almost the same development length.

The development length required by the JSCE equation was very close to the proposed equation. For FRP rebars with low ultimate tensile strength and $\frac{c}{d_b} \leq 1.5$, the proposed equation gives a conservative estimate of the development length compared to the JSCE equation, which is 10% higher than that required by the JSCE equation, but for $\frac{c}{d_b} > 1.5$, the proposed equation gives a development length that is 30%-40%% lower than that required by the JSCE equation.. For FRP rebars with high ultimate tensile strength and $\frac{c}{d_b} \leq 2$, the proposed equation gives a conservative estimate of the development length compared to the JSCE equation, which is 20% higher than that required by the JSCE equation, but for $\frac{c}{d_b} > 2$, the proposed equation gives a development length that is 20-25% lower than that required by the JSCE equation.

Based on the analysis, it can be concluded that the proposed equation can save on an average 10%-15% of the required development length compared to the code equations. This will reduce the cost of materials, which will eventually reduce the cost of construction. Therefore, the proposed equation can be a reasonable and a cost-effective option to estimate the development length required for FRP rebar in the design of RC structures.

## 5.5 Summary

In this chapter, a generalized bond stress-slip relationship of FRP rebars in concrete has been developed by performing nonlinear regression of the experimental data. Modification factors were proposed so that the derived bond stress-slip relationship can be applied to any type of FRP rebar with different surface textures. It was observed that the proposed bond stress-slip relationship was in good agreement with the experimental data. Based on the data analysis and the comparison with the experimental data, it was concluded that the proposed bond stress-slip relationship can be a reasonable mean to predict the bond behaviour of FRP rebars in concrete with acceptable accuracy. Moreover, the finite element analysis results of the confined beam specimens have been presented in this chapter which indicated that confinement provided by the transverse reinforcement increased the bond strength of FRP rebars in concrete and based on the FEA results, the proposed peak bond stress and the development length equations have been modified. The proposed development length equation was compared with the available code equations and it was noted that the proposed development length equation can save 10%-15% of the development length required by the code equations and thereby, reduce the overall cost of construction.

# Chapter 6: Conclusions

## 6.1 General

The objective of the present study was to investigate the effect of different parameters on the bond behaviour of FRP rebars in concrete and thereby, to propose equations for predicting the peak bond stress and the corresponding slip, to establish a general bond stress-slip law, to derive a design equation for determining the development length which can be applied to different types of FRP rebars. For this purpose, all the experimental data on beam bond test was accumulated from the literature up to 2009 and the database was analysed statistically. Based on the analysis of the experimental data, expressions were derived for the peak bond stress and the corresponding slip, the development length and a general bond stress-slip law. In addition, a finite element analysis was performed to validate the proposed expressions. The results of the statistical and the finite element analyses lead to the following conclusions;

- Type of fibres does not affect the peak bond stress and the corresponding slip of FRP rebars in concrete. Rebar surface does not influence the peak bond stress, but it affects the slip corresponding to the peak bond stress. Helical lugged/ribbed bars show larger slip before attaining the peak bond stress than spiral wrapped or sand coated bars. Spiral wrapped and sand coated bars show almost the same slip at the peak bond stress. This means initial stiffness of the bond stress-slip curves of spiral wrapped and sand coated bars are larger than that of the helical lugged/ribbed bars.

- Compressive strength of concrete, concrete cover, embedment length and bar diameter affect the peak bond stress and the corresponding slip of FRP rebars in concrete significantly. With increase in concrete strength and concrete cover, the peak bond stress increases, whereas slip at peak bond stress decreases. This indicates that there is an increase in the initial stiffness of the bond stress-slip curve with increase in concrete strength and concrete cover. On the contrary, with increase in the bar diameter and the embedment length, the peak bond stress decreases, whereas slip at peak bond stress increases i.e. there is a decrease in the initial stiffness of the bond stress-slip curve.

- Bar cast position has a significant effect on the peak bond stress of FRP rebars in concrete. When there is more than 300 mm of concrete cast below the reinforcing bars (known as top bars), the bars usually show 50% decrease in the peak bond stress than the bottom bars.

- Confinement provided by the transverse reinforcement influences the peak bond stress and the corresponding slip. Peak bond stress increases with increase in the amount of transverse reinforcement, whereas slip at peak bond stress decreases due to the confining action of the transverse reinforcements. It has been observed from the experimental data that there is 10%-15% increase in the peak bond stress in presence of transverse reinforcement. This indicates a decrease in the required development length of FRP rebars in concrete due to the confinement provided by the transverse reinforcement.

- By considering all the parameters that influence the peak bond stress and the corresponding slip, relationships have been derived to evaluate the peak bond stress and the corresponding slip by using linear regression analysis. The confining effect of transverse reinforcement has been taken into consideration for deriving the equations. Rebar surface modification factors have been proposed for the slip at the peak bond stress equation. It has been observed that the proposed equations are in good agreement with the experimental results and they can predict the peak bond stress and the corresponding slip with acceptable accuracy. The proposed peak bond stress equation has also been compared with the ACI 440.1R-06 equation and it has been observed that the ACI equation underestimates the peak bond stress in presence of transverse reinforcements, whereas the proposed equation shows good correlation with the experimental results since it takes into account the confinement provided by the transverse reinforcements.

- Based on the peak bond stress equation, a design equation has been derived to determine the development length required to achieve the design tensile strength of FRP rebars in concrete.

- After defining relations for the peak bond stress and the corresponding slip, a general bond stress-slip relationship has been developed for splitting mode of failure. It has been observed that all types of FRP bars show similar behaviour for the initial ascending part of the bond stress-slip curves, but for the softening post-peak branch, the behaviour varied for different rebar surfaces and hence, rebar surface modification factors have been proposed. It has also been noted that the proposed bond stress-slip relationship shows good agreement with the experimental results, and it provides a reasonable means of predicting the bond behaviour of FRP rebars in concrete.

- Finite element analysis has been performed to validate the proposed bond stress-slip relationship and the effect of transverse reinforcement on the bond strength of FRP rebars in concrete. Based on the finite element analysis results, the equations for the peak bond stress and the development length were modified.

- Sensitivity analysis of the proposed development length equation with the ACI 440.1R-06, CSA S806-02, CSA S6-06 and JSCE equations reveals that the proposed development length can save about 10%-15% of the development length required by the code equations on an average, since it takes the advantage of the confining action provided by the transverse reinforcement. A reduction in the development length leads to a reduction in the cost of materials which will eventually decrease the overall cost of construction and encourage the use of FRP in the construction of reinforced concrete structures.

## 6.2 Limitations of the Study

There are some limitations which need to be acknowledged and addressed regarding the present study. The limitations of the study are summarized below:

- The effect of transverse reinforcement was accounted for in the development of the proposed design equations and this was based on 105 confined beam specimens which failed by splitting of concrete. Also, no comprehensive and systematic study was performed on the effect of transverse reinforcement on the bond behaviour of FRP rebars in concrete. Hence, more experiments are required to modify the proposed design equations.

- The equation proposed for the slip corresponding to the peak bond stress was based on 97 beam bond tests. The data was not splitted based on the failure mode due to the lack of sufficient data. Moreover, there was no specimen with sand coated bars for splitting mode of failure and hence, no conclusion could be made for sand coated bars having splitting failures.

- The bond stress-slip curves of the specimens failed by splitting of concrete showed three branches-two pre-peak and one post-peak. For simplicity and due to the lack of enough experimental data, one pre-peak and one post-peak branches were considered.

- There was no bond stress-slip curve for specimens with sand coated FRP bars having splitting failure and hence, no equation was proposed for sand coated bars.

- The number of bond tests with $f_c' > 50$ MPa was very small and hence, more tests are needed with high strength concrete.

## 6.3 Future Recommendations

This study can be further improved with the availability of more literature. However, following are some recommendations for future investigation:

- More experimental works are needed on AFRP and CFRP reinforcing bars to verify whether there is any effect of the type of fibre on the bond behaviour of FRP rebars in concrete.

- Studies are required to determine particularly the effect of rebar surface on the bond behaviour of FRP rebars in concrete.

- Extensive experimental investigation is necessary for confined beam specimens to assure the effect of concrete confinement provided by the transverse reinforcement. Effect of transverse reinforcements made of FRP bars should also be investigated.

- Bond behaviour of FRP rebars in high strength concrete should be investigated by using beam bond tests.

- More bond stress-slip measurements are required to validate and modify the proposed bond stress-slip model.

# Appendices

# Appendix A

**Table A.1 Consolidated database of beam-type specimens for evaluating peak bond stress of FRP rebars in concrete**

| SI | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f_c'}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 12.7 | 5.56 | 3.00 | 16.00 | nr | nr | Tensile |
| 2 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 12.7 | 5.56 | 3.00 | 16.00 | nr | nr | Tensile |
| 3 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 12.7 | 5.56 | 3.00 | 16.00 | nr | nr | Tensile |
| 4 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 12.7 | 5.56 | 3.00 | 24.00 | nr | nr | Tensile |
| 5 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 12.7 | 5.56 | 3.00 | 24.00 | nr | nr | Tensile |
| 6 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 12.7 | 5.56 | 3.00 | 24.00 | nr | nr | Tensile |
| 7 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 12.7 | 5.56 | 3.00 | 32.00 | nr | nr | Tensile |
| 8 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 12.7 | 5.56 | 3.00 | 32.00 | nr | nr | Tensile |
| 9 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 12.7 | 5.56 | 3.00 | 32.00 | nr | nr | Tensile |
| 10 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 19.05 | 5.56 | 3.00 | 16.00 | nr | nr | Pullout |
| 11 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 19.05 | 5.56 | 3.00 | 16.00 | nr | nr | Pullout |
| 12 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 19.05 | 5.56 | 3.00 | 16.00 | nr | nr | Pullout |
| 13 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 19.05 | 5.56 | 3.00 | 24.00 | nr | nr | Splitting |
| 14 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 19.05 | 5.56 | 3.00 | 24.00 | nr | nr | Splitting |
| 15 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 19.05 | 5.56 | 3.00 | 24.00 | nr | nr | Splitting |
| 16 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 19.05 | 5.56 | 3.00 | 32.00 | nr | nr | Tensile |
| 17 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 19.05 | 5.56 | 3.00 | 32.00 | nr | nr | Tensile |
| 18 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 19.05 | 5.56 | 3.00 | 32.00 | nr | nr | Tensile |
| 19 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 25.4 | 5.56 | 3.00 | 20.00 | nr | nr | Pullout |
| 20 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 25.4 | 5.56 | 3.00 | 20.00 | nr | nr | Pullout |
| 21 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 25.4 | 5.56 | 3.00 | 20.00 | nr | nr | Pullout |
| 22 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 25.4 | 5.56 | 3.00 | 25.00 | nr | nr | Pullout |
| 23 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 25.4 | 5.56 | 3.00 | 25.00 | nr | nr | Pullout |

| SI | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f'_c}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f'_c}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 25.4 | 5.56 | 3.00 | 25.00 | nr | nr | Pullout |
| 25 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 25.4 | 5.56 | 3.00 | 30.00 | nr | nr | Pullout |
| 26 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 25.4 | 5.56 | 3.00 | 30.00 | nr | nr | Splitting |
| 27 | Daniali (1990) | NB | GFRP | Confined | Bottom | SW | 25.4 | 5.56 | 3.00 | 30.00 | nr | nr | Splitting |
| 28 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | nr | 9.525 | 5.38 | 2.67 | 64.00 | 0.079 | 0.498 | Tensile |
| 29 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | nr | 9.525 | 5.38 | 2.67 | 64.00 | 0.079 | 0.494 | Tensile |
| 30 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | nr | 9.525 | 5.38 | 2.67 | 32.00 | 0.079 | 0.743 | Tensile |
| 31 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | nr | 9.525 | 5.38 | 2.67 | 32.00 | 0.079 | 0.734 | Tensile |
| 32 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | nr | 9.525 | 5.38 | 2.67 | 21.33 | 0.079 | 1.277 | Tensile |
| 33 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | nr | 9.525 | 5.38 | 2.67 | 21.33 | 0.079 | 1.087 | Tensile |
| 34 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | nr | 25.4 | 5.38 | 1.00 | 16.00 | 0.029 | 0.572 | Pullout |
| 35 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | nr | 25.4 | 5.38 | 1.00 | 16.00 | 0.029 | 0.611 | Pullout |
| 36 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | nr | 25.4 | 5.38 | 1.00 | 24.00 | 0.029 | 0.493 | Pullout |
| 37 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | nr | 25.4 | 5.38 | 1.00 | 24.00 | 0.029 | 0.510 | Pullout |
| 38 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | nr | 9.525 | 5.38 | 2.67 | 42.67 | 0.079 | nr | Grip Failure |
| 39 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | nr | 9.525 | 5.38 | 2.67 | 42.67 | 0.079 | nr | Grip Failure |
| 40 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | SW | 25.4 | 5.25 | 1.00 | 16.00 | 0.029 | 0.590 | Splitting |
| 41 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | SW | 25.4 | 5.25 | 1.00 | 16.00 | 0.029 | 0.630 | Splitting |
| 42 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | SW | 25.4 | 5.25 | 1.00 | 24.00 | 0.029 | 0.508 | Splitting |
| 43 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | SW | 25.4 | 5.25 | 1.00 | 24.00 | 0.029 | 0.525 | Splitting |
| 44 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | SW | 9.525 | 5.25 | 2.67 | 42.67 | 0.079 | na | Grip |
| 45 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | SW | 9.525 | 5.25 | 2.67 | 42.67 | 0.079 | na | Grip |
| 46 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | SW | 9.525 | 5.25 | 2.67 | 64.00 | 0.079 | 0.510 | Tensile |
| 47 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | SW | 9.525 | 5.25 | 2.67 | 64.00 | 0.079 | 0.510 | Tensile |
| 48 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | SW | 9.525 | 7.18 | 2.67 | 32.00 | 0.079 | 0.556 | Tensile |
| 49 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | SW | 9.525 | 7.18 | 2.67 | 32.00 | 0.079 | 0.549 | Tensile |

| Sl | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f_c'}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 50 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | SW | 9.525 | 7.18 | 2.67 | 21.33 | 0.079 | 0.955 | Tensile |
| 51 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | SW | 9.525 | 7.18 | 2.67 | 21.33 | 0.079 | 0.813 | Tensile |
| 52 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | SW | 12.7 | 7.18 | 6.00 | 8.00 | 0.059 | 1.253 | Slip |
| 53 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | SW | 12.7 | 7.18 | 6.00 | 8.00 | 0.059 | 1.423 | Slip |
| 54 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | SW | 6.35 | 7.18 | 12.00 | 24.00 | 0.118 | 1.676 | Tensile |
| 55 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | SW | 6.35 | 7.18 | 12.00 | 24.00 | 0.118 | 1.737 | Tensile |
| 56 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | SW | 12.7 | 8.08 | 6.00 | 16.00 | 0.059 | 1.137 | Splitting |
| 57 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | SW | 12.7 | 8.08 | 6.00 | 16.00 | 0.059 | 0.970 | Splitting |
| 58 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | SW | 9.525 | 8.08 | 8.00 | 10.67 | 0.079 | 1.739 | Pullout |
| 59 | Faza & GangaRao (1990) | IHB | GFRP | Confined | Bottom | SW | 9.525 | 8.08 | 8.00 | 10.67 | 0.079 | 1.217 | Pullout |
| 60 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 12.7 | 5.25 | 3.00 | 16.00 | nr | nr | Tensile |
| 61 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 12.7 | 5.25 | 3.00 | 16.00 | nr | nr | Tensile |
| 62 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 12.7 | 5.25 | 3.00 | 16.00 | nr | nr | Tensile |
| 63 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 12.7 | 5.25 | 3.00 | 24.00 | nr | nr | Tensile |
| 64 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 19.05 | 5.25 | 2.00 | 24.00 | nr | nr | Tensile |
| 65 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 12.7 | 5.25 | 3.00 | 24.00 | nr | nr | Tensile |
| 66 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 12.7 | 5.25 | 3.00 | 24.00 | nr | nr | Tensile |
| 67 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 19.05 | 5.25 | 2.00 | 32.00 | nr | nr | Tensile |
| 68 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 12.7 | 5.25 | 3.00 | 32.00 | nr | nr | Tensile |
| 69 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 12.7 | 5.25 | 3.00 | 32.00 | nr | nr | Tensile |
| 70 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 12.7 | 5.25 | 3.00 | 32.00 | nr | nr | Tensile |
| 71 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 19.05 | 5.25 | 2.00 | 16.00 | nr | nr | Pullout |
| 72 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 19.05 | 5.25 | 2.00 | 16.00 | nr | nr | Pullout |
| 73 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 19.05 | 5.25 | 2.00 | 16.00 | nr | nr | Pullout |
| 74 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 19.05 | 5.25 | 2.00 | 24.00 | nr | nr | Splitting |
| 75 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 19.05 | 5.25 | 2.00 | 24.00 | nr | nr | Splitting |

| SI | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f_c'}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 76 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 19.05 | 5.25 | 2.00 | 32.00 | nr | nr | Pullout |
| 77 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 25.4 | 5.25 | 1.75 | 20.00 | nr | nr | Pullout |
| 78 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 25.4 | 5.25 | 1.75 | 20.00 | nr | nr | Pullout |
| 79 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 25.4 | 5.25 | 1.75 | 20.00 | nr | nr | Pullout |
| 80 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 25.4 | 5.25 | 1.75 | 25.00 | nr | nr | Pullout |
| 81 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 25.4 | 5.25 | 1.75 | 25.00 | nr | nr | Pullout |
| 82 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 25.4 | 5.25 | 1.75 | 25.00 | nr | nr | Pullout |
| 83 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 25.4 | 5.25 | 1.75 | 30.00 | nr | nr | Pullout |
| 84 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 25.4 | 5.25 | 1.75 | 30.00 | nr | nr | Splitting |
| 85 | Daniali (1991) | IHB | GFRP | Confined | Bottom | SW | 25.4 | 5.25 | 1.75 | 30.00 | nr | nr | Splitting |
| 86 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 9.6774 | 5.46 | 2.00 | 10.50 | 0.000 | 2.028 | Tensile |
| 87 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 9.6774 | 5.91 | 4.00 | 15.75 | 0.000 | 1.621 | Tensile |
| 88 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 9.6774 | 5.91 | 6.00 | 21.00 | 0.000 | 1.277 | Tensile |
| 89 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 9.6774 | 6.99 | 2.00 | 10.50 | 0.000 | 1.728 | Tensile |
| 90 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 9.6774 | 6.99 | 4.00 | 15.75 | 0.000 | 1.330 | Tensile |
| 91 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 9.6774 | 6.99 | 6.00 | 21.00 | 0.000 | 0.885 | Tensile |
| 92 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 9.6774 | 5.25 | 1.00 | 3.94 | 0.000 | 3.723 | Splitting |
| 93 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 9.6774 | 5.25 | 2.00 | 3.94 | 0.000 | 4.671 | Pullout |
| 94 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 9.6774 | 5.25 | 2.00 | 7.87 | 0.000 | 2.518 | Pullout |
| 95 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 9.6774 | 5.46 | 2.00 | 10.50 | 0.000 | 2.186 | Tensile |
| 96 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 9.6774 | 5.91 | 4.00 | 15.75 | 0.000 | 1.443 | Tensile |
| 97 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 9.6774 | 5.91 | 6.00 | 21.00 | 0.000 | 1.070 | Tensile |
| 98 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 9.6774 | 6.99 | 2.00 | 10.50 | 0.000 | 1.851 | Tensile |
| 99 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 9.6774 | 6.99 | 4.00 | 15.75 | 0.000 | 1.166 | Tensile |
| 100 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 9.6774 | 6.99 | 6.00 | 21.00 | 0.000 | 0.998 | Splitting |
| 101 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 18.44 | 5.25 | 1.00 | 4.13 | 0.000 | 2.624 | Splitting |

| SI | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f_c'}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 102 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 18.44 | 5.25 | 2.00 | 4.13 | 0.000 | 3.352 | Pullout |
| 103 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 18.44 | 5.25 | 2.00 | 8.26 | 0.000 | 1.820 | Pullout |
| 104 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 18.44 | 6.25 | 2.00 | 16.53 | 0.000 | 0.925 | Pullout |
| 105 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 18.44 | 6.25 | 4.00 | 22.04 | 0.000 | 0.899 | Pullout |
| 106 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 18.44 | 6.25 | 6.00 | 24.79 | 0.000 | 0.842 | Tensile |
| 107 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 18.44 | 6.90 | 2.00 | 16.53 | 0.000 | 0.849 | Pullout |
| 108 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 18.44 | 6.90 | 4.00 | 22.04 | 0.000 | 0.776 | Pullout |
| 109 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 18.44 | 6.90 | 6.00 | 24.79 | 0.000 | 0.809 | Tensile |
| 110 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 18.44 | 5.25 | 1.00 | 4.13 | 0.000 | 2.107 | Pullout |
| 111 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 18.44 | 5.25 | 2.00 | 4.13 | 0.000 | 2.796 | Pullout |
| 112 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 18.44 | 5.25 | 2.00 | 8.26 | 0.000 | 1.484 | Pullout |
| 113 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 18.44 | 6.25 | 2.00 | 16.53 | 0.000 | 0.865 | Pullout |
| 114 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 18.44 | 6.25 | 4.00 | 22.04 | 0.000 | 0.845 | Pullout |
| 115 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 18.44 | 6.25 | 6.00 | 24.79 | 0.000 | 0.856 | Tensile |
| 116 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 18.44 | 6.90 | 2.00 | 16.53 | 0.000 | 0.824 | Pullout |
| 117 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 18.44 | 6.90 | 4.00 | 22.04 | 0.000 | 0.744 | Pullout |
| 118 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 18.44 | 6.90 | 6.00 | 24.79 | 0.000 | 0.719 | Tensile |
| 119 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 27.407 | 5.25 | 1.00 | 3.71 | 0.000 | 2.175 | Splitting |
| 120 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 27.407 | 5.25 | 2.00 | 3.71 | 0.000 | 3.093 | Pullout |
| 121 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 27.407 | 5.25 | 2.00 | 7.41 | 0.000 | 1.720 | Pullout |
| 122 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 27.407 | 6.30 | 2.00 | 20.39 | 0.000 | 0.708 | Pullout |
| 123 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 27.407 | 6.30 | 4.00 | 24.10 | 0.000 | 0.653 | Pullout |
| 124 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 27.407 | 6.30 | 6.00 | 27.80 | 0.000 | 0.602 | Tensile |
| 125 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 27.407 | 6.68 | 2.00 | 20.39 | 0.000 | 0.620 | Pullout |
| 126 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 27.407 | 6.68 | 4.00 | 24.10 | 0.000 | 0.567 | Pullout |
| 127 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Bottom | SW | 27.407 | 6.68 | 6.00 | 27.80 | 0.000 | 0.513 | Tensile |

| SI | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f_c'}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 128 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 27.407 | 6.30 | 2.00 | 20.39 | 0.000 | 0.694 | Pullout |
| 129 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 27.407 | 6.30 | 4.00 | 24.10 | 0.000 | 0.625 | Pullout |
| 130 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 27.407 | 6.30 | 6.00 | 27.80 | 0.000 | 0.610 | Tensile |
| 131 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 27.407 | 6.68 | 2.00 | 20.39 | 0.000 | 0.594 | Pullout |
| 132 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 27.407 | 6.68 | 4.00 | 24.10 | 0.000 | 0.546 | Pullout |
| 133 | Ehsani *et al.* (1993) | IHB | GFRP | Unconfined | Top | SW | 27.407 | 6.68 | 6.00 | 27.80 | 0.000 | 0.534 | Tensile |
| 134 | Kanakubo *et al.* (1993) | IHB | CFRP | Unconfined | Top | SC | 8 | 7.01 | 3.13 | 15.00 | 0.000 | 0.120 | Slip |
| 135 | Kanakubo *et al.* (1993) | IHB | CFRP | Unconfined | Top | SC | 8 | 7.01 | 3.13 | 15.00 | 0.000 | 0.823 | Splitting |
| 136 | Kanakubo *et al.* (1993) | IHB | CFRP | Unconfined | Top | SC | 10 | 7.01 | 2.50 | 15.00 | 0.000 | 1.326 | Splitting |
| 137 | Kanakubo *et al.* (1993) | IHB | CFRP | Unconfined | Top | SC | 13 | 7.01 | 1.92 | 15.00 | 0.000 | 0.707 | Splitting |
| 138 | Kanakubo *et al.* (1993) | IHB | CFRP | Unconfined | Top | SC | 10 | 7.01 | 2.50 | 15.00 | 0.000 | 1.112 | Splitting |
| 139 | Kanakubo *et al.* (1993) | IHB | CFRP | Unconfined | Top | SC | 11 | 7.01 | 2.27 | 15.00 | 0.000 | 1.065 | Tensile |
| 140 | Kanakubo *et al.* (1993) | IHB | CFRP | Unconfined | Top | SC | 12.5 | 7.01 | 2.00 | 15.00 | 0.000 | 0.850 | Splitting |
| 141 | Kanakubo *et al.* (1993) | IHB | CFRP | Unconfined | Top | SC | 8 | 7.01 | 3.13 | 15.00 | 0.000 | 1.195 | Splitting |
| 142 | Kanakubo *et al.* (1993) | IHB | AFRP | Unconfined | Top | SC | 12 | 7.01 | 2.08 | 15.00 | 0.000 | 1.076 | Splitting |
| 143 | Kanakubo *et al.* (1993) | IHB | AFRP | Unconfined | Top | SC | 12 | 7.01 | 2.08 | 15.00 | 0.000 | 1.004 | Break of Coupler |
| 144 | Kanakubo *et al.* (1993) | IHB | AFRP | Unconfined | Top | SC | 10 | 7.01 | 2.50 | 15.00 | 0.000 | 1.206 | Splitting |
| 145 | Kanakubo *et al.* (1993) | IHB | GFRP | Unconfined | Top | SC | 10 | 7.01 | 2.50 | 15.00 | 0.000 | 1.051 | Splitting |
| 146 | Makitani *et al.* (1993) | HB | CFRP | Confined | Bottom | SW | 10 | 5.10 | 4.00 | 40.00 | 0.314 | na | Tensile |
| 147 | Makitani *et al.* (1993) | HB | CFRP | Confined | Bottom | SW | 10 | 5.81 | 4.00 | 40.00 | 0.314 | na | Tensile |
| 148 | Makitani *et al.* (1993) | HB | CFRP | Confined | Bottom | SW | 10 | 5.42 | 4.00 | 40.00 | 0.314 | 0.941 | Pullout |
| 149 | Makitani *et al.* (1993) | HB | CFRP | Confined | Bottom | SW | 10 | 5.89 | 4.00 | 40.00 | 0.314 | na | Tensile |
| 150 | Makitani *et al.* (1993) | HB | CFRP | Confined | Bottom | SW | 10 | 5.16 | 4.00 | 20.00 | 0.314 | 2.210 | Pullout |
| 151 | Makitani *et al.* (1993) | HB | CFRP | Confined | Bottom | SW | 10 | 5.38 | 4.00 | 20.00 | 0.314 | 1.972 | Pullout |
| 152 | Makitani *et al.* (1993) | HB | CFRP | Confined | Bottom | SW | 10 | 5.28 | 4.00 | 20.00 | 0.314 | 1.060 | Pullout |
| 153 | Makitani *et al.* (1993) | HB | CFRP | Confined | Bottom | SW | 10 | 5.76 | 4.00 | 20.00 | 0.314 | 1.840 | Pullout |

| SI | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f_c'}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 154 | Makitani *et al.* (1993) | HB | CFRP | Confined | Bottom | SW | 10 | 5.37 | 4.00 | 10.00 | 0.314 | 2.497 | Pullout |
| 155 | Makitani *et al.* (1993) | HB | CFRP | Confined | Bottom | SW | 10 | 5.16 | 4.00 | 10.00 | 0.314 | 2.637 | Pullout |
| 156 | Makitani *et al.* (1993) | HB | CFRP | Confined | Bottom | SW | 10 | 5.19 | 4.00 | 10.00 | 0.314 | 0.791 | Pullout |
| 157 | Makitani *et al.* (1993) | HB | CFRP | Confined | Bottom | SW | 10 | 5.48 | 4.00 | 10.00 | 0.314 | 2.903 | Pullout |
| 158 | Makitani *et al.* (1993) | HB | AFRP | Confined | Bottom | SW | 10 | 5.38 | 4.00 | 40.00 | 0.314 | na | Tensile |
| 159 | Makitani *et al.* (1993) | HB | AFRP | Confined | Bottom | SW | 10 | 5.49 | 4.00 | 40.00 | 0.314 | na | Tensile |
| 160 | Makitani *et al.* (1993) | HB | AFRP | Confined | Bottom | SW | 10 | 5.22 | 4.00 | 40.00 | 0.314 | 1.340 | Pullout |
| 161 | Makitani *et al.* (1993) | HB | AFRP | Confined | Bottom | SW | 10 | 5.59 | 4.00 | 20.00 | 0.314 | 1.680 | Pullout |
| 162 | Makitani *et al.* (1993) | HB | AFRP | Confined | Bottom | SW | 10 | 5.64 | 4.00 | 20.00 | 0.314 | 2.181 | Pullout |
| 163 | Makitani *et al.* (1993) | HB | AFRP | Confined | Bottom | SW | 10 | 5.49 | 4.00 | 20.00 | 0.314 | 1.640 | Pullout |
| 164 | Makitani *et al.* (1993) | HB | AFRP | Confined | Bottom | SW | 10 | 5.01 | 4.00 | 10.00 | 0.314 | 3.194 | Pullout |
| 165 | Makitani *et al.* (1993) | HB | AFRP | Confined | Bottom | SW | 10 | 5.41 | 4.00 | 10.00 | 0.314 | 3.455 | Pullout |
| 166 | Makitani *et al.* (1993) | HB | AFRP | Confined | Bottom | SW | 10 | 5.39 | 4.00 | 10.00 | 0.314 | 2.206 | Pullout |
| 167 | Makitani *et al.* (1993) | HB | GFRP | Confined | Bottom | SW | 10 | 5.56 | 4.00 | 40.00 | 0.314 | na | Tensile |
| 168 | Makitani *et al.* (1993) | HB | GFRP | Confined | Bottom | SW | 10 | 5.10 | 4.00 | 20.00 | 0.314 | na | Tensile |
| 169 | Makitani *et al.* (1993) | HB | GFRP | Confined | Bottom | SW | 10 | 5.43 | 4.00 | 10.00 | 0.314 | 2.762 | Pullout |
| 170 | Makitani *et al.* (1993) | S | CFRP | Confined | Bottom | HL | 8 | 5.57 | 5.00 | 10.00 | 0.393 | 1.563 | Pullout |
| 171 | Makitani *et al.* (1993) | S | CFRP | Confined | Bottom | HL | 8 | 5.57 | 5.00 | 15.00 | 0.393 | 1.832 | Pullout |
| 172 | Makitani *et al.* (1993) | S | CFRP | Confined | Bottom | HL | 8 | 5.57 | 5.00 | 20.00 | 0.393 | 1.976 | Pullout |
| 173 | Makitani *et al.* (1993) | S | CFRP | Confined | Bottom | HL | 8 | 5.57 | 5.00 | 25.00 | 0.393 | 2.119 | Pullout |
| 174 | Makitani *et al.* (1993) | S | CFRP | Confined | Bottom | HL | 8 | 5.57 | 5.00 | 30.00 | 0.393 | 2.245 | Pullout |
| 175 | Makitani *et al.* (1993) | S | CFRP | Confined | Bottom | HL | 8 | 5.57 | 5.00 | 40.00 | 0.393 | 2.335 | Pullout |
| 176 | Makitani *et al.* (1993) | S | CFRP | Confined | Bottom | HL | 8 | 5.57 | 5.00 | 50.00 | 0.393 | 2.030 | Pullout |
| 177 | Makitani *et al.* (1993) | S | CFRP | Confined | Bottom | HL | 8 | 5.57 | 5.00 | 60.00 | 0.393 | 1.473 | Pullout |
| 178 | Benmokrane *et al.* (1996) | HB | GFRP | Confined | Bottom | HL | 12.7 | 5.57 | 3.44 | 10.00 | 0.082 | 1.904 | Pullout |
| 179 | Benmokrane *et al.* (1996) | HB | GFRP | Confined | Bottom | HL | 15.9 | 5.57 | 2.64 | 10.00 | 0.066 | 1.311 | Pullout |

| SI | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f_c'}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 180 | Benmokrane *et al.* (1996) | HB | GFRP | Confined | Bottom | HL | 19.1 | 5.57 | 2.12 | 10.00 | 0.055 | 1.185 | Pullout |
| 181 | Benmokrane *et al.* (1996) | HB | GFRP | Confined | Bottom | HL | 25.4 | 5.57 | 1.47 | 10.00 | 0.041 | 1.149 | Pullout |
| 182 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 19.05 | 5.25 | 1.00 | 4.00 | 0.000 | 2.551 | Splitting |
| 183 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 19.05 | 5.25 | 2.00 | 4.00 | 0.000 | 3.255 | Pullout |
| 184 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 19.05 | 5.25 | 2.00 | 8.00 | 0.000 | 1.770 | Pullout |
| 185 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 19.05 | 6.26 | 2.00 | 16.00 | 0.000 | 0.894 | Pullout |
| 186 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 19.05 | 6.91 | 2.00 | 16.00 | 0.000 | 0.825 | Pullout |
| 187 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 19.05 | 6.26 | 4.00 | 21.33 | 0.000 | 0.862 | Pullout |
| 188 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 19.05 | 6.91 | 4.00 | 21.33 | 0.000 | 0.753 | Pullout |
| 189 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 28.575 | 5.25 | 1.00 | 3.56 | 0.000 | 2.037 | Splitting |
| 190 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 28.575 | 5.25 | 2.00 | 3.56 | 0.000 | 2.893 | Pullout |
| 191 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 28.575 | 5.25 | 2.00 | 7.11 | 0.000 | 1.618 | Pullout |
| 192 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 28.575 | 6.30 | 2.00 | 19.56 | 0.000 | 0.667 | Pullout |
| 193 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 28.575 | 6.69 | 2.00 | 19.56 | 0.000 | 0.598 | Pullout |
| 194 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 28.575 | 6.30 | 4.00 | 23.11 | 0.000 | 0.619 | Pullout |
| 195 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 28.575 | 6.88 | 4.00 | 23.11 | 0.000 | 0.553 | Pullout |
| 196 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 9.525 | 5.25 | 1.00 | 4.00 | 0.000 | 3.921 | Splitting |
| 197 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 9.525 | 5.25 | 2.00 | 4.00 | 0.000 | 4.854 | Pullout |
| 198 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 9.525 | 5.25 | 2.00 | 8.00 | 0.000 | 2.627 | Pullout |
| 199 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 19.05 | 5.25 | 1.00 | 4.00 | 0.000 | 2.037 | Splitting |
| 200 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 19.05 | 5.25 | 2.00 | 4.00 | 0.000 | 2.703 | Pullout |
| 201 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 19.05 | 5.25 | 2.00 | 8.00 | 0.000 | 1.447 | Pullout |
| 202 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 19.05 | 6.26 | 2.00 | 16.00 | 0.000 | 0.831 | Pullout |
| 203 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 19.05 | 6.91 | 2.00 | 16.00 | 0.000 | 0.796 | Pullout |
| 204 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 19.05 | 6.26 | 4.00 | 21.33 | 0.000 | 0.815 | Pullout |
| 205 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 19.05 | 6.91 | 4.00 | 21.33 | 0.000 | 0.724 | Pullout |

| SI | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f_c'}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 206 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 28.575 | 6.30 | 2.00 | 19.56 | 0.000 | 0.651 | Pullout |
| 207 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 28.575 | 6.69 | 2.00 | 19.56 | 0.000 | 0.568 | Pullout |
| 208 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 28.575 | 6.30 | 4.00 | 23.11 | 0.000 | 0.587 | Pullout |
| 209 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 28.575 | 6.88 | 4.00 | 23.11 | 0.000 | 0.523 | Pullout |
| 210 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 9.525 | 5.46 | 2.00 | 10.67 | 0.000 | 2.107 | Tensile |
| 211 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 9.525 | 7.00 | 2.00 | 10.67 | 0.000 | 1.729 | Tensile |
| 212 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 9.525 | 5.92 | 4.00 | 16.00 | 0.000 | 1.673 | Tensile |
| 213 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 9.525 | 7.00 | 4.00 | 16.00 | 0.000 | 1.329 | Tensile |
| 214 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 9.525 | 5.92 | 6.00 | 21.33 | 0.000 | 1.318 | Tensile |
| 215 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 9.525 | 7.00 | 6.00 | 21.33 | 0.000 | 0.886 | Tensile |
| 216 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 9.525 | 5.92 | 6.00 | 21.33 | 0.000 | 1.116 | Tensile |
| 217 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 9.525 | 7.00 | 6.00 | 21.33 | 0.000 | 1.000 | Tensile |
| 218 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 19.05 | 6.26 | 6.00 | 24.00 | 0.000 | 0.815 | Tensile |
| 219 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 19.05 | 6.91 | 6.00 | 24.00 | 0.000 | 0.709 | Tensile |
| 220 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 28.575 | 6.30 | 6.00 | 26.67 | 0.000 | 0.571 | Tensile |
| 221 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Bottom | HL | 28.575 | 6.88 | 6.00 | 26.67 | 0.000 | 0.494 | Tensile |
| 222 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 9.525 | 5.46 | 2.00 | 10.67 | 0.000 | 2.308 | Tensile |
| 223 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 9.525 | 7.00 | 2.00 | 10.67 | 0.000 | 1.871 | Tensile |
| 224 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 9.525 | 5.92 | 4.00 | 16.00 | 0.000 | 1.504 | Tensile |
| 225 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 9.525 | 7.00 | 4.00 | 16.00 | 0.000 | 1.171 | Tensile |
| 226 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 19.05 | 6.26 | 6.00 | 24.00 | 0.000 | 0.831 | Tensile |
| 227 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 19.05 | 6.91 | 6.00 | 24.00 | 0.000 | 0.695 | Tensile |
| 228 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 28.575 | 6.30 | 6.00 | 26.67 | 0.000 | 0.571 | Tensile |
| 229 | Ehsani *et al.* (1996) | HB | GFRP | Unconfined | Top | HL | 28.575 | 6.88 | 6.00 | 26.67 | 0.000 | 0.523 | Tensile |
| 230 | Shield and Retika (1996) | IHB | GFRP | Unconfined | Bottom | SW | 13.462 | 6.22 | 2.00 | 10.38 | 0.000 | 1.389 | Splitting |
| 231 | Shield and Retika (1996) | IHB | GFRP | Unconfined | Bottom | SW | 13.462 | 6.22 | 2.00 | 10.38 | 0.000 | 1.558 | Splitting |

| SI | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f_c'}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 232 | Shield and Retika (1996) | IHB | GFRP | Unconfined | Bottom | SW | 13.462 | 6.22 | 2.00 | 10.38 | 0.000 | 1.268 | Splitting |
| 233 | Shield and Retika (1996) | IHB | GFRP | Unconfined | Bottom | SW | 19.304 | 6.22 | 2.00 | 13.16 | 0.000 | 1.084 | Splitting |
| 234 | Shield and Retika (1996) | IHB | GFRP | Unconfined | Bottom | SW | 19.304 | 6.22 | 2.00 | 13.16 | 0.000 | 1.038 | Splitting |
| 235 | Shield and Retika (1996) | IHB | GFRP | Unconfined | Bottom | SW | 19.304 | 6.22 | 2.00 | 13.16 | 0.000 | 1.014 | Splitting |
| 236 | Shield and Retika (1996) | IHB | GFRP | Unconfined | Bottom | SW | 19.304 | 6.22 | 2.00 | 13.16 | 0.000 | 1.149 | Splitting |
| 237 | Shield and Retika (1996) | IHB | GFRP | Unconfined | Bottom | SW | 19.304 | 6.22 | 2.00 | 13.16 | 0.000 | 0.903 | Splitting |
| 238 | Shield and Retika (1996) | IHB | GFRP | Unconfined | Bottom | SW | 19.304 | 6.22 | 2.00 | 13.16 | 0.000 | 0.982 | Splitting |
| 239 | Tighiouart (1996) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 5.56 | 3.40 | 10.00 | 0.000 | 1.900 | Pullout |
| 240 | Tighiouart (1996) | HB | GFRP | Unconfined | Bottom | SW | 12.7 | 5.56 | 3.40 | 10.00 | 0.000 | 2.206 | Pullout |
| 241 | Tighiouart (1996) | HB | GFRP | Unconfined | Bottom | HL | 15.875 | 5.56 | 2.60 | 10.08 | 0.000 | 1.309 | Pullout |
| 242 | Tighiouart (1996) | HB | GFRP | Unconfined | Bottom | SW | 15.875 | 5.56 | 2.60 | 10.08 | 0.000 | 1.936 | Pullout |
| 243 | Tighiouart (1996) | HB | GFRP | Unconfined | Bottom | HL | 19.05 | 5.56 | 2.10 | 10.00 | 0.000 | 1.183 | Pullout |
| 244 | Tighiouart (1996) | HB | GFRP | Unconfined | Bottom | HL | 25.4 | 5.56 | 1.50 | 10.00 | 0.000 | 1.147 | Pullout |
| 245 | Tighiouart (1996) | HB | GFRP | Unconfined | Bottom | SW | 25.4 | 5.56 | 1.50 | 10.00 | 0.000 | 1.327 | Pullout |
| 246 | Tighiouart (1996) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 5.56 | 3.40 | 16.00 | 0.000 | 1.560 | Tensile |
| 247 | Tighiouart (1996) | HB | GFRP | Unconfined | Bottom | HL | 19.05 | 5.56 | 2.10 | 16.00 | 0.000 | 0.951 | Pullout |
| 248 | Tighiouart (1996) | HB | GFRP | Unconfined | Bottom | HL | 25.4 | 5.56 | 1.50 | 16.00 | 0.000 | 0.915 | Pullout |
| 249 | Tighiouart (1996) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 5.56 | 3.40 | 6.00 | 0.000 | 2.027 | Pullout |
| 250 | Tighiouart (1996) | HB | GFRP | Unconfined | Bottom | HL | 15.875 | 5.56 | 2.60 | 6.08 | 0.000 | 1.900 | Pullout |
| 251 | Tighiouart (1996) | HB | GFRP | Unconfined | Bottom | HL | 19.05 | 5.56 | 2.10 | 6.00 | 0.000 | 1.274 | Pullout |
| 252 | Tighiouart (1996) | HB | GFRP | Unconfined | Bottom | HL | 25.4 | 5.56 | 1.50 | 6.00 | 0.000 | 1.255 | Pullout |
| 253 | Tighiouart *et al.* (1998) | S | GFRP | Confined | Bottom | HL | 12.446 | 5.56 | 2.40 | 36.94 | 0.036 | 0.639 | Splitting |
| 254 | Tighiouart *et al.* (1998) | S | GFRP | Confined | Bottom | HL | 12.446 | 5.56 | 2.40 | 36.94 | 0.073 | 0.657 | Splitting |
| 255 | Tighiouart *et al.* (1998) | S | GFRP | Confined | Bottom | HL | 12.446 | 5.56 | 2.40 | 43.47 | 0.073 | 0.479 | Splitting |
| 256 | Tighiouart *et al.* (1998) | S | GFRP | Confined | Bottom | HL | 12.446 | 5.56 | 2.40 | 43.47 | 0.073 | 0.638 | Splitting |
| 257 | Tighiouart *et al.* (1998) | S | GFRP | Confined | Bottom | HL | 12.446 | 5.56 | 2.40 | 80.41 | 0.073 | 0.359 | Splitting |

| SI | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f_c'}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 258 | Tighiouart *et al.* (1998) | S | GFRP | Confined | Bottom | HL | 12.446 | 5.56 | 2.40 | 80.41 | 0.073 | 0.359 | Splitting |
| 259 | Tighiouart *et al.* (1998) | S | GFRP | Confined | Bottom | HL | 12.446 | 5.56 | 2.40 | 99.18 | 0.073 | 0.301 | Splitting |
| 260 | Tighiouart *et al.* (1998) | S | GFRP | Confined | Bottom | HL | 12.446 | 5.56 | 2.40 | 99.18 | 0.073 | 0.298 | Splitting |
| 261 | Tighiouart *et al.* (1998) | S | GFRP | Confined | Bottom | HL | 15.494 | 5.56 | 1.90 | 43.61 | 0.073 | 0.573 | Splitting |
| 262 | Tighiouart *et al.* (1998) | S | GFRP | Confined | Bottom | HL | 15.494 | 5.56 | 1.90 | 43.61 | 0.058 | 0.578 | Splitting |
| 263 | Tighiouart *et al.* (1998) | S | GFRP | Confined | Bottom | HL | 15.494 | 5.56 | 1.90 | 56.23 | 0.058 | 0.454 | Splitting |
| 264 | Tighiouart *et al.* (1998) | S | GFRP | Confined | Bottom | HL | 15.494 | 5.56 | 1.90 | 56.23 | 0.058 | 0.491 | Splitting |
| 265 | Tighiouart *et al.* (1998) | S | GFRP | Confined | Bottom | HL | 15.494 | 5.56 | 1.90 | 99.67 | 0.058 | 0.407 | Splitting |
| 266 | Tighiouart *et al.* (1998) | S | GFRP | Confined | Bottom | HL | 15.494 | 5.56 | 1.90 | 99.67 | 0.058 | 0.425 | Splitting |
| 267 | Tighiouart *et al.* (1998) | HB | GFRP | Confined | Bottom | HL | 12.7 | 5.57 | 3.44 | 6.00 | 0.058 | 2.030 | Pullout |
| 268 | Tighiouart *et al.* (1998) | HB | GFRP | Confined | Bottom | HL | 15.9 | 5.57 | 2.64 | 6.00 | 0.071 | 1.904 | Pullout |
| 269 | Tighiouart *et al.* (1998) | HB | GFRP | Confined | Bottom | HL | 19.1 | 5.57 | 2.12 | 6.00 | 0.057 | 1.275 | Pullout |
| 270 | Tighiouart *et al.* (1998) | HB | GFRP | Confined | Bottom | HL | 25.4 | 5.57 | 1.47 | 6.00 | 0.047 | 1.257 | Pullout |
| 271 | Tighiouart *et al.* (1998) | HB | GFRP | Confined | Bottom | HL | 12.7 | 5.57 | 3.44 | 10.00 | 0.036 | 1.904 | Pullout |
| 272 | Tighiouart *et al.* (1998) | HB | GFRP | Confined | Bottom | HL | 12.7 | 5.57 | 3.44 | 10.00 | 0.071 | 2.209 | Pullout |
| 273 | Tighiouart *et al.* (1998) | HB | GFRP | Confined | Bottom | HL | 15.9 | 5.57 | 2.64 | 10.00 | 0.071 | 1.311 | Pullout |
| 274 | Tighiouart *et al.* (1998) | HB | GFRP | Confined | Bottom | HL | 15.9 | 5.57 | 2.64 | 10.00 | 0.057 | 1.940 | Pullout |
| 275 | Tighiouart *et al.* (1998) | HB | GFRP | Confined | Bottom | HL | 19.1 | 5.57 | 2.12 | 10.00 | 0.057 | 1.185 | Pullout |
| 276 | Tighiouart *et al.* (1998) | HB | GFRP | Confined | Bottom | HL | 25.4 | 5.57 | 1.47 | 10.00 | 0.047 | 1.149 | Pullout |
| 277 | Tighiouart *et al.* (1998) | HB | GFRP | Confined | Bottom | HL | 25.4 | 5.57 | 1.47 | 10.00 | 0.036 | 1.329 | Pullout |
| 278 | Tighiouart *et al.* (1998) | HB | GFRP | Confined | Bottom | HL | 12.7 | 5.57 | 3.44 | 16.00 | 0.036 | 1.563 | Slip |
| 279 | Tighiouart *et al.* (1998) | HB | GFRP | Confined | Bottom | HL | 19.1 | 5.57 | 2.12 | 16.00 | 0.071 | 0.952 | Pullout |
| 280 | Tighiouart *et al.* (1998) | HB | GFRP | Confined | Bottom | HL | 25.4 | 5.57 | 1.47 | 16.00 | 0.047 | 0.593 | Pullout |
| 281 | Tepfers *et al. et al.* (1998) | S | GFRP | Confined | Bottom | SW+SC | 25 | 5.40 | 1.20 | 16.00 | nr | 0.790 | Pullout |
| 282 | Tepfers *et al. et al.* (1998) | S | GFRP | Confined | Bottom | SW+SC | 25 | 5.40 | 1.20 | 24.00 | nr | 0.744 | Pullout |
| 283 | Tepfers *et al. et al.* (1998) | S | GFRP | Confined | Bottom | SW+SC | 25 | 5.40 | 1.20 | 32.00 | nr | 0.588 | Pullout |

| SI | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f_c'}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 284 | Cosenza *et al.* (1999) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 6.08 | 5.41 | 5.00 | 0.000 | 1.858 | Pullout |
| 285 | Cosenza *et al.* (1999) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 6.32 | 5.41 | 5.00 | 0.000 | 2.609 | Pullout |
| 286 | Cosenza *et al.* (1999) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 6.16 | 5.41 | 10.00 | 0.000 | 1.995 | Tensile |
| 287 | Cosenza *et al.* (1999) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 6.32 | 5.41 | 10.00 | 0.000 | 2.293 | Pullout |
| 288 | Cosenza *et al.* (1999) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 7.21 | 5.41 | 20.00 | 0.000 | 1.040 | Tensile |
| 289 | Cosenza *et al.* (1999) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 7.42 | 5.41 | 20.00 | 0.000 | 0.998 | Tensile |
| 290 | Cosenza *et al.* (1999) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 7.07 | 5.41 | 30.00 | 0.000 | 0.651 | Tensile |
| 291 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 3.00 | 24.19 | 0.000 | 0.647 | Tensile Spaghetti |
| 292 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 3.00 | 24.19 | 0.000 | 0.668 | Tensile Spaghetti |
| 293 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 3.00 | 24.19 | 0.000 | 0.665 | Tensile Spaghetti |
| 294 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 3.00 | 24.19 | 0.000 | 0.644 | Tensile Spaghetti |
| 295 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 3.00 | 24.19 | 0.000 | 0.697 | Tensile Spaghetti |
| 296 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 3.00 | 24.19 | 0.000 | 0.711 | Tensile Spaghetti |
| 297 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 3.00 | 20.16 | 0.000 | 0.840 | Splitting |
| 298 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 3.00 | 20.16 | 0.000 | 0.747 | Splitting |
| 299 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 3.00 | 20.16 | 0.000 | 0.772 | Splitting |
| 300 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 3.00 | 20.16 | 0.000 | 0.751 | Tensile |
| 301 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 3.00 | 20.16 | 0.000 | 0.836 | Splitting |
| 302 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 3.00 | 20.16 | 0.000 | 0.879 | Splitting |
| 303 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 3.00 | 16.13 | 0.000 | 0.849 | Splitting |
| 304 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 3.00 | 16.13 | 0.000 | 0.897 | Tensile Spaghetti |
| 305 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 3.00 | 16.13 | 0.000 | 0.923 | Tensile Spaghetti |
| 306 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 3.00 | 16.13 | 0.000 | 0.891 | Tensile Spaghetti |
| 307 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 3.00 | 16.13 | 0.000 | 1.103 | Tensile Spaghetti |
| 308 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 3.00 | 16.13 | 0.000 | 0.918 | Splitting |
| 309 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 2.00 | 75.81 | 0.000 | 0.183 | Tensile Spaghetti |

| SI | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f_c'}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 310 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 2.00 | 75.81 | 0.000 | 0.247 | Tensile Spaghetti |
| 311 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 2.00 | 75.81 | 0.000 | 0.146 | Tensile Spaghetti |
| 312 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 2.00 | 75.81 | 0.000 | 0.211 | Tensile Spaghetti |
| 313 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 2.00 | 75.81 | 0.000 | 0.161 | Tensile Spaghetti |
| 314 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 2.00 | 75.81 | 0.000 | 0.255 | Tensile Spaghetti |
| 315 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 2.00 | 24.19 | 0.000 | 0.707 | Tensile Spaghetti |
| 316 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 2.00 | 24.19 | 0.000 | 0.485 | Tensile Spaghetti |
| 317 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 2.00 | 24.19 | 0.000 | 0.796 | Splitting |
| 318 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 2.00 | 24.19 | 0.000 | 0.562 | Tensile Spaghetti |
| 319 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 2.00 | 24.19 | 0.000 | 0.615 | Tensile Spaghetti |
| 320 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 2.00 | 24.19 | 0.000 | 0.640 | Tensile Spaghetti |
| 321 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 2.00 | 20.16 | 0.000 | 0.386 | Tensile |
| 322 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 2.00 | 20.16 | 0.000 | 0.785 | Splitting |
| 323 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 2.00 | 20.16 | 0.000 | 0.760 | Tensile Spaghetti |
| 324 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 2.00 | 20.16 | 0.000 | 0.683 | Tensile Spaghetti |
| 325 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 2.00 | 20.16 | 0.000 | 0.709 | Splitting |
| 326 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.66 | 2.00 | 20.16 | 0.000 | 0.726 | Splitting |
| 327 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.60 | 2.00 | 20.16 | 0.000 | 0.800 | Tensile |
| 328 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.60 | 2.00 | 20.16 | 0.000 | 0.706 | Splitting |
| 329 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | HL | 15.748 | 6.60 | 2.00 | 20.16 | 0.000 | 0.732 | Tensile Spaghetti |
| 330 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 3.00 | 25.84 | 0.000 | 0.703 | Splitting |
| 331 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 3.00 | 25.84 | 0.000 | 0.746 | Splitting |
| 332 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 3.00 | 25.84 | 0.000 | 0.757 | Splitting |
| 333 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 3.00 | 25.84 | 0.000 | 0.720 | Splitting |
| 334 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 3.00 | 19.38 | 0.000 | 0.786 | Splitting |
| 335 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 3.00 | 19.38 | 0.000 | 0.752 | Splitting |

| Sl | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f_c'}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 336 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 3.00 | 19.38 | 0.000 | 0.729 | Splitting |
| 337 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 3.00 | 19.38 | 0.000 | 0.954 | Splitting |
| 338 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 3.00 | 19.38 | 0.000 | 0.912 | Splitting |
| 339 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 3.00 | 19.38 | 0.000 | 0.877 | Splitting |
| 340 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 2.00 | 60.72 | 0.000 | 0.324 | Tensile Spaghetti |
| 341 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 2.00 | 32.30 | 0.000 | 0.621 | Splitting |
| 342 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 2.00 | 32.30 | 0.000 | 0.516 | Splitting |
| 343 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 2.00 | 32.30 | 0.000 | 0.712 | Splitting |
| 344 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 2.00 | 32.30 | 0.000 | 0.622 | Splitting |
| 345 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 2.00 | 25.84 | 0.000 | 0.686 | Splitting |
| 346 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 2.00 | 25.84 | 0.000 | 0.699 | Splitting |
| 347 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 2.00 | 25.84 | 0.000 | 0.808 | Splitting |
| 348 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 2.00 | 25.84 | 0.000 | 0.742 | Splitting |
| 349 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 2.00 | 25.84 | 0.000 | 0.814 | Splitting |
| 350 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 2.00 | 19.38 | 0.000 | 0.737 | Splitting |
| 351 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 2.00 | 19.38 | 0.000 | 0.760 | Splitting |
| 352 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 2.00 | 19.38 | 0.000 | 0.834 | Splitting |
| 353 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 2.00 | 19.38 | 0.000 | 0.709 | Splitting |
| 354 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 2.00 | 19.38 | 0.000 | 0.803 | Splitting |
| 355 | Shield and Hanus (1999) | IHB | GFRP | Unconfined | Bottom | SW | 19.66 | 6.60 | 2.00 | 19.38 | 0.000 | 0.814 | Splitting |
| 356 | Shield *et al.* (1999) | IHB | GFRP | Unconfined | Top | HL | 15.875 | 6.66 | 2.00 | 12.50 | 0.000 | 1.172 | Splitting |
| 357 | Shield *et al.* (1999) | IHB | GFRP | Unconfined | Top | HL | 15.875 | 6.66 | 2.00 | 15.00 | 0.000 | 1.257 | Splitting |
| 358 | Shield *et al.* (1999) | IHB | GFRP | Unconfined | Top | HL | 15.875 | 6.66 | 2.00 | 47.00 | 0.000 | 0.319 | Tensile |
| 359 | Shield *et al.* (1999) | IHB | GFRP | Unconfined | Top | HL | 15.875 | 6.66 | 3.00 | 10.00 | 0.000 | 1.406 | Splitting |
| 360 | Shield *et al.* (1999) | IHB | GFRP | Unconfined | Top | HL | 15.875 | 6.66 | 3.00 | 12.50 | 0.000 | 1.293 | Splitting |
| 361 | Shield *et al.* (1999) | IHB | GFRP | Unconfined | Top | HL | 15.875 | 6.66 | 3.00 | 15.00 | 0.000 | 1.067 | Tensile |

| SI | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f_c'}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 362 | Shield *et al.* (1999) | IHB | GFRP | Unconfined | Top | HL | 19.05 | 6.60 | 2.00 | 15.00 | 0.000 | 1.069 | Splitting |
| 363 | Shield *et al.* (1999) | IHB | GFRP | Unconfined | Top | HL | 19.05 | 6.60 | 2.00 | 20.00 | 0.000 | 1.032 | Splitting |
| 364 | Shield *et al.* (1999) | IHB | GFRP | Unconfined | Top | HL | 19.05 | 6.60 | 2.00 | 25.00 | 0.000 | 0.849 | Splitting |
| 365 | Shield *et al.* (1999) | IHB | GFRP | Unconfined | Top | HL | 19.05 | 6.60 | 2.00 | 47.00 | 0.000 | 0.482 | Tensile |
| 366 | Shield *et al.* (1999) | IHB | GFRP | Unconfined | Top | HL | 19.05 | 6.60 | 3.00 | 15.00 | 0.000 | 1.148 | Splitting |
| 367 | Shield *et al.* (1999) | IHB | GFRP | Unconfined | Top | HL | 19.05 | 6.60 | 3.00 | 20.00 | 0.000 | 1.006 | Splitting |
| 368 | Tighiouart *et al.* (1999) | S | GFRP | Confined | Bottom | HL | 12.7 | 5.57 | 2.36 | 36.22 | 0.049 | 0.670 | Splitting |
| 369 | Tighiouart *et al.* (1999) | S | GFRP | Confined | Bottom | HL | 12.7 | 5.57 | 2.36 | 36.22 | 0.049 | 0.688 | Splitting |
| 370 | Tighiouart *et al.* (1999) | S | GFRP | Confined | Bottom | HL | 12.7 | 5.57 | 2.36 | 42.52 | 0.049 | 0.453 | Splitting |
| 371 | Tighiouart *et al.* (1999) | S | GFRP | Confined | Bottom | HL | 12.7 | 5.57 | 2.36 | 42.52 | 0.049 | 0.602 | Splitting |
| 372 | Tighiouart *et al.* (1999) | S | GFRP | Confined | Bottom | HL | 12.7 | 5.57 | 2.36 | 78.74 | 0.049 | 0.352 | Splitting |
| 373 | Tighiouart *et al.* (1999) | S | GFRP | Confined | Bottom | HL | 12.7 | 5.57 | 2.36 | 78.74 | 0.049 | 0.352 | Splitting |
| 374 | Tighiouart *et al.* (1999) | S | GFRP | Confined | Bottom | HL | 12.7 | 5.57 | 2.36 | 97.24 | 0.049 | 0.296 | Splitting |
| 375 | Tighiouart *et al.* (1999) | S | GFRP | Confined | Bottom | HL | 12.7 | 5.57 | 2.36 | 97.24 | 0.049 | 0.293 | Splitting |
| 376 | Tighiouart *et al.* (1999) | S | GFRP | Confined | Bottom | HL | 15.9 | 5.57 | 1.89 | 42.45 | 0.039 | 0.559 | Splitting |
| 377 | Tighiouart *et al.* (1999) | S | GFRP | Confined | Bottom | HL | 15.9 | 5.57 | 1.89 | 42.45 | 0.039 | 0.564 | Splitting |
| 378 | Tighiouart *et al.* (1999) | S | GFRP | Confined | Bottom | HL | 15.9 | 5.57 | 1.89 | 54.72 | 0.039 | 0.438 | Splitting |
| 379 | Tighiouart *et al.* (1999) | S | GFRP | Confined | Bottom | HL | 15.9 | 5.57 | 1.89 | 54.72 | 0.039 | 0.474 | Splitting |
| 380 | Tighiouart *et al.* (1999) | S | GFRP | Confined | Bottom | HL | 15.9 | 5.57 | 1.89 | 97.17 | 0.039 | 0.397 | Splitting |
| 381 | Tighiouart *et al.* (1999) | S | GFRP | Confined | Bottom | HL | 15.9 | 5.57 | 1.89 | 97.17 | 0.039 | 0.415 | Splitting |
| 382 | Tighiouart *et al.* (1999) | S | GFRP | Confined | Bottom | HL | 15.9 | 5.57 | 1.89 | 78.93 | 0.039 | 0.498 | Compression |
| 383 | Tighiouart *et al.* (1999) | S | GFRP | Confined | Bottom | HL | 15.9 | 5.57 | 1.89 | 78.93 | 0.039 | 0.535 | Compression |
| 384 | Mosely (2000) | S | GFRP | Confined | Top | SW | 15.875 | 6.21 | 2.40 | 28.80 | 0.022 | 0.368 | Splitting |
| 385 | Mosely (2000) | S | GFRP | Confined | Top | HL | 15.875 | 6.21 | 2.40 | 28.80 | 0.022 | 0.313 | Splitting |
| 386 | Mosely (2000) | S | AFRP | Confined | Top | SW | 15.875 | 6.21 | 2.40 | 28.80 | 0.022 | 0.389 | Splitting |
| 387 | Mosely (2000) | S | GFRP | Confined | Top | SW | 15.875 | 5.31 | 2.40 | 19.20 | 0.022 | 0.325 | Splitting |

| SI | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f_c'}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 388 | Mosely (2000) | S | GFRP | Confined | Top | HL | 15.875 | 5.31 | 2.40 | 19.20 | 0.022 | 0.332 | Splitting |
| 389 | Mosely (2000) | S | AFRP | Confined | Top | SW | 15.875 | 5.31 | 2.40 | 19.20 | 0.022 | 0.350 | Splitting |
| 390 | Mosely (2000) | S | GFRP | Confined | Top | SW | 15.875 | 6.37 | 2.40 | 19.20 | 0.022 | 0.462 | Splitting |
| 391 | Mosely (2000) | S | GFRP | Confined | Top | HL | 15.875 | 6.37 | 2.40 | 19.20 | 0.022 | 0.437 | Splitting |
| 392 | Mosely (2000) | S | AFRP | Confined | Top | SW | 15.875 | 6.37 | 2.40 | 19.20 | 0.022 | 0.485 | Splitting |
| 393 | Peece (2000) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 6.32 | 9.30 | 5.00 | 0.000 | 2.603 | Pullout |
| 394 | Peece (2000) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 6.08 | 9.30 | 5.00 | 0.000 | 1.856 | Pullout |
| 395 | Peece (2000) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 6.32 | 9.30 | 10.00 | 0.000 | 1.939 | Tensile |
| 396 | Peece (2000) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 6.08 | 9.30 | 10.00 | 0.000 | 2.377 | Tensile |
| 397 | Peece (2000) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 6.16 | 9.30 | 20.00 | 0.000 | 1.218 | Tensile |
| 398 | Peece (2000) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 6.32 | 9.30 | 20.00 | 0.000 | 1.165 | Tensile |
| 399 | Peece (2000) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 7.20 | 9.30 | 30.00 | 0.000 | 0.640 | Tensile |
| 400 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SW | 12.7 | 5.38 | 5.50 | 5.00 | 0.018 | 3.302 | Pullout |
| 401 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SW | 12.7 | 5.38 | 5.50 | 5.00 | 0.018 | 2.765 | Pullout |
| 402 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SW | 12.7 | 5.38 | 5.50 | 5.00 | 0.018 | 3.968 | Pullout |
| 403 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SW | 12.7 | 5.38 | 5.50 | 5.00 | 0.018 | 3.596 | Pullout |
| 404 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SW | 12.7 | 5.38 | 5.50 | 7.50 | 0.018 | 2.816 | Pullout |
| 405 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SW | 12.7 | 5.38 | 5.50 | 7.50 | 0.018 | 3.021 | Pullout |
| 406 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SW | 15.875 | 5.38 | 4.40 | 5.00 | 0.015 | 3.507 | Pullout |
| 407 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SW | 15.875 | 5.38 | 4.40 | 5.00 | 0.015 | 3.737 | Pullout |
| 408 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SW | 15.875 | 5.38 | 4.40 | 7.50 | 0.015 | 4.620 | Pullout |
| 409 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SW | 15.875 | 5.38 | 4.40 | 7.50 | 0.015 | 2.278 | Pullout |
| 410 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SW | 19.05 | 5.38 | 3.70 | 5.00 | 0.012 | 2.918 | Pullout |
| 411 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SW | 19.05 | 5.38 | 3.70 | 5.00 | 0.012 | 3.085 | Pullout |
| 412 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SW | 19.05 | 5.38 | 3.70 | 7.50 | 0.012 | 2.688 | Pullout |
| 413 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SW | 19.05 | 5.38 | 3.70 | 7.50 | 0.012 | 2.726 | Pullout |

| Sl | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f_c'}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 414 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | HL | 12.7 | 5.38 | 5.50 | 5.00 | 0.018 | 3.763 | Pullout |
| 415 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | HL | 12.7 | 5.38 | 5.50 | 5.00 | 0.018 | 3.904 | Pullout |
| 416 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | HL | 12.7 | 5.38 | 5.50 | 5.00 | 0.018 | 3.558 | Pullout |
| 417 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | HL | 12.7 | 5.38 | 5.50 | 5.00 | 0.018 | 4.032 | Pullout |
| 418 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | HL | 12.7 | 5.38 | 5.50 | 7.50 | 0.018 | 3.213 | Pullout |
| 419 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | HL | 12.7 | 5.38 | 5.50 | 7.50 | 0.018 | 3.417 | Pullout |
| 420 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | HL | 15.875 | 5.38 | 4.40 | 5.00 | 0.015 | 3.225 | Pullout |
| 421 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | HL | 15.875 | 5.38 | 4.40 | 5.00 | 0.015 | 2.061 | Pullout |
| 422 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | HL | 15.875 | 5.38 | 4.40 | 7.50 | 0.015 | 4.070 | Pullout |
| 423 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | HL | 15.875 | 5.38 | 4.40 | 7.50 | 0.015 | 4.236 | Pullout |
| 424 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | HL | 19.05 | 5.38 | 3.70 | 5.00 | 0.012 | 2.854 | Pullout |
| 425 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | HL | 19.05 | 5.38 | 3.70 | 5.00 | 0.012 | 3.136 | Pullout |
| 426 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | HL | 19.05 | 5.38 | 3.70 | 7.50 | 0.012 | 2.675 | Pullout |
| 427 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | HL | 19.05 | 5.38 | 3.70 | 7.50 | 0.012 | 2.880 | Pullout |
| 428 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SC | 12.7 | 4.84 | 5.50 | 5.00 | 0.018 | 4.367 | Pullout |
| 429 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SC | 12.7 | 4.84 | 5.50 | 5.00 | 0.018 | 2.304 | Pullout |
| 430 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SC | 12.7 | 4.84 | 5.50 | 7.50 | 0.018 | 3.770 | Pullout |
| 431 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SC | 12.7 | 4.84 | 5.50 | 7.50 | 0.018 | 3.755 | Pullout |
| 432 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SC | 15.875 | 4.84 | 4.40 | 5.00 | 0.015 | 3.983 | Pullout |
| 433 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SC | 15.875 | 4.84 | 4.40 | 5.00 | 0.015 | 3.528 | Pullout |
| 434 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SC | 15.875 | 4.84 | 4.40 | 7.50 | 0.015 | 3.940 | Pullout |
| 435 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SC | 15.875 | 4.84 | 4.40 | 7.50 | 0.015 | 1.892 | Pullout |
| 436 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SC | 19.05 | 4.84 | 3.70 | 5.00 | 0.012 | 3.215 | Pullout |
| 437 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SC | 19.05 | 4.84 | 3.70 | 5.00 | 0.012 | 3.030 | Pullout |
| 438 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SC | 19.05 | 4.84 | 3.70 | 7.50 | 0.012 | 3.386 | Pullout |
| 439 | Defreese & Wollmann (2001) | IHB | GFRP | Confined | Bottom | SC | 19.05 | 4.84 | 3.70 | 7.50 | 0.012 | 3.058 | Pullout |

| SI | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f_c'}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 440 | Pecce *et al.* (2001) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 6.08 | 9.34 | 5.00 | 0.000 | 1.858 | Pullout |
| 441 | Pecce *et al.* (2001) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 6.32 | 9.34 | 5.00 | 0.000 | 2.609 | Pullout |
| 442 | Pecce *et al.* (2001) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 6.32 | 9.34 | 10.00 | 0.000 | 2.293 | Pullout |
| 443 | Pecce *et al.* (2001) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 6.16 | 9.34 | 10.00 | 0.000 | 1.995 | Tensile |
| 444 | Pecce *et al.* (2001) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 7.21 | 9.34 | 20.00 | 0.000 | 1.040 | Tensile |
| 445 | Pecce *et al.* (2001) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 7.42 | 9.34 | 20.00 | 0.000 | 0.998 | Tensile |
| 446 | Pecce *et al.* (2001) | HB | GFRP | Unconfined | Bottom | HL | 12.7 | 7.07 | 9.34 | 30.00 | 0.000 | 0.651 | Tensile |
| 447 | Maji and Orozco (2005) | HB | CFRP | Unconfined | Bottom | SW | 6.35 | 6.82 | 3.12 | 78.00 | 0.000 | 0.111 | Pullout |
| 448 | Maji and Orozco (2005) | HB | CFRP | Unconfined | Bottom | SW | 6.35 | 6.82 | 3.12 | 78.00 | 0.000 | 0.148 | Pullout |
| 449 | Maji and Orozco (2005) | HB | CFRP | Unconfined | Bottom | SW | 6.35 | 6.82 | 3.12 | 78.00 | 0.000 | 0.223 | Pullout |
| 450 | Maji and Orozco (2005) | HB | CFRP | Unconfined | Bottom | SW | 6.35 | 6.82 | 3.12 | 78.00 | 0.000 | 0.257 | Pullout |
| 451 | Maji and Orozco (2005) | HB | CFRP | Unconfined | Bottom | SW | 6.35 | 6.82 | 3.12 | 78.00 | 0.000 | 0.279 | Pullout |
| 452 | Maji and Orozco (2005) | HB | CFRP | Unconfined | Bottom | SW | 6.35 | 6.82 | 3.12 | 78.00 | 0.000 | 0.316 | Compression |
| 453 | Maji and Orozco (2005) | HB | CFRP | Unconfined | Bottom | SW | 6.35 | 6.82 | 3.12 | 78.00 | 0.000 | 0.347 | Compression |
| 454 | Aly and Benmokrane (2005) | S | GFRP | Confined | Bottom | SC | 19.1 | 6.32 | 2.09 | 36.65 | 0.018 | 0.443 | Splitting |
| 455 | Aly and Benmokrane (2005) | S | GFRP | Confined | Bottom | SC | 19.1 | 6.32 | 1.31 | 36.65 | 0.018 | 0.506 | Splitting |
| 456 | Aly and Benmokrane (2005) | S | GFRP | Confined | Bottom | SC | 19.1 | 6.32 | 2.09 | 36.65 | 0.018 | 0.522 | Splitting |
| 457 | Aly and Benmokrane (2005) | S | GFRP | Confined | Bottom | SC | 19.1 | 6.32 | 3.66 | 36.65 | 0.018 | 0.459 | Splitting |
| 458 | Aly and Benmokrane (2005) | S | GFRP | Confined | Bottom | SC | 19.1 | 6.32 | 2.09 | 36.65 | 0.018 | 0.569 | Splitting |
| 459 | Aly and Benmokrane (2005) | S | GFRP | Confined | Bottom | SC | 19.1 | 6.32 | 3.66 | 36.65 | 0.018 | 0.506 | Splitting |
| 460 | Aly *et al.* (2006) | S | CFRP | Confined | Bottom | SC | 9.5 | 7.00 | 3.37 | 68.42 | 0.035 | 0.993 | Tensile |
| 461 | Aly *et al.* (2006) | S | CFRP | Confined | Bottom | SC | 9.5 | 6.40 | 3.37 | 52.63 | 0.035 | 0.907 | Splitting |
| 462 | Aly *et al.* (2006) | S | CFRP | Confined | Bottom | SC | 9.5 | 6.40 | 3.37 | 52.63 | 0.035 | 0.828 | Splitting |
| 463 | Aly *et al.* (2006) | S | CFRP | Confined | Bottom | SC | 9.5 | 7.00 | 3.37 | 68.42 | 0.035 | 0.733 | Splitting |
| 464 | Aly *et al.* (2006) | S | CFRP | Confined | Bottom | SC | 9.5 | 6.56 | 3.37 | 84.21 | 0.035 | 0.570 | Splitting |
| 465 | Aly *et al.* (2006) | S | CFRP | Confined | Bottom | SC | 9.5 | 6.40 | 3.37 | 52.63 | 0.035 | 0.747 | Splitting |

| Sl | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f_c'}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 466 | Aly *et al.* (2006) | S | CFRP | Confined | Bottom | SC | 9.5 | 6.56 | 3.37 | 68.42 | 0.035 | 0.868 | Splitting |
| 467 | Aly *et al.* (2006) | S | CFRP | Confined | Bottom | SC | 9.5 | 6.40 | 3.37 | 115.79 | 0.035 | 0.743 | Splitting |
| 468 | Aly *et al.* (2006) | S | CFRP | Confined | Bottom | SC | 9.5 | 6.32 | 3.37 | 52.63 | 0.035 | 1.094 | Splitting |
| 469 | Aly *et al.* (2006) | S | CFRP | Confined | Bottom | SC | 12.7 | 7.00 | 2.52 | 39.37 | 0.026 | 0.859 | Splitting |
| 470 | Aly *et al.* (2006) | S | CFRP | Confined | Bottom | SC | 12.7 | 6.56 | 2.52 | 62.99 | 0.026 | 0.718 | Splitting |
| 471 | Aly *et al.* (2006) | S | GFRP | Confined | Bottom | SC | 19.1 | 6.40 | 1.68 | 26.18 | 0.018 | 0.562 | Splitting |
| 472 | Aly *et al.* (2006) | S | GFRP | Confined | Bottom | SC | 19.1 | 6.56 | 1.68 | 36.65 | 0.018 | 0.500 | Splitting |
| 473 | Aly *et al.* (2006) | S | GFRP | Confined | Bottom | SC | 19.1 | 6.40 | 1.68 | 41.88 | 0.018 | 0.515 | Splitting |
| 474 | Aly *et al.* (2006) | S | CFRP | Confined | Bottom | SC | 9.5 | 6.32 | 3.37 | 84.21 | 0.035 | 0.816 | Tensile |
| 475 | Aly *et al.* (2006) | S | CFRP | Confined | Bottom | SC | 9.5 | 6.32 | 3.37 | 147.37 | 0.035 | 0.360 | Shear |
| 476 | Aly *et al.* (2006) | S | GFRP | Confined | Bottom | SC | 15.9 | 7.00 | 2.01 | 31.45 | 0.021 | 0.577 | Tensile |
| 477 | Aly *et al.* (2006) | S | GFRP | Confined | Bottom | SC | 15.9 | 6.56 | 2.01 | 44.03 | 0.021 | 0.450 | Tensile |
| 478 | Aly *et al.* (2006) | S | GFRP | Confined | Bottom | SC | 19.1 | 6.40 | 1.68 | 57.59 | 0.018 | 0.400 | Tensile |
| 479 | Aly (2007) | S | CFRP | Confined | Bottom | SC | 9.5 | 6.32 | 4.21 | 52.63 | 0.035 | 1.094 | Splitting |
| 480 | Aly (2007) | S | CFRP | Confined | Bottom | SC | 9.5 | 6.32 | 4.21 | 84.21 | 0.035 | 0.816 | Tensile |
| 481 | Aly (2007) | S | CFRP | Confined | Bottom | SC | 12.7 | 6.32 | 3.15 | 39.37 | 0.026 | 0.950 | Splitting |
| 482 | Aly (2007) | S | CFRP | Confined | Bottom | SC | 12.7 | 6.32 | 3.15 | 62.99 | 0.026 | 0.745 | Splitting |
| 483 | Aly (2007) | S | CFRP | Confined | Bottom | SC | 9.5 | 6.32 | 4.21 | 52.63 | 0.035 | 0.838 | Splitting |
| 484 | Aly (2007) | S | CFRP | Confined | Bottom | SC | 9.5 | 6.32 | 4.21 | 68.42 | 0.035 | 0.811 | Splitting |
| 485 | Aly (2007) | S | CFRP | Confined | Bottom | SC | 9.5 | 6.32 | 4.21 | 84.21 | 0.035 | 0.591 | Splitting |
| 486 | Aly (2007) | S | CFRP | Confined | Bottom | SC | 9.5 | 6.32 | 4.21 | 52.63 | 0.035 | 0.756 | Splitting |
| 487 | Aly (2007) | S | CFRP | Confined | Bottom | SC | 9.5 | 6.32 | 4.21 | 68.42 | 0.035 | 0.900 | Splitting |
| 488 | Aly (2007) | S | CFRP | Confined | Bottom | SC | 9.5 | 6.32 | 4.21 | 115.79 | 0.035 | 0.753 | Splitting |
| 489 | Aly (2007) | S | CFRP | Confined | Bottom | SC | 15.9 | 6.32 | 2.52 | 31.45 | 0.021 | 0.640 | Tensile |
| 490 | Aly (2007) | S | CFRP | Confined | Bottom | SC | 15.9 | 6.32 | 2.52 | 44.03 | 0.021 | 0.466 | Tensile |
| 491 | Aly (2007) | S | CFRP | Confined | Bottom | SC | 19.1 | 6.32 | 2.09 | 26.18 | 0.018 | 0.569 | Splitting |

| SI | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f_c'}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 492 | Aly (2007) | S | CFRP | Confined | Bottom | SC | 19.1 | 6.32 | 2.09 | 36.65 | 0.018 | 0.519 | Splitting |
| 493 | Aly (2007) | S | CFRP | Confined | Bottom | SC | 19.1 | 6.32 | 2.09 | 41.88 | 0.018 | 0.522 | Splitting |
| 494 | Aly (2007) | S | CFRP | Confined | Bottom | SC | 19.1 | 6.32 | 2.09 | 57.59 | 0.018 | 0.405 | Tensile |
| 495 | Okelo (2007) | HB | CFRP | Confined | Bottom | SW | 10 | 5.77 | 3.80 | 10.00 | 0.154 | 1.629 | Pullout |
| 496 | Okelo (2007) | HB | CFRP | Confined | Bottom | SW | 16 | 5.77 | 2.38 | 10.00 | 0.096 | 0.399 | Pullout |
| 497 | Okelo (2007) | HB | CFRP | Confined | Bottom | SW | 10 | 5.69 | 3.80 | 15.00 | 0.154 | 1.774 | Pullout |
| 498 | Okelo (2007) | HB | CFRP | Confined | Bottom | SW | 10 | 5.59 | 3.80 | 20.00 | 0.154 | 2.163 | Pullout |
| 499 | Okelo (2007) | HB | CFRP | Confined | Bottom | SW | 16 | 5.59 | 2.38 | 20.00 | 0.096 | 1.716 | Pullout |
| 500 | Okelo (2007) | HB | CFRP | Confined | Bottom | SW | 10 | 6.07 | 3.80 | 10.00 | 0.154 | 2.206 | Pullout |
| 501 | Okelo (2007) | HB | CFRP | Confined | Bottom | SW | 16 | 6.07 | 2.38 | 10.00 | 0.096 | 1.268 | Pullout |
| 502 | Okelo (2007) | HB | CFRP | Confined | Bottom | SW | 10 | 6.43 | 3.80 | 15.00 | 0.154 | 2.471 | Pullout |
| 503 | Okelo (2007) | HB | CFRP | Confined | Bottom | SW | 16 | 6.44 | 2.38 | 15.00 | 0.096 | 1.847 | Splitting |
| 504 | Okelo (2007) | HB | CFRP | Confined | Bottom | SW | 10 | 6.27 | 3.80 | 20.00 | 0.154 | 1.882 | Pullout |
| 505 | Okelo (2007) | HB | CFRP | Confined | Bottom | SW | 16 | 6.27 | 2.38 | 20.00 | 0.096 | 1.468 | Pullout |
| 506 | Okelo (2007) | HB | GFRP | Confined | Bottom | SW | 10 | 5.77 | 3.80 | 10.00 | 0.154 | 0.139 | Pullout |
| 507 | Okelo (2007) | HB | GFRP | Confined | Bottom | SW | 19 | 5.77 | 2.00 | 10.00 | 0.081 | 0.589 | Pullout |
| 508 | Okelo (2007) | HB | CFRP | Confined | Bottom | SW | 16 | 5.69 | 2.38 | 15.00 | 0.096 | 1.599 | Compression |
| 509 | Okelo (2007) | HB | GFRP | Confined | Bottom | SW | 10 | 5.69 | 3.80 | 15.00 | 0.154 | 1.827 | Tensile |
| 510 | Okelo (2007) | HB | GFRP | Confined | Bottom | SW | 19 | 5.69 | 2.00 | 15.00 | 0.081 | 1.195 | Compression |
| 511 | Okelo (2007) | HB | GFRP | Confined | Bottom | SW | 10 | 5.59 | 3.80 | 20.00 | 0.154 | 2.038 | Tensile |
| 512 | Okelo (2007) | HB | GFRP | Confined | Bottom | SW | 19 | 5.59 | 2.00 | 20.00 | 0.081 | 1.233 | Compression |
| 513 | Okelo (2007) | HB | GFRP | Confined | Bottom | SW | 10 | 6.07 | 3.80 | 10.00 | 0.154 | 2.831 | Tensile |
| 514 | Okelo (2007) | HB | GFRP | Confined | Bottom | SW | 19 | 6.07 | 2.00 | 10.00 | 0.081 | 1.119 | Compression |
| 515 | Okelo (2007) | HB | GFRP | Confined | Bottom | SW | 10 | 6.44 | 3.80 | 15.00 | 0.154 | 1.847 | Tensile |
| 516 | Okelo (2007) | HB | GFRP | Confined | Bottom | SW | 19 | 6.52 | 2.00 | 15.00 | 0.081 | 1.058 | Compression |
| 517 | Okelo (2007) | HB | GFRP | Confined | Bottom | SW | 10 | 6.27 | 3.80 | 20.00 | 0.154 | 1.531 | Tensile |

| SI | Ref | Test Type | FRP Type | Confinement | Bar Position | Bar Surface | $d_b$ (mm) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $\frac{l_{embed}}{d_b}$ | $\frac{A_{tr}}{snd_b}$ | $\frac{\tau_m}{\sqrt{f_c'}}$ | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 518 | Okelo (2007) | HB | GFRP | Confined | Bottom | SW | 19 | 6.27 | 2.00 | 20.00 | 0.081 | 1.133 | Compression |
| 519 | Thamrin and Kaku (2007) | nr | CFRP | Confined | Bottom | HL | 10.6 | 6.19 | 1.89 | 76.42 | 0.041 | 0.646 | Splitting |
| 520 | Thamrin and Kaku (2007) | nr | CFRP | Confined | Bottom | HL | 10.6 | 6.19 | 1.89 | 82.08 | 0.041 | 0.743 | Splitting |
| 521 | Thamrin and Kaku (2007) | nr | CFRP | Confined | Bottom | HL | 10.6 | 6.19 | 1.89 | 82.08 | 0.041 | 0.873 | Splitting |
| 522 | Thamrin and Kaku (2007) | nr | CFRP | Confined | Bottom | HL | 10.6 | 6.34 | 1.89 | 61.32 | 0.041 | 0.410 | Splitting |
| 523 | Thamrin and Kaku (2007) | nr | CFRP | Confined | Bottom | HL | 10.6 | 6.34 | 1.89 | 61.32 | 0.041 | 0.473 | Splitting |
| 524 | Thamrin and Kaku (2007) | nr | CFRP | Confined | Bottom | HL | 10.6 | 6.34 | 1.89 | 61.32 | 0.041 | 0.615 | Splitting |
| 525 | Thamrin and Kaku (2007) | nr | CFRP | Confined | Bottom | HL | 10.6 | 6.34 | 1.89 | 61.32 | 0.041 | 0.584 | Splitting |
| 526 | Thamrin and Kaku (2007) | nr | CFRP | Confined | Bottom | HL | 10.6 | 5.92 | 1.89 | 66.04 | 0.041 | 0.355 | Splitting |
| 527 | Thamrin and Kaku (2007) | nr | CFRP | Confined | Bottom | HL | 10.6 | 5.92 | 1.89 | 66.04 | 0.041 | 0.744 | Splitting |
| 528 | Thamrin and Kaku (2007) | nr | CFRP | Confined | Bottom | HL | 10.6 | 5.92 | 1.89 | 66.04 | 0.041 | 0.507 | Splitting |
| 529 | Thamrin and Kaku (2007) | nr | CFRP | Confined | Bottom | HL | 10.6 | 5.92 | 1.89 | 70.75 | 0.041 | 0.558 | Splitting |
| 530 | Thamrin and Kaku (2007) | nr | CFRP | Confined | Bottom | HL | 10.6 | 5.92 | 1.89 | 75.47 | 0.041 | 0.372 | Splitting |
| 531 | Rafi *et al.* (2007) | nr | CFRP | Confined | Bottom | SW | 9.5 | 6.93 | 2.11 | 95.26 | 0.046 | 0.462 | Shear |
| 532 | Rafi *et al.* (2007) | nr | CFRP | Confined | Bottom | SW | 9.5 | 6.86 | 2.11 | 95.26 | 0.046 | 0.481 | Compression |
| 533 | Mosley *et al.* (2008) | S | GFRP | Confined | Bottom | HL | 16 | 6.21 | 2.38 | 28.56 | 0.021 | 0.369 | Splitting |
| 534 | Mosley *et al.* (2008) | S | GFRP | Confined | Bottom | HL | 16 | 6.15 | 2.38 | 28.56 | 0.032 | 0.316 | Splitting |
| 535 | Mosley *et al.* (2008) | S | GFRP | Confined | Bottom | HL | 16 | 5.39 | 2.38 | 19.06 | 0.032 | 0.321 | Splitting |
| 536 | Mosley *et al.* (2008) | S | GFRP | Confined | Bottom | HL | 16 | 5.20 | 2.38 | 19.06 | 0.032 | 0.341 | Splitting |
| 537 | Mosley *et al.* (2008) | S | GFRP | Confined | Bottom | HL | 16 | 6.42 | 2.38 | 19.06 | 0.032 | 0.460 | Splitting |
| 538 | Mosley *et al.* (2008) | S | GFRP | Confined | Bottom | HL | 16 | 6.40 | 2.38 | 19.06 | 0.032 | 0.436 | Splitting |
| 539 | Mosley *et al.* (2008) | S | AFRP | Confined | Bottom | HL | 16 | 6.26 | 2.38 | 28.56 | 0.032 | 0.387 | Splitting |
| 540 | Mosley *et al.* (2008) | S | AFRP | Confined | Bottom | HL | 16 | 5.36 | 2.38 | 19.06 | 0.032 | 0.347 | Splitting |
| 541 | Mosley *et al.* (2008) | S | AFRP | Confined | Bottom | HL | 16 | 6.29 | 2.38 | 19.06 | 0.032 | 0.493 | Splitting |

**Note:** Ref = Reference article; NB = Notched beam specimen; HB = Hinged beam specimen; S = Splice beam specimen; IHB = Inverted hinged beam specimen; nr = Not reported; HL = Helical lugged bars; SC = Sand coated bars; SW = Spiral wrapped bars; SW+SC = Spiral wrapped bars with sand coating

# Appendix B

**Table B.1 Database of beam-type specimens failed by concrete splitting for deriving bond stress-slip relationship of FRP rebars in concrete**

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $c$ (mm) | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Kanakubo *et al.* (1993) | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0000 | 0 | 0.75 | 0 | 3.4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0000 | 0.25 | 0.75 | 1.5 | 3.4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0000 | 0.5 | 0.75 | 2.5 | 3.4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0000 | 0.75 | 0.75 | 3.4 | 3.4 |
| 2 | Kanakubo *et al.* (1993) | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0084 | 0 | 1.5 | 0 | 4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0084 | 0.25 | 1.5 | 2 | 4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0084 | 0.5 | 1.5 | 2.5 | 4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0084 | 1 | 1.5 | 3.7 | 4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0084 | 1.5 | 1.5 | 4 | 4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0084 | 2 | 1.5 | 3.6 | 4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0084 | 3 | 1.5 | 2.4 | 4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0084 | 4 | 1.5 | 1.7 | 4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0084 | 5 | 1.5 | 1.5 | 4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0084 | 6 | 1.5 | 1.3 | 4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0084 | 7 | 1.5 | 1.2 | 4 |
| 3 | Kanakubo *et al.* (1993) | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 0 | 1.25 | 0 | 4.3 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 0.25 | 1.25 | 2 | 4.3 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 0.5 | 1.25 | 2.5 | 4.3 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 1 | 1.25 | 4.2 | 4.3 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 1.25 | 1.25 | 4.3 | 4.3 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 2 | 1.25 | 3.6 | 4.3 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $c$ (mm) | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 3 | 1.25 | 2.7 | 4.3 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 4 | 1.25 | 2.5 | 4.3 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 5 | 1.25 | 2.3 | 4.3 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 6 | 1.25 | 2.2 | 4.3 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 7 | 1.25 | 2.1 | 4.3 |
| 4 | Kanakubo *et al.* (1993) | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0249 | 0 | 1.5 | 0 | 4.5 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0249 | 0.25 | 1.5 | 1.7 | 4.5 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0249 | 0.5 | 1.5 | 2.3 | 4.5 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0249 | 1 | 1.5 | 3.9 | 4.5 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0249 | 1.5 | 1.5 | 4.5 | 4.5 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0249 | 2 | 1.5 | 4 | 4.5 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0249 | 3 | 1.5 | 2.7 | 4.5 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0249 | 4 | 1.5 | 2.5 | 4.5 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0249 | 5 | 1.5 | 2.3 | 4.5 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0249 | 6 | 1.5 | 2.2 | 4.5 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0249 | 7 | 1.5 | 2.1 | 4.5 |
| 5 | Kanakubo *et al.* (1993) | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0000 | 0 | 1.5 | 0 | 3.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0000 | 0.25 | 1.5 | 1.5 | 3.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0000 | 0.5 | 1.5 | 2 | 3.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0000 | 1 | 1.5 | 2.6 | 3.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0000 | 1.5 | 1.5 | 3.7 | 3.7 |
| 6 | Kanakubo *et al.* (1993) | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 0 | 3.2 | 0 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 0.25 | 3.2 | 1.5 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 0.5 | 3.2 | 2 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 1 | 3.2 | 2.7 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 2 | 3.2 | 3.8 | 4.7 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $c$ (mm) | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 3 | 3.2 | 4.2 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 3.2 | 3.2 | 4.7 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 4 | 3.2 | 3.5 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 5 | 3.2 | 3 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 6 | 3.2 | 2.5 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 7 | 3.2 | 2.3 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0168 | 8 | 3.2 | 2.1 | 4.7 |
| 7 | Kanakubo *et al.* (1993) | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0147 | 0 | 2 | 0 | 3.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0147 | 0.25 | 2 | 1 | 3.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0147 | 0.5 | 2 | 1.5 | 3.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0147 | 1 | 2 | 2.2 | 3.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0147 | 2 | 2 | 3.5 | 3.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0147 | 6 | 2 | 3 | 3.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0147 | 7 | 2 | 2.9 | 3.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0147 | 8 | 2 | 2.7 | 3.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0147 | 9 | 2 | 2.5 | 3.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 27.50 | 2.292 | 300 | 0.0147 | 10 | 2 | 2.3 | 3.5 |
| 8 | Kanakubo *et al.* (1993) | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0000 | 0 | 0.75 | 0 | 2.8 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0000 | 0.5 | 0.75 | 2 | 2.8 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0000 | 0.75 | 0.75 | 2.8 | 2.8 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0000 | 1 | 0.75 | 2.6 | 2.8 |
| 9 | Kanakubo *et al.* (1993) | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0084 | 0 | 1 | 0 | 4.1 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0084 | 0.5 | 1 | 3 | 4.1 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0084 | 1 | 1 | 4.1 | 4.1 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0084 | 2 | 1 | 3 | 4.1 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0084 | 3 | 1 | 2.2 | 4.1 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $c$ (mm) | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0084 | 4 | 1 | 2 | 4.1 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0084 | 5 | 1 | 1.8 | 4.1 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0084 | 6 | 1 | 1.7 | 4.1 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0084 | 7 | 1 | 1.6 | 4.1 |
| 10 | Kanakubo *et al.* (1993) | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0168 | 0 | 1.2 | 0 | 4.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0168 | 0.5 | 1.2 | 3.2 | 4.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0168 | 1 | 1.2 | 4.2 | 4.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0168 | 1.2 | 1.2 | 4.5 | 4.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0168 | 2 | 1.2 | 4.2 | 4.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0168 | 3 | 1.2 | 4 | 4.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0168 | 4 | 1.2 | 3.8 | 4.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0168 | 5 | 1.2 | 3.5 | 4.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0168 | 6 | 1.2 | 3.3 | 4.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0168 | 7 | 1.2 | 3.1 | 4.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0168 | 8 | 1.2 | 2.8 | 4.5 |
| 11 | Kanakubo *et al.* (1993) | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0147 | 0 | 1.2 | 0 | 4.6 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0147 | 0.5 | 1.2 | 3.3 | 4.6 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0147 | 1 | 1.2 | 4.4 | 4.6 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0147 | 1.2 | 1.2 | 4.6 | 4.6 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0147 | 2 | 1.2 | 4.2 | 4.6 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0147 | 3 | 1.2 | 4.1 | 4.6 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0147 | 4 | 1.2 | 3.8 | 4.6 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0147 | 5 | 1.2 | 3.7 | 4.6 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0147 | 6 | 1.2 | 3.5 | 4.6 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0147 | 7 | 1.2 | 3.3 | 4.6 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 27.50 | 2.292 | 300 | 0.0147 | 8 | 1.2 | 3 | 4.6 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $c$ (mm) | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 25.00 | 1.923 | 300 | 0.0000 | 0 | 0.75 | 0 | 3.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 25.00 | 1.923 | 300 | 0.0000 | 0.25 | 0.75 | 2.3 | 3.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 25.00 | 1.923 | 300 | 0.0000 | 0.5 | 0.75 | 3.2 | 3.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 25.00 | 1.923 | 300 | 0.0000 | 0.75 | 0.75 | 3.5 | 3.5 |
| 13 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 0 | 1.25 | 0 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 0.25 | 1.25 | 2.3 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 0.5 | 1.25 | 3.2 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 1 | 1.25 | 4.2 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 1.25 | 1.25 | 4.3 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 2 | 1.25 | 3.6 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 3 | 1.25 | 2.6 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 4 | 1.25 | 2.1 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 5 | 1.25 | 1.9 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 6 | 1.25 | 1.7 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 7 | 1.25 | 1.5 | 4.3 |
| 14 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 0 | 1.25 | 0 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 0.25 | 1.25 | 2.3 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 0.5 | 1.25 | 3.2 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 1 | 1.25 | 4.2 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 1.25 | 1.25 | 4.3 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 2 | 1.25 | 3.5 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 3 | 1.25 | 3.1 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 4 | 1.25 | 3 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 5 | 1.25 | 2.8 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 6 | 1.25 | 2.6 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 7 | 1.25 | 2.4 | 4.3 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $c$ (mm) | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 8 | 1.25 | 2 | 4.3 |
| 15 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0230 | 0 | 1.1 | 0 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0230 | 0.25 | 1.1 | 2.3 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0230 | 0.5 | 1.1 | 3.2 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0230 | 1 | 1.1 | 4.4 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0230 | 1.1 | 1.1 | 4.5 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0230 | 2 | 1.1 | 3.8 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0230 | 3 | 1.1 | 3.2 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0230 | 4 | 1.1 | 3 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0230 | 5 | 1.1 | 2.8 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0230 | 6 | 1.1 | 2.5 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0230 | 7 | 1.1 | 2.3 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0230 | 8 | 1.1 | 2.1 | 4.5 |
| 16 | Kanakubo *et al.* (1993) | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0000 | 0 | 0.75 | 0 | 2.4 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0000 | 0.25 | 0.75 | 1.5 | 2.4 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0000 | 0.5 | 0.75 | 2 | 2.4 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0000 | 0.75 | 0.75 | 2.4 | 2.4 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0000 | 1 | 0.75 | 2.3 | 2.4 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0000 | 2 | 0.75 | 2.2 | 2.4 |
| 17 | Kanakubo *et al.* (1993) | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 0 | 1.5 | 0 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 0.25 | 1.5 | 1.5 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 0.5 | 1.5 | 2 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 1 | 1.5 | 2.6 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 1.5 | 1.5 | 3.5 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 2 | 1.5 | 3.5 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 3 | 1.5 | 2.7 | 3.5 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $c$ (mm) | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 4 | 1.5 | 2 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 5 | 1.5 | 1.4 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 6 | 1.5 | 1 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 7 | 1.5 | 0.8 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0078 | 8 | 1.5 | 0.7 | 3.5 |
| 18 | Kanakubo *et al.* (1993) | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 0 | 2 | 0 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 0.25 | 2 | 1.5 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 0.5 | 2 | 2 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 1 | 2 | 2.6 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 2 | 2 | 3.5 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 3 | 2 | 2.5 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 4 | 2 | 2 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 5 | 2 | 1.7 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 6 | 2 | 1.6 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0155 | 7 | 2 | 1.5 | 3.5 |
| 19 | Kanakubo *et al.* (1993) | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0130 | 0 | 2.75 | 0 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0130 | 0.25 | 2.75 | 1.5 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0130 | 0.5 | 2.75 | 2 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0130 | 1 | 2.75 | 2.6 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0130 | 2 | 2.75 | 3.4 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0130 | 2.75 | 2.75 | 3.8 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0130 | 3 | 2.75 | 3.7 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0130 | 4 | 2.75 | 3.1 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0130 | 5 | 2.75 | 2.4 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0130 | 6 | 2.75 | 1.8 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0130 | 7 | 2.75 | 1.3 | 3.8 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $c$ (mm) | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 27.50 | 2.115 | 300 | 0.0130 | 8 | 2.75 | 1.2 | 3.8 |
| 20 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0000 | 0 | 1.5 | 0 | 2.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0000 | 0.5 | 1.5 | 1.5 | 2.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0000 | 1 | 1.5 | 2 | 2.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0000 | 1.5 | 1.5 | 2.5 | 2.5 |
| 21 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0078 | 0 | 1.2 | 0 | 3.7 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0078 | 0.5 | 1.2 | 2.6 | 3.7 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0078 | 1 | 1.2 | 3.5 | 3.7 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0078 | 1.2 | 1.2 | 3.7 | 3.7 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0078 | 2 | 1.2 | 3 | 3.7 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0078 | 3 | 1.2 | 2.4 | 3.7 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0078 | 4 | 1.2 | 2 | 3.7 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0078 | 5 | 1.2 | 1.8 | 3.7 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0078 | 6 | 1.2 | 1.7 | 3.7 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0078 | 7 | 1.2 | 1.6 | 3.7 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0078 | 8 | 1.2 | 1.5 | 3.7 |
| 22 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0155 | 0 | 1.7 | 0 | 3.9 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0155 | 0.5 | 1.7 | 2.2 | 3.9 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0155 | 1 | 1.7 | 3.2 | 3.9 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0155 | 1.7 | 1.7 | 3.9 | 3.9 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0155 | 2 | 1.7 | 3.8 | 3.9 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0155 | 3 | 1.7 | 3.1 | 3.9 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0155 | 4 | 1.7 | 3.1 | 3.9 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0155 | 5 | 1.7 | 3 | 3.9 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0155 | 6 | 1.7 | 2.5 | 3.9 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0155 | 7 | 1.7 | 2.4 | 3.9 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $c$ (mm) | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0155 | 8 | 1.7 | 2.2 | 3.9 |
| 23 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0135 | 0 | 1.7 | 0 | 4 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0135 | 0.5 | 1.7 | 1.8 | 4 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0135 | 1 | 1.7 | 3 | 4 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0135 | 1.7 | 1.7 | 4 | 4 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0135 | 2 | 1.7 | 3.6 | 4 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0135 | 3 | 1.7 | 3.4 | 4 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0135 | 4 | 1.7 | 3.2 | 4 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0135 | 5 | 1.7 | 3.1 | 4 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0135 | 6 | 1.7 | 2.9 | 4 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0135 | 7 | 1.7 | 2.8 | 4 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 27.50 | 2.115 | 300 | 0.0135 | 8 | 1.7 | 2.7 | 4 |

**Table B.2 Database of beam-type specimens failed by rebar pullout for deriving bond stress-slip relationship of FRP rebars in concrete**

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Makitani *et al.* (1993) | CFRP | HB | SC | Confined | 10 | 33.7 | 5.805 | 5.00 | 100 | 0.1570 | 0 | 0.05 | 0 | 13.8 |
| | | CFRP | HB | SC | Confined | 10 | 33.7 | 5.805 | 5.00 | 100 | 0.1570 | 0.05 | 0.05 | 13.8 | 13.8 |
| | | CFRP | HB | SC | Confined | 10 | 33.7 | 5.805 | 5.00 | 100 | 0.1570 | 0.1 | 0.05 | 13.6 | 13.8 |
| | | CFRP | HB | SC | Confined | 10 | 33.7 | 5.805 | 5.00 | 100 | 0.1570 | 0.2 | 0.05 | 13.4 | 13.8 |
| | | CFRP | HB | SC | Confined | 10 | 33.7 | 5.805 | 5.00 | 100 | 0.1570 | 0.5 | 0.05 | 13 | 13.8 |
| | | CFRP | HB | SC | Confined | 10 | 33.7 | 5.805 | 5.00 | 100 | 0.1570 | 1 | 0.05 | 12.8 | 13.8 |
| | | CFRP | HB | SC | Confined | 10 | 33.7 | 5.805 | 5.00 | 100 | 0.1570 | 2 | 0.05 | 13.2 | 13.8 |
| | | CFRP | HB | SC | Confined | 10 | 33.7 | 5.805 | 5.00 | 100 | 0.1570 | 3 | 0.05 | 13.6 | 13.8 |
| | | CFRP | HB | SC | Confined | 10 | 33.7 | 5.805 | 5.00 | 100 | 0.1570 | 4 | 0.05 | 13.8 | 13.8 |
| | | CFRP | HB | SC | Confined | 10 | 33.7 | 5.805 | 5.00 | 100 | 0.1570 | 5 | 0.05 | 13.6 | 13.8 |
| | | CFRP | HB | SC | Confined | 10 | 33.7 | 5.805 | 5.00 | 100 | 0.1570 | 6 | 0.05 | 13.5 | 13.8 |
| | | CFRP | HB | SC | Confined | 10 | 33.7 | 5.805 | 5.00 | 100 | 0.1570 | 7 | 0.05 | 13.4 | 13.8 |
| | | CFRP | HB | SC | Confined | 10 | 33.7 | 5.805 | 5.00 | 100 | 0.1570 | 8 | 0.05 | 13.2 | 13.8 |
| | | CFRP | HB | SC | Confined | 10 | 33.7 | 5.805 | 5.00 | 100 | 0.1570 | 9 | 0.05 | 13 | 13.8 |
| | | CFRP | HB | SC | Confined | 10 | 33.7 | 5.805 | 5.00 | 100 | 0.1570 | 10 | 0.05 | 12.8 | 13.8 |
| 2 | Makitani *et al.* (1993) | AFRP | HB | SC | Confined | 10 | 30.1 | 5.486 | 5.00 | 100 | 0.1570 | 0 | 0.15 | 0 | 19 |
| | | AFRP | HB | SC | Confined | 10 | 30.1 | 5.486 | 5.00 | 100 | 0.1570 | 0.1 | 0.15 | 18.2 | 19 |
| | | AFRP | HB | SC | Confined | 10 | 30.1 | 5.486 | 5.00 | 100 | 0.1570 | 0.15 | 0.15 | 19 | 19 |
| | | AFRP | HB | SC | Confined | 10 | 30.1 | 5.486 | 5.00 | 100 | 0.1570 | 0.5 | 0.15 | 18.6 | 19 |
| | | AFRP | HB | SC | Confined | 10 | 30.1 | 5.486 | 5.00 | 100 | 0.1570 | 1 | 0.15 | 18 | 19 |
| | | AFRP | HB | SC | Confined | 10 | 30.1 | 5.486 | 5.00 | 100 | 0.1570 | 2 | 0.15 | 17 | 19 |
| | | AFRP | HB | SC | Confined | 10 | 30.1 | 5.486 | 5.00 | 100 | 0.1570 | 3 | 0.15 | 15.6 | 19 |
| | | AFRP | HB | SC | Confined | 10 | 30.1 | 5.486 | 5.00 | 100 | 0.1570 | 4 | 0.15 | 15 | 19 |
| | | AFRP | HB | SC | Confined | 10 | 30.1 | 5.486 | 5.00 | 100 | 0.1570 | 5 | 0.15 | 14 | 19 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AFRP | HB | SC | Confined | 10 | 30.1 | 5.486 | 5.00 | 100 | 0.1570 | 6 | 0.15 | 13.2 | 19 |
| | | AFRP | HB | SC | Confined | 10 | 30.1 | 5.486 | 5.00 | 100 | 0.1570 | 7 | 0.15 | 12.6 | 19 |
| | | AFRP | HB | SC | Confined | 10 | 30.1 | 5.486 | 5.00 | 100 | 0.1570 | 8 | 0.15 | 12 | 19 |
| | | AFRP | HB | SC | Confined | 10 | 30.1 | 5.486 | 5.00 | 100 | 0.1570 | 9 | 0.15 | 11.8 | 19 |
| 3 | Makitani *et al.* (1993) | CFRP | HB | SW | Confined | 10 | 29.4 | 5.422 | 5.00 | 100 | 0.1570 | 0 | 0.5 | 0 | 4.3 |
| | | CFRP | HB | SW | Confined | 10 | 29.4 | 5.422 | 5.00 | 100 | 0.1570 | 0.2 | 0.5 | 3.8 | 4.3 |
| | | CFRP | HB | SW | Confined | 10 | 29.4 | 5.422 | 5.00 | 100 | 0.1570 | 0.5 | 0.5 | 4.3 | 4.3 |
| | | CFRP | HB | SW | Confined | 10 | 29.4 | 5.422 | 5.00 | 100 | 0.1570 | 1 | 0.5 | 4.1 | 4.3 |
| | | CFRP | HB | SW | Confined | 10 | 29.4 | 5.422 | 5.00 | 100 | 0.1570 | 2 | 0.5 | 3.9 | 4.3 |
| | | CFRP | HB | SW | Confined | 10 | 29.4 | 5.422 | 5.00 | 100 | 0.1570 | 3 | 0.5 | 3.7 | 4.3 |
| | | CFRP | HB | SW | Confined | 10 | 29.4 | 5.422 | 5.00 | 100 | 0.1570 | 4 | 0.5 | 3.5 | 4.3 |
| | | CFRP | HB | SW | Confined | 10 | 29.4 | 5.422 | 5.00 | 100 | 0.1570 | 5 | 0.5 | 3 | 4.3 |
| | | CFRP | HB | SW | Confined | 10 | 29.4 | 5.422 | 5.00 | 100 | 0.1570 | 6 | 0.5 | 3.6 | 4.3 |
| | | CFRP | HB | SW | Confined | 10 | 29.4 | 5.422 | 5.00 | 100 | 0.1570 | 7 | 0.5 | 3.8 | 4.3 |
| | | CFRP | HB | SW | Confined | 10 | 29.4 | 5.422 | 5.00 | 100 | 0.1570 | 8 | 0.5 | 3.8 | 4.3 |
| | | CFRP | HB | SW | Confined | 10 | 29.4 | 5.422 | 5.00 | 100 | 0.1570 | 9 | 0.5 | 3.8 | 4.3 |
| | | CFRP | HB | SW | Confined | 10 | 29.4 | 5.422 | 5.00 | 100 | 0.1570 | 10 | 0.5 | 3.8 | 4.3 |
| 4 | Makitani *et al.* (1993) | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 95.4 | 0.0494 | 0 | 0.33 | 0 | 10.6 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 95.4 | 0.0494 | 0.01 | 0.33 | 3.5 | 10.6 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 95.4 | 0.0494 | 0.1 | 0.33 | 6.7 | 10.6 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 95.4 | 0.0494 | 0.2 | 0.33 | 9.2 | 10.6 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 95.4 | 0.0494 | 0.33 | 0.33 | 10.6 | 10.6 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 95.4 | 0.0494 | 0.5 | 0.33 | 9.5 | 10.6 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 95.4 | 0.0494 | 0.75 | 0.33 | 9.3 | 10.6 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 95.4 | 0.0494 | 1 | 0.33 | 8.8 | 10.6 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 95.4 | 0.0494 | 1.25 | 0.33 | 8.6 | 10.6 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 95.4 | 0.0494 | 1.5 | 0.33 | 8.2 | 10.6 |
| 5 | Makitani *et al.* (1993) | GFRP | HB | SW | Confined | 19.1 | 31 | 5.568 | 2.62 | 114.6 | 0.0411 | 0 | 0.16 | 0 | 7.1 |
| | | GFRP | HB | SW | Confined | 19.1 | 31 | 5.568 | 2.62 | 114.6 | 0.0411 | 0.01 | 0.16 | 3.5 | 7.1 |
| | | GFRP | HB | SW | Confined | 19.1 | 31 | 5.568 | 2.62 | 114.6 | 0.0411 | 0.1 | 0.16 | 6.8 | 7.1 |
| | | GFRP | HB | SW | Confined | 19.1 | 31 | 5.568 | 2.62 | 114.6 | 0.0411 | 0.16 | 0.16 | 7.1 | 7.1 |
| | | GFRP | HB | SW | Confined | 19.1 | 31 | 5.568 | 2.62 | 114.6 | 0.0411 | 0.2 | 0.16 | 7 | 7.1 |
| | | GFRP | HB | SW | Confined | 19.1 | 31 | 5.568 | 2.62 | 114.6 | 0.0411 | 0.5 | 0.16 | 6.8 | 7.1 |
| | | GFRP | HB | SW | Confined | 19.1 | 31 | 5.568 | 2.62 | 114.6 | 0.0411 | 0.75 | 0.16 | 6.5 | 7.1 |
| | | GFRP | HB | SW | Confined | 19.1 | 31 | 5.568 | 2.62 | 114.6 | 0.0411 | 1 | 0.16 | 6.1 | 7.1 |
| 6 | Makitani *et al.* (1993) | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 152.4 | 0.0309 | 0 | 0.075 | 0 | 7 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 152.4 | 0.0309 | 0.01 | 0.075 | 1.6 | 7 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 152.4 | 0.0309 | 0.075 | 0.075 | 7 | 7 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 152.4 | 0.0309 | 0.1 | 0.075 | 6.9 | 7 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 152.4 | 0.0309 | 0.2 | 0.075 | 6.8 | 7 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 152.4 | 0.0309 | 0.5 | 0.075 | 6.5 | 7 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 152.4 | 0.0309 | 0.75 | 0.075 | 5.8 | 7 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 152.4 | 0.0309 | 1 | 0.075 | 5.1 | 7 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 152.4 | 0.0309 | 1.25 | 0.075 | 4.7 | 7 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 152.4 | 0.0309 | 1.5 | 0.075 | 4.4 | 7 |
| 7 | Makitani *et al.* (1993) | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0618 | 0 | 0.3 | 0 | 10.6 |
| | | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0618 | 0.01 | 0.3 | 1.9 | 10.6 |
| | | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0618 | 0.1 | 0.3 | 7.3 | 10.6 |
| | | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0618 | 0.2 | 0.3 | 8.3 | 10.6 |
| | | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0618 | 0.3 | 0.3 | 10.6 | 10.6 |
| | | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0618 | 0.5 | 0.3 | 10 | 10.6 |
| | | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0618 | 0.75 | 0.3 | 9.8 | 10.6 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0618 | 1 | 0.3 | 9.3 | 10.6 |
| | | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0618 | 1.25 | 0.3 | 8.9 | 10.6 |
| | | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0618 | 1.5 | 0.3 | 8.2 | 10.6 |
| 8 | Makitani *et al.* (1993) | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 159 | 0.0494 | 0 | 0.85 | 0 | 7.8 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 159 | 0.0494 | 0.01 | 0.85 | 1.1 | 7.8 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 159 | 0.0494 | 0.1 | 0.85 | 5.8 | 7.8 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 159 | 0.0494 | 0.2 | 0.85 | 6.1 | 7.8 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 159 | 0.0494 | 0.5 | 0.85 | 7.6 | 7.8 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 159 | 0.0494 | 0.75 | 0.85 | 7.7 | 7.8 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 159 | 0.0494 | 0.85 | 0.85 | 7.8 | 7.8 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 159 | 0.0494 | 1 | 0.85 | 7.5 | 7.8 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 159 | 0.0494 | 1.25 | 0.85 | 7.3 | 7.8 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 159 | 0.0494 | 1.5 | 0.85 | 7.2 | 7.8 |
| 9 | Makitani *et al.* (1993) | GFRP | HB | SW | Confined | 19.1 | 31 | 5.568 | 2.62 | 191 | 0.0411 | 0 | 0.25 | 0 | 6.6 |
| | | GFRP | HB | SW | Confined | 19.1 | 31 | 5.568 | 2.62 | 191 | 0.0411 | 0.01 | 0.25 | 1 | 6.6 |
| | | GFRP | HB | SW | Confined | 19.1 | 31 | 5.568 | 2.62 | 191 | 0.0411 | 0.1 | 0.25 | 3.8 | 6.6 |
| | | GFRP | HB | SW | Confined | 19.1 | 31 | 5.568 | 2.62 | 191 | 0.0411 | 0.2 | 0.25 | 5.6 | 6.6 |
| | | GFRP | HB | SW | Confined | 19.1 | 31 | 5.568 | 2.62 | 191 | 0.0411 | 0.25 | 0.25 | 6.6 | 6.6 |
| | | GFRP | HB | SW | Confined | 19.1 | 31 | 5.568 | 2.62 | 191 | 0.0411 | 0.5 | 0.25 | 6.5 | 6.6 |
| | | GFRP | HB | SW | Confined | 19.1 | 31 | 5.568 | 2.62 | 191 | 0.0411 | 0.75 | 0.25 | 6.4 | 6.6 |
| | | GFRP | HB | SW | Confined | 19.1 | 31 | 5.568 | 2.62 | 191 | 0.0411 | 1 | 0.25 | 6.2 | 6.6 |
| | | GFRP | HB | SW | Confined | 19.1 | 31 | 5.568 | 2.62 | 191 | 0.0411 | 1.25 | 0.25 | 6 | 6.6 |
| | | GFRP | HB | SW | Confined | 19.1 | 31 | 5.568 | 2.62 | 191 | 0.0411 | 1.5 | 0.25 | 6 | 6.6 |
| 10 | Makitani *et al.* (1993) | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0309 | 0 | 0.2 | 0 | 6.4 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0309 | 0.01 | 0.2 | 0.8 | 6.4 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0309 | 0.1 | 0.2 | 3.4 | 6.4 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0309 | 0.15 | 0.2 | 5.7 | 6.4 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0309 | 0.2 | 0.2 | 6.4 | 6.4 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0309 | 0.5 | 0.2 | 6.2 | 6.4 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0309 | 0.75 | 0.2 | 6 | 6.4 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0309 | 1 | 0.2 | 5.8 | 6.4 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0309 | 1.25 | 0.2 | 5.3 | 6.4 |
| 11 | Makitani *et al.* (1993) | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.94 | 203.2 | 0.0618 | 0 | 0.25 | 0 | 10 |
| | | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.94 | 203.2 | 0.0618 | 0.01 | 0.25 | 2 | 10 |
| | | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.94 | 203.2 | 0.0618 | 0.1 | 0.25 | 6.6 | 10 |
| | | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.94 | 203.2 | 0.0618 | 0.2 | 0.25 | 7.5 | 10 |
| | | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.94 | 203.2 | 0.0618 | 0.25 | 0.25 | 10 | 10 |
| | | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.94 | 203.2 | 0.0618 | 0.5 | 0.25 | 10 | 10 |
| | | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.94 | 203.2 | 0.0618 | 0.75 | 0.25 | 9.9 | 10 |
| | | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.94 | 203.2 | 0.0618 | 1 | 0.25 | 9.8 | 10 |
| | | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.94 | 203.2 | 0.0618 | 1.25 | 0.25 | 9.6 | 10 |
| | | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.94 | 203.2 | 0.0618 | 1.5 | 0.25 | 9.5 | 10 |
| 12 | Makitani *et al.* (1993) | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 305.6 | 0.0494 | 0 | 0.75 | 0 | 6.2 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 305.6 | 0.0494 | 0.01 | 0.75 | 2.7 | 6.2 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 305.6 | 0.0494 | 0.1 | 0.75 | 4.8 | 6.2 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 305.6 | 0.0494 | 0.2 | 0.75 | 5.3 | 6.2 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 305.6 | 0.0494 | 0.5 | 0.75 | 6.1 | 6.2 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 305.6 | 0.0494 | 0.75 | 0.75 | 6.2 | 6.2 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 305.6 | 0.0494 | 1 | 0.75 | 6 | 6.2 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 305.6 | 0.0494 | 1.25 | 0.75 | 6 | 6.2 |
| | | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.14 | 305.6 | 0.0494 | 1.5 | 0.75 | 6 | 6.2 |
| 13 | Makitani *et al.* (1993) | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 406.4 | 0.0309 | 0 | 0.5 | 0 | 5.8 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f'_c$ (MPa) | $\sqrt{f'_c}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 406.4 | 0.0309 | 0.01 | 0.5 | 1 | 5.8 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 406.4 | 0.0309 | 0.1 | 0.5 | 3.3 | 5.8 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 406.4 | 0.0309 | 0.2 | 0.5 | 3.6 | 5.8 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 406.4 | 0.0309 | 0.5 | 0.5 | 5.8 | 5.8 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 406.4 | 0.0309 | 0.75 | 0.5 | 5.5 | 5.8 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 406.4 | 0.0309 | 1 | 0.5 | 5.2 | 5.8 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 406.4 | 0.0309 | 1.25 | 0.5 | 5 | 5.8 |
| | | GFRP | HB | SW | Confined | 25.4 | 31 | 5.568 | 1.97 | 406.4 | 0.0309 | 1.5 | 0.5 | 4.9 | 5.8 |
| 14 | Makitani *et al.* (1993) | CFRP | HB | HL | Confined | 10 | 26 | 5.099 | 5.00 | 100 | 0.1570 | 0 | 5.8 | 0 | 14 |
| | | CFRP | HB | HL | Confined | 10 | 26 | 5.099 | 5.00 | 100 | 0.1570 | 0.5 | 5.8 | 7.8 | 14 |
| | | CFRP | HB | HL | Confined | 10 | 26 | 5.099 | 5.00 | 100 | 0.1570 | 1 | 5.8 | 9 | 14 |
| | | CFRP | HB | HL | Confined | 10 | 26 | 5.099 | 5.00 | 100 | 0.1570 | 2 | 5.8 | 10.6 | 14 |
| | | CFRP | HB | HL | Confined | 10 | 26 | 5.099 | 5.00 | 100 | 0.1570 | 3 | 5.8 | 12 | 14 |
| | | CFRP | HB | HL | Confined | 10 | 26 | 5.099 | 5.00 | 100 | 0.1570 | 4 | 5.8 | 13 | 14 |
| | | CFRP | HB | HL | Confined | 10 | 26 | 5.099 | 5.00 | 100 | 0.1570 | 5 | 5.8 | 13.6 | 14 |
| | | CFRP | HB | HL | Confined | 10 | 26 | 5.099 | 5.00 | 100 | 0.1570 | 5.8 | 5.8 | 14 | 14 |
| | | CFRP | HB | HL | Confined | 10 | 26 | 5.099 | 5.00 | 100 | 0.1570 | 6 | 5.8 | 13.6 | 14 |
| | | CFRP | HB | HL | Confined | 10 | 26 | 5.099 | 5.00 | 100 | 0.1570 | 7 | 5.8 | 12.6 | 14 |
| | | CFRP | HB | HL | Confined | 10 | 26 | 5.099 | 5.00 | 100 | 0.1570 | 8 | 5.8 | 10.3 | 14 |
| | | CFRP | HB | HL | Confined | 10 | 26 | 5.099 | 5.00 | 100 | 0.1570 | 9 | 5.8 | 7.6 | 14 |
| | | CFRP | HB | HL | Confined | 10 | 26 | 5.099 | 5.00 | 100 | 0.1570 | 10 | 5.8 | 6 | 14 |
| 15 | Makitani *et al.* (1993) | GFRP | HB | HL | Confined | 10 | 30.9 | 5.559 | 5.00 | 100 | 0.1570 | 0 | 10 | 0 | 15.6 |
| | | GFRP | HB | HL | Confined | 10 | 30.9 | 5.559 | 5.00 | 100 | 0.1570 | 0.5 | 10 | 10.2 | 15.6 |
| | | GFRP | HB | HL | Confined | 10 | 30.9 | 5.559 | 5.00 | 100 | 0.1570 | 1 | 10 | 10.8 | 15.6 |
| | | GFRP | HB | HL | Confined | 10 | 30.9 | 5.559 | 5.00 | 100 | 0.1570 | 2 | 10 | 11.4 | 15.6 |
| | | GFRP | HB | HL | Confined | 10 | 30.9 | 5.559 | 5.00 | 100 | 0.1570 | 3 | 10 | 12 | 15.6 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GFRP | HB | HL | Confined | 10 | 30.9 | 5.559 | 5.00 | 100 | 0.1570 | 4 | 10 | 12.8 | 15.6 |
| | | GFRP | HB | HL | Confined | 10 | 30.9 | 5.559 | 5.00 | 100 | 0.1570 | 5 | 10 | 13.4 | 15.6 |
| | | GFRP | HB | HL | Confined | 10 | 30.9 | 5.559 | 5.00 | 100 | 0.1570 | 6 | 10 | 14 | 15.6 |
| | | GFRP | HB | HL | Confined | 10 | 30.9 | 5.559 | 5.00 | 100 | 0.1570 | 7 | 10 | 14.8 | 15.6 |
| | | GFRP | HB | HL | Confined | 10 | 30.9 | 5.559 | 5.00 | 100 | 0.1570 | 8 | 10 | 15 | 15.6 |
| | | GFRP | HB | HL | Confined | 10 | 30.9 | 5.559 | 5.00 | 100 | 0.1570 | 9 | 10 | 15.2 | 15.6 |
| | | GFRP | HB | HL | Confined | 10 | 30.9 | 5.559 | 5.00 | 100 | 0.1570 | 10 | 10 | 15.6 | 15.6 |
| 16 | Makitani *et al.* (1993) | AFRP | HB | HL | Confined | 10 | 28.9 | 5.376 | 5.00 | 100 | 0.1570 | 0 | 4.5 | 0 | 16.6 |
| | | AFRP | HB | HL | Confined | 10 | 28.9 | 5.376 | 5.00 | 100 | 0.1570 | 0.5 | 4.5 | 8 | 16.6 |
| | | AFRP | HB | HL | Confined | 10 | 28.9 | 5.376 | 5.00 | 100 | 0.1570 | 1 | 4.5 | 9.6 | 16.6 |
| | | AFRP | HB | HL | Confined | 10 | 28.9 | 5.376 | 5.00 | 100 | 0.1570 | 2 | 4.5 | 11 | 16.6 |
| | | AFRP | HB | HL | Confined | 10 | 28.9 | 5.376 | 5.00 | 100 | 0.1570 | 3 | 4.5 | 14.2 | 16.6 |
| | | AFRP | HB | HL | Confined | 10 | 28.9 | 5.376 | 5.00 | 100 | 0.1570 | 4 | 4.5 | 15.6 | 16.6 |
| | | AFRP | HB | HL | Confined | 10 | 28.9 | 5.376 | 5.00 | 100 | 0.1570 | 4.5 | 4.5 | 16.6 | 16.6 |
| | | AFRP | HB | HL | Confined | 10 | 28.9 | 5.376 | 5.00 | 100 | 0.1570 | 5 | 4.5 | 16 | 16.6 |
| | | AFRP | HB | HL | Confined | 10 | 28.9 | 5.376 | 5.00 | 100 | 0.1570 | 6 | 4.5 | 15.6 | 16.6 |
| | | AFRP | HB | HL | Confined | 10 | 28.9 | 5.376 | 5.00 | 100 | 0.1570 | 7 | 4.5 | 15.2 | 16.6 |
| | | AFRP | HB | HL | Confined | 10 | 28.9 | 5.376 | 5.00 | 100 | 0.1570 | 8 | 4.5 | 15 | 16.6 |
| | | AFRP | HB | HL | Confined | 10 | 28.9 | 5.376 | 5.00 | 100 | 0.1570 | 9 | 4.5 | 14.8 | 16.6 |
| | | AFRP | HB | HL | Confined | 10 | 28.9 | 5.376 | 5.00 | 100 | 0.1570 | 10 | 4.5 | 14.6 | 16.6 |
| 17 | Kanakubo *et al.* (1993) | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0000 | 0 | 0.75 | 0 | 3.4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0000 | 0.25 | 0.75 | 1.5 | 3.4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0000 | 0.5 | 0.75 | 2.5 | 3.4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0000 | 0.75 | 0.75 | 3.4 | 3.4 |
| 18 | Kanakubo *et al.* (1993) | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0084 | 0 | 1.5 | 0 | 4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0084 | 0.25 | 1.5 | 2 | 4 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0084 | 0.5 | 1.5 | 2.5 | 4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0084 | 1 | 1.5 | 3.7 | 4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0084 | 1.5 | 1.5 | 4 | 4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0084 | 2 | 1.5 | 3.6 | 4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0084 | 3 | 1.5 | 2.4 | 4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0084 | 4 | 1.5 | 1.7 | 4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0084 | 5 | 1.5 | 1.5 | 4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0084 | 6 | 1.5 | 1.3 | 4 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0084 | 7 | 1.5 | 1.2 | 4 |
| 19 | Kanakubo *et al.* (1993) | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 0 | 1.25 | 0 | 4.3 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 0.25 | 1.25 | 2 | 4.3 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 0.5 | 1.25 | 2.5 | 4.3 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 1 | 1.25 | 4.2 | 4.3 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 1.25 | 1.25 | 4.3 | 4.3 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 2 | 1.25 | 3.6 | 4.3 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 3 | 1.25 | 2.7 | 4.3 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 4 | 1.25 | 2.5 | 4.3 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 5 | 1.25 | 2.3 | 4.3 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 6 | 1.25 | 2.2 | 4.3 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 7 | 1.25 | 2.1 | 4.3 |
| 20 | Kanakubo *et al.* (1993) | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0249 | 0 | 1.5 | 0 | 4.5 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0249 | 0.25 | 1.5 | 1.7 | 4.5 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0249 | 0.5 | 1.5 | 2.3 | 4.5 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0249 | 1 | 1.5 | 3.9 | 4.5 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0249 | 1.5 | 1.5 | 4.5 | 4.5 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0249 | 2 | 1.5 | 4 | 4.5 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0249 | 3 | 1.5 | 2.7 | 4.5 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0249 | 4 | 1.5 | 2.5 | 4.5 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0249 | 5 | 1.5 | 2.3 | 4.5 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0249 | 6 | 1.5 | 2.2 | 4.5 |
| | | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0249 | 7 | 1.5 | 2.1 | 4.5 |
| 21 | Kanakubo *et al.* (1993) | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0000 | 0 | 1.5 | 0 | 3.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0000 | 0.25 | 1.5 | 1.5 | 3.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0000 | 0.5 | 1.5 | 2 | 3.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0000 | 1 | 1.5 | 2.6 | 3.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0000 | 1.5 | 1.5 | 3.7 | 3.7 |
| 22 | Kanakubo *et al.* (1993) | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 0 | 3.2 | 0 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 0.25 | 3.2 | 1.5 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 0.5 | 3.2 | 2 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 1 | 3.2 | 2.7 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 2 | 3.2 | 3.8 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 3 | 3.2 | 4.2 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 3.2 | 3.2 | 4.7 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 4 | 3.2 | 3.5 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 5 | 3.2 | 3 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 6 | 3.2 | 2.5 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 7 | 3.2 | 2.3 | 4.7 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0168 | 8 | 3.2 | 2.1 | 4.7 |
| 23 | Kanakubo *et al.* (1993) | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0147 | 0 | 4 | 0 | 5.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0147 | 0.25 | 4 | 1 | 5.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0147 | 0.5 | 4 | 1.5 | 5.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0147 | 1 | 4 | 2.2 | 5.5 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f'_c$ (MPa) | $\sqrt{f'_c}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0147 | 2 | 4 | 3.5 | 5.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0147 | 3 | 4 | 4.6 | 5.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0147 | 4 | 4 | 5.5 | 5.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0147 | 5 | 4 | 4.3 | 5.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0147 | 6 | 4 | 3 | 5.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0147 | 7 | 4 | 2.9 | 5.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0147 | 8 | 4 | 2.7 | 5.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0147 | 9 | 4 | 2.5 | 5.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.29 | 300 | 0.0147 | 10 | 4 | 2.3 | 5.5 |
| 24 | Kanakubo *et al.* (1993) | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0000 | 0 | 0.75 | 0 | 2.8 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0000 | 0.5 | 0.75 | 2 | 2.8 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0000 | 0.75 | 0.75 | 2.8 | 2.8 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0000 | 1 | 0.75 | 2.6 | 2.8 |
| 25 | Kanakubo *et al.* (1993) | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0084 | 0 | 1 | 0 | 4.1 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0084 | 0.5 | 1 | 3 | 4.1 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0084 | 1 | 1 | 4.1 | 4.1 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0084 | 2 | 1 | 3 | 4.1 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0084 | 3 | 1 | 2.2 | 4.1 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0084 | 4 | 1 | 2 | 4.1 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0084 | 5 | 1 | 1.8 | 4.1 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0084 | 6 | 1 | 1.7 | 4.1 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0084 | 7 | 1 | 1.6 | 4.1 |
| 26 | Kanakubo *et al.* (1993) | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0168 | 0 | 1.2 | 0 | 4.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0168 | 0.5 | 1.2 | 3.2 | 4.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0168 | 1 | 1.2 | 4.2 | 4.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0168 | 1.2 | 1.2 | 4.5 | 4.5 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0168 | 2 | 1.2 | 4.2 | 4.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0168 | 3 | 1.2 | 4 | 4.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0168 | 4 | 1.2 | 3.8 | 4.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0168 | 5 | 1.2 | 3.5 | 4.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0168 | 6 | 1.2 | 3.3 | 4.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0168 | 7 | 1.2 | 3.1 | 4.5 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0168 | 8 | 1.2 | 2.8 | 4.5 |
| 27 | Kanakubo *et al.* (1993) | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0147 | 0 | 1.2 | 0 | 4.6 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0147 | 0.5 | 1.2 | 3.3 | 4.6 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0147 | 1 | 1.2 | 4.4 | 4.6 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0147 | 1.2 | 1.2 | 4.6 | 4.6 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0147 | 2 | 1.2 | 4.2 | 4.6 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0147 | 3 | 1.2 | 4.1 | 4.6 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0147 | 4 | 1.2 | 3.8 | 4.6 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0147 | 5 | 1.2 | 3.7 | 4.6 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0147 | 6 | 1.2 | 3.5 | 4.6 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0147 | 7 | 1.2 | 3.3 | 4.6 |
| | | AFRP | IHB | HL | Unconfined | 12 | 34.5 | 5.874 | 2.29 | 300 | 0.0147 | 8 | 1.2 | 3 | 4.6 |
| 28 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 1.92 | 300 | 0.0000 | 0 | 0.75 | 0 | 3.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 1.92 | 300 | 0.0000 | 0.25 | 0.75 | 2.3 | 3.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 1.92 | 300 | 0.0000 | 0.5 | 0.75 | 3.2 | 3.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 1.92 | 300 | 0.0000 | 0.75 | 0.75 | 3.5 | 3.5 |
| 29 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 0 | 1.25 | 0 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 0.25 | 1.25 | 2.3 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 0.5 | 1.25 | 3.2 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 1 | 1.25 | 4.2 | 4.3 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 1.25 | 1.25 | 4.3 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 2 | 1.25 | 3.6 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 3 | 1.25 | 2.6 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 4 | 1.25 | 2.1 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 5 | 1.25 | 1.9 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 6 | 1.25 | 1.7 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 7 | 1.25 | 1.5 | 4.3 |
| 30 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 0 | 1.25 | 0 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 0.25 | 1.25 | 2.3 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 0.5 | 1.25 | 3.2 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 1 | 1.25 | 4.2 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 1.25 | 1.25 | 4.3 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 2 | 1.25 | 3.5 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 3 | 1.25 | 3.1 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 4 | 1.25 | 3 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 5 | 1.25 | 2.8 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 6 | 1.25 | 2.6 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 7 | 1.25 | 2.4 | 4.3 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 8 | 1.25 | 2 | 4.3 |
| 31 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0230 | 0 | 1.1 | 0 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0230 | 0.25 | 1.1 | 2.3 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0230 | 0.5 | 1.1 | 3.2 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0230 | 1 | 1.1 | 4.4 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0230 | 1.1 | 1.1 | 4.5 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0230 | 2 | 1.1 | 3.8 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0230 | 3 | 1.1 | 3.2 | 4.5 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0230 | 4 | 1.1 | 3 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0230 | 5 | 1.1 | 2.8 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0230 | 6 | 1.1 | 2.5 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0230 | 7 | 1.1 | 2.3 | 4.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0230 | 8 | 1.1 | 2.1 | 4.5 |
| 32 | Kanakubo *et al.* (1993) | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0000 | 0 | 0.75 | 0 | 2.4 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0000 | 0.25 | 0.75 | 1.5 | 2.4 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0000 | 0.5 | 0.75 | 2 | 2.4 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0000 | 0.75 | 0.75 | 2.4 | 2.4 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0000 | 1 | 0.75 | 2.3 | 2.4 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0000 | 2 | 0.75 | 2.2 | 2.4 |
| 33 | Kanakubo *et al.* (1993) | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 0 | 1.5 | 0 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 0.25 | 1.5 | 1.5 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 0.5 | 1.5 | 2 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 1 | 1.5 | 2.6 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 1.5 | 1.5 | 3.5 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 2 | 1.5 | 3.5 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 3 | 1.5 | 2.7 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 4 | 1.5 | 2 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 5 | 1.5 | 1.4 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 6 | 1.5 | 1 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 7 | 1.5 | 0.8 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0078 | 8 | 1.5 | 0.7 | 3.5 |
| 34 | Kanakubo *et al.* (1993) | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 0 | 2 | 0 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 0.25 | 2 | 1.5 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 0.5 | 2 | 2 | 3.5 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 1 | 2 | 2.6 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 2 | 2 | 3.5 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 3 | 2 | 2.5 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 4 | 2 | 2 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 5 | 2 | 1.7 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 6 | 2 | 1.6 | 3.5 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0155 | 7 | 2 | 1.5 | 3.5 |
| 35 | Kanakubo *et al.* (1993) | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0130 | 0 | 2.75 | 0 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0130 | 0.25 | 2.75 | 1.5 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0130 | 0.5 | 2.75 | 2 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0130 | 1 | 2.75 | 2.6 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0130 | 2 | 2.75 | 3.4 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0130 | 2.75 | 2.75 | 3.8 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0130 | 3 | 2.75 | 3.7 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0130 | 4 | 2.75 | 3.1 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0130 | 5 | 2.75 | 2.4 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0130 | 6 | 2.75 | 1.8 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0130 | 7 | 2.75 | 1.3 | 3.8 |
| | | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.12 | 300 | 0.0130 | 8 | 2.75 | 1.2 | 3.8 |
| 36 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0000 | 0 | 1.5 | 0 | 2.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0000 | 0.5 | 1.5 | 1.5 | 2.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0000 | 1 | 1.5 | 2 | 2.5 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0000 | 1.5 | 1.5 | 2.5 | 2.5 |
| 37 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0078 | 0 | 1.2 | 0 | 3.7 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0078 | 0.5 | 1.2 | 2.6 | 3.7 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0078 | 1 | 1.2 | 3.5 | 3.7 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0078 | 1.2 | 1.2 | 3.7 | 3.7 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0078 | 2 | 1.2 | 3 | 3.7 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0078 | 3 | 1.2 | 2.4 | 3.7 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0078 | 4 | 1.2 | 2 | 3.7 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0078 | 5 | 1.2 | 1.8 | 3.7 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0078 | 6 | 1.2 | 1.7 | 3.7 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0078 | 7 | 1.2 | 1.6 | 3.7 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0078 | 8 | 1.2 | 1.5 | 3.7 |
| 38 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0155 | 0 | 1.7 | 0 | 3.9 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0155 | 0.5 | 1.7 | 2.2 | 3.9 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0155 | 1 | 1.7 | 3.2 | 3.9 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0155 | 1.7 | 1.7 | 3.9 | 3.9 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0155 | 2 | 1.7 | 3.8 | 3.9 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0155 | 3 | 1.7 | 3.1 | 3.9 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0155 | 4 | 1.7 | 3.1 | 3.9 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0155 | 5 | 1.7 | 3 | 3.9 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0155 | 6 | 1.7 | 2.5 | 3.9 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0155 | 7 | 1.7 | 2.4 | 3.9 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0155 | 8 | 1.7 | 2.2 | 3.9 |
| 39 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0135 | 0 | 1.7 | 0 | 4 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0135 | 0.5 | 1.7 | 1.8 | 4 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0135 | 1 | 1.7 | 3 | 4 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0135 | 1.7 | 1.7 | 4 | 4 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0135 | 2 | 1.7 | 3.6 | 4 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0135 | 3 | 1.7 | 3.4 | 4 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0135 | 4 | 1.7 | 3.2 | 4 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0135 | 5 | 1.7 | 3.1 | 4 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0135 | 6 | 1.7 | 2.9 | 4 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0135 | 7 | 1.7 | 2.8 | 4 |
| | | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.12 | 300 | 0.0135 | 8 | 1.7 | 2.7 | 4 |
| 40 | Larralde *et al.* (1994) | GFRP | IHB | SW | Unconfined | 12.7 | 29 | 5.385 | 2.99 | 127 | 0.0000 | 0 | 0.012 | 0 | 3.77 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 29 | 5.385 | 2.99 | 127 | 0.0000 | 0.002 | 0.012 | 1.49 | 3.77 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 29 | 5.385 | 2.99 | 127 | 0.0000 | 0.004 | 0.012 | 1.71 | 3.77 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 29 | 5.385 | 2.99 | 127 | 0.0000 | 0.006 | 0.012 | 2.28 | 3.77 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 29 | 5.385 | 2.99 | 127 | 0.0000 | 0.008 | 0.012 | 2.63 | 3.77 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 29 | 5.385 | 2.99 | 127 | 0.0000 | 0.01 | 0.012 | 3.29 | 3.77 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 29 | 5.385 | 2.99 | 127 | 0.0000 | 0.012 | 0.012 | 3.77 | 3.77 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 29 | 5.385 | 2.99 | 127 | 0.0000 | 0.014 | 0.012 | 3.51 | 3.77 |
| 41 | Larralde *et al.* (1994) | GFRP | IHB | SW | Unconfined | 12.7 | 34 | 5.831 | 2.99 | 178 | 0.0000 | 0 | 0.02 | 0 | 4.35 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 34 | 5.831 | 2.99 | 178 | 0.0000 | 0.002 | 0.02 | 1 | 4.35 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 34 | 5.831 | 2.99 | 178 | 0.0000 | 0.004 | 0.02 | 1.25 | 4.35 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 34 | 5.831 | 2.99 | 178 | 0.0000 | 0.006 | 0.02 | 1.62 | 4.35 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 34 | 5.831 | 2.99 | 178 | 0.0000 | 0.008 | 0.02 | 1.87 | 4.35 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 34 | 5.831 | 2.99 | 178 | 0.0000 | 0.01 | 0.02 | 2.36 | 4.35 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 34 | 5.831 | 2.99 | 178 | 0.0000 | 0.012 | 0.02 | 2.75 | 4.35 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 34 | 5.831 | 2.99 | 178 | 0.0000 | 0.014 | 0.02 | 3.06 | 4.35 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 34 | 5.831 | 2.99 | 178 | 0.0000 | 0.016 | 0.02 | 3.44 | 4.35 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 34 | 5.831 | 2.99 | 178 | 0.0000 | 0.018 | 0.02 | 3.88 | 4.35 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 34 | 5.831 | 2.99 | 178 | 0.0000 | 0.02 | 0.02 | 4.35 | 4.35 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 34 | 5.831 | 2.99 | 178 | 0.0000 | 0.022 | 0.02 | 4 | 4.35 |
| 42 | Larralde *et al.* (1994) | GFRP | IHB | SW | Unconfined | 12.7 | 37 | 6.083 | 2.99 | 279 | 0.0000 | 0 | 0.007 | 0 | 2.48 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 37 | 6.083 | 2.99 | 279 | 0.0000 | 0.002 | 0.007 | 1.4 | 2.48 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GFRP | IHB | SW | Unconfined | 12.7 | 37 | 6.083 | 2.99 | 279 | 0.0000 | 0.004 | 0.007 | 1.92 | 2.48 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 37 | 6.083 | 2.99 | 279 | 0.0000 | 0.006 | 0.007 | 2 | 2.48 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 37 | 6.083 | 2.99 | 279 | 0.0000 | 0.007 | 0.007 | 2.48 | 2.48 |
| | | GFRP | IHB | SW | Unconfined | 12.7 | 37 | 6.083 | 2.99 | 279 | 0.0000 | 0.008 | 0.007 | 1.88 | 2.48 |
| 43 | Benmokrane *et al.* (1996) | GFRP | HB | HL | Unconfined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0606 | 0 | 4 | 0 | 7.7 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0606 | 0.01 | 4 | 1.7 | 7.7 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0606 | 0.1 | 4 | 5.6 | 7.7 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0606 | 0.2 | 4 | 5.7 | 7.7 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0606 | 1 | 4 | 6.3 | 7.7 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0606 | 2 | 4 | 7.1 | 7.7 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0606 | 3 | 4 | 7.5 | 7.7 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0606 | 4 | 4 | 7.7 | 7.7 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0606 | 5 | 4 | 7.7 | 7.7 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0606 | 6 | 4 | 7.7 | 7.7 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 31 | 5.568 | 3.94 | 127 | 0.0606 | 7 | 4 | 7 | 7.7 |
| 44 | Benmokrane *et al.* (1996) | GFRP | HB | HL | Unconfined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0303 | 0 | 1.5 | 0 | 7 |
| | | GFRP | HB | HL | Unconfined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0303 | 0.01 | 1.5 | 0.5 | 7 |
| | | GFRP | HB | HL | Unconfined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0303 | 0.1 | 1.5 | 3.6 | 7 |
| | | GFRP | HB | HL | Unconfined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0303 | 0.2 | 1.5 | 6.2 | 7 |
| | | GFRP | HB | HL | Unconfined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0303 | 1 | 1.5 | 6.9 | 7 |
| | | GFRP | HB | HL | Unconfined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0303 | 1.5 | 1.5 | 7 | 7 |
| | | GFRP | HB | HL | Unconfined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0303 | 2 | 1.5 | 7 | 7 |
| | | GFRP | HB | HL | Unconfined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0303 | 3 | 1.5 | 6.9 | 7 |
| | | GFRP | HB | HL | Unconfined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0303 | 4 | 1.5 | 6.7 | 7 |
| | | GFRP | HB | HL | Unconfined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0303 | 5 | 1.5 | 6.4 | 7 |
| | | GFRP | HB | HL | Unconfined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0303 | 6 | 1.5 | 6 | 7 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GFRP | HB | HL | Unconfined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0303 | 7 | 1.5 | 5.9 | 7 |
| | | GFRP | HB | HL | Unconfined | 25.4 | 31 | 5.568 | 1.97 | 254 | 0.0303 | 8 | 1.5 | 5.7 | 7 |
| 45 | Ehsani *et al.* (1996) | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 2.00 | 203 | 0.0000 | 0 | 1.27 | 0 | 9.6 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 2.00 | 203 | 0.0000 | 0.025 | 1.27 | 6.8 | 9.6 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 2.00 | 203 | 0.0000 | 0.06 | 1.27 | 8.4 | 9.6 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 2.00 | 203 | 0.0000 | 0.38 | 1.27 | 8.8 | 9.6 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 2.00 | 203 | 0.0000 | 0.76 | 1.27 | 9.3 | 9.6 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 2.00 | 203 | 0.0000 | 1.02 | 1.27 | 9.5 | 9.6 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 2.00 | 203 | 0.0000 | 1.27 | 1.27 | 9.6 | 9.6 |
| 46 | Ehsani *et al.* (1996) | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 2.00 | 559 | 0.0000 | 0 | 1.02 | 0 | 3.87 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 2.00 | 559 | 0.0000 | 0.025 | 1.02 | 2.67 | 3.87 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 2.00 | 559 | 0.0000 | 0.06 | 1.02 | 3.38 | 3.87 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 2.00 | 559 | 0.0000 | 0.38 | 1.02 | 3.7 | 3.87 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 2.00 | 559 | 0.0000 | 0.76 | 1.02 | 3.83 | 3.87 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 2.00 | 559 | 0.0000 | 1.02 | 1.02 | 3.87 | 3.87 |
| 47 | Ehsani *et al.* (1996) | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 4.00 | 661 | 0.0000 | 0 | 1.27 | 0 | 3.58 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 4.00 | 661 | 0.0000 | 0.025 | 1.27 | 2.25 | 3.58 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 4.00 | 661 | 0.0000 | 0.06 | 1.27 | 3 | 3.58 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 4.00 | 661 | 0.0000 | 0.38 | 1.27 | 3.23 | 3.58 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 4.00 | 661 | 0.0000 | 0.76 | 1.27 | 3.53 | 3.58 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 4.00 | 661 | 0.0000 | 1.02 | 1.27 | 3.56 | 3.58 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 4.00 | 661 | 0.0000 | 1.27 | 1.27 | 3.58 | 3.58 |
| 48 | Ehsani *et al.* (1996) | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 6.00 | 762 | 0.0000 | 0 | 1.02 | 0 | 3.28 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 6.00 | 762 | 0.0000 | 0.025 | 1.02 | 1.95 | 3.28 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 6.00 | 762 | 0.0000 | 0.06 | 1.02 | 2.6 | 3.28 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 6.00 | 762 | 0.0000 | 0.38 | 1.02 | 3.02 | 3.28 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 6.00 | 762 | 0.0000 | 0.76 | 1.02 | 3.25 | 3.28 |
| | | GFRP | HB | HL | Unconfined | 28.575 | 28 | 5.292 | 6.00 | 762 | 0.0000 | 1.02 | 1.02 | 3.28 | 3.28 |
| 49 | Cosenza *et al.* (1999) | GFRP | HB | HL | Unconfined | 12.7 | 37 | 6.083 | 5.91 | 63.5 | 0.0000 | 0 | 0.5 | 0 | 11.3 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 37 | 6.083 | 5.91 | 63.5 | 0.0000 | 0.05 | 0.5 | 1.7 | 11.3 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 37 | 6.083 | 5.91 | 63.5 | 0.0000 | 0.1 | 0.5 | 3 | 11.3 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 37 | 6.083 | 5.91 | 63.5 | 0.0000 | 0.25 | 0.5 | 8.2 | 11.3 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 37 | 6.083 | 5.91 | 63.5 | 0.0000 | 0.5 | 0.5 | 11.3 | 11.3 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 37 | 6.083 | 5.91 | 63.5 | 0.0000 | 0.75 | 0.5 | 10.9 | 11.3 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 37 | 6.083 | 5.91 | 63.5 | 0.0000 | 1 | 0.5 | 9.4 | 11.3 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 37 | 6.083 | 5.91 | 63.5 | 0.0000 | 1.5 | 0.5 | 8.5 | 11.3 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 37 | 6.083 | 5.91 | 63.5 | 0.0000 | 2 | 0.5 | 8 | 11.3 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 37 | 6.083 | 5.91 | 63.5 | 0.0000 | 2.5 | 0.5 | 7.6 | 11.3 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 37 | 6.083 | 5.91 | 63.5 | 0.0000 | 3 | 0.5 | 7.3 | 11.3 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 37 | 6.083 | 5.91 | 63.5 | 0.0000 | 3.5 | 0.5 | 7 | 11.3 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 37 | 6.083 | 5.91 | 63.5 | 0.0000 | 4 | 0.5 | 6.8 | 11.3 |
| 50 | Cosenza *et al.* (1999) | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 63.5 | 0.0000 | 0 | 0.25 | 0 | 16.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 63.5 | 0.0000 | 0.05 | 0.25 | 9 | 16.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 63.5 | 0.0000 | 0.1 | 0.25 | 13.6 | 16.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 63.5 | 0.0000 | 0.25 | 0.25 | 16.5 | 16.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 63.5 | 0.0000 | 0.5 | 0.25 | 15.5 | 16.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 63.5 | 0.0000 | 0.75 | 0.25 | 14.2 | 16.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 63.5 | 0.0000 | 1 | 0.25 | 13.2 | 16.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 63.5 | 0.0000 | 1.5 | 0.25 | 10.8 | 16.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 63.5 | 0.0000 | 2 | 0.25 | 8.5 | 16.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 63.5 | 0.0000 | 2.5 | 0.25 | 6 | 16.5 |
| 51 | Cosenza *et al.* (1999) | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 127 | 0.0000 | 0 | 0.22 | 0 | 14.5 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 127 | 0.0000 | 0.05 | 0.22 | 9 | 14.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 127 | 0.0000 | 0.1 | 0.22 | 13.2 | 14.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 127 | 0.0000 | 0.22 | 0.22 | 14.5 | 14.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 127 | 0.0000 | 0.25 | 0.22 | 14.2 | 14.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 127 | 0.0000 | 0.5 | 0.22 | 14.2 | 14.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 127 | 0.0000 | 0.75 | 0.22 | 14.1 | 14.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 127 | 0.0000 | 1 | 0.22 | 14 | 14.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 127 | 0.0000 | 1.5 | 0.22 | 13.8 | 14.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 127 | 0.0000 | 2 | 0.22 | 13.7 | 14.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 127 | 0.0000 | 2.5 | 0.22 | 13.7 | 14.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 127 | 0.0000 | 3 | 0.22 | 13.7 | 14.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 127 | 0.0000 | 3.5 | 0.22 | 13.7 | 14.5 |
| | | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.91 | 127 | 0.0000 | 4 | 0.22 | 13.7 | 14.5 |
| 52 | Defreese & Wollmann (2002) | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 0 | 0.32 | 0 | 15.7 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 0.025 | 0.32 | 7 | 15.7 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 0.05 | 0.32 | 8.75 | 15.75 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 0.15 | 0.32 | 10.5 | 15.75 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 0.32 | 0.32 | 15.75 | 15.75 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 0.64 | 0.32 | 10.5 | 15.75 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 1.27 | 0.32 | 9.8 | 15.75 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 2.54 | 0.32 | 9.45 | 15.75 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 5.06 | 0.32 | 9.63 | 15.75 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 7.62 | 0.32 | 10.85 | 15.75 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 10.16 | 0.32 | 11.55 | 15.75 |
| 53 | Defreese & Wollmann (2002) | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 0 | 0.32 | 0 | 10.71 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 0.16 | 0.32 | 8.78 | 10.71 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 0.32 | 0.32 | 10.71 | 10.71 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 0.64 | 0.32 | 10.7 | 10.71 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 1.27 | 0.32 | 10 | 10.71 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 1.91 | 0.32 | 9.66 | 10.71 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 2.54 | 0.32 | 9.48 | 10.71 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 5.06 | 0.32 | 10 | 10.71 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 7.62 | 0.32 | 10.88 | 10.71 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 63.5 | 0.0000 | 10.16 | 0.32 | 11.24 | 10.71 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 95.3 | 0.0000 | 12.7 | 0.32 | 8.78 | 10.71 |
| 54 | Defreese & Wollmann (2002) | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 95.3 | 0.0000 | 0 | 0.64 | 0 | 17.6 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 95.3 | 0.0000 | 0.32 | 0.64 | 17.2 | 17.6 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 95.3 | 0.0000 | 0.64 | 0.64 | 17.6 | 17.6 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 95.3 | 0.0000 | 1.27 | 0.64 | 17.2 | 17.6 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 95.3 | 0.0000 | 2.54 | 0.64 | 16.38 | 17.6 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 95.3 | 0.0000 | 5.08 | 0.64 | 15.8 | 17.6 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 95.3 | 0.0000 | 7.62 | 0.64 | 16.15 | 17.6 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 95.3 | 0.0000 | 10.16 | 0.64 | 16.38 | 17.6 |
| | | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.50 | 95.3 | 0.0000 | 12.7 | 0.64 | 9.36 | 17.6 |
| 55 | Defreese & Wollmann (2002) | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 79.5 | 0.0000 | 0 | 0.64 | 0 | 18.26 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 79.5 | 0.0000 | 0.32 | 0.64 | 17.36 | 18.26 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 79.5 | 0.0000 | 0.64 | 0.64 | 18.26 | 18.26 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 79.5 | 0.0000 | 1.27 | 0.64 | 17.3 | 18.26 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 79.5 | 0.0000 | 2.54 | 0.64 | 15.7 | 18.26 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 79.5 | 0.0000 | 5.08 | 0.64 | 11.65 | 18.26 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 79.5 | 0.0000 | 10.16 | 0.64 | 10.98 | 18.26 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 79.5 | 0.0000 | 15.24 | 0.64 | 10.08 | 18.26 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f'_c$ (MPa) | $\sqrt{f'_c}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 79.5 | 0.0000 | 20.32 | 0.64 | 9.52 | 18.26 |
| 56 | Defreese & Wollmann (2002) | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 79.5 | 0.0000 | 0 | 0.51 | 0 | 16.6 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 79.5 | 0.0000 | 0.25 | 0.51 | 15.7 | 16.6 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 79.5 | 0.0000 | 0.5 | 0.51 | 16.6 | 16.6 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 79.5 | 0.0000 | 0.51 | 0.51 | 16.6 | 16.6 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 79.5 | 0.0000 | 1.27 | 0.51 | 14.1 | 16.6 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 79.5 | 0.0000 | 2.54 | 0.51 | 13.2 | 16.6 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 79.5 | 0.0000 | 5.08 | 0.51 | 10.1 | 16.6 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 79.5 | 0.0000 | 7.62 | 0.51 | 10.1 | 16.6 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 79.5 | 0.0000 | 10.16 | 0.51 | 8.85 | 16.6 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 79.5 | 0.0000 | 12.7 | 0.51 | 7.84 | 16.6 |
| 57 | Defreese & Wollmann (2002) | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 119.3 | 0.0000 | 0 | 0.32 | 0 | 16.8 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 119.3 | 0.0000 | 0.13 | 0.32 | 14.9 | 16.8 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 119.3 | 0.0000 | 0.32 | 0.32 | 16.8 | 16.8 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 119.3 | 0.0000 | 0.64 | 0.32 | 16.39 | 16.8 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 119.3 | 0.0000 | 1.27 | 0.32 | 14.53 | 16.8 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 119.3 | 0.0000 | 2.54 | 0.32 | 12.14 | 16.8 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 119.3 | 0.0000 | 5.08 | 0.32 | 10.36 | 16.8 |
| | | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.39 | 119.3 | 0.0000 | 7.62 | 0.32 | 8.2 | 16.8 |
| 58 | Defreese & Wollmann (2002) | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 95.5 | 0.0000 | 0 | 0.32 | 0 | 15.04 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 95.5 | 0.0000 | 0.13 | 0.32 | 13.9 | 15.04 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 95.5 | 0.0000 | 0.32 | 0.32 | 15.04 | 15.04 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 95.5 | 0.0000 | 0.64 | 0.32 | 15 | 15.04 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 95.5 | 0.0000 | 1.27 | 0.32 | 14.42 | 15.04 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 95.5 | 0.0000 | 2.54 | 0.32 | 13.18 | 15.04 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 95.5 | 0.0000 | 5.08 | 0.32 | 10.7 | 15.04 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 95.5 | 0.0000 | 7.62 | 0.32 | 9.69 | 15.04 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 95.5 | 0.0000 | 10.16 | 0.32 | 9.6 | 15.04 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 95.5 | 0.0000 | 12.7 | 0.32 | 9.58 | 15.04 |
| 59 | Defreese & Wollmann (2002) | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 95.5 | 0.0000 | 0 | 0.32 | 0 | 13.8 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 95.5 | 0.0000 | 0.13 | 0.32 | 13.04 | 13.8 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 95.5 | 0.0000 | 0.32 | 0.32 | 13.8 | 13.8 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 95.5 | 0.0000 | 0.64 | 0.32 | 12.8 | 13.8 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 95.5 | 0.0000 | 1.27 | 0.32 | 11.2 | 13.8 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 95.5 | 0.0000 | 2.54 | 0.32 | 9.31 | 13.8 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 95.5 | 0.0000 | 5.08 | 0.32 | 8.2 | 13.8 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 95.5 | 0.0000 | 10.16 | 0.32 | 7.38 | 13.8 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 95.5 | 0.0000 | 15.24 | 0.32 | 7.08 | 13.8 |
| 60 | Defreese & Wollmann (2002) | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 143.3 | 0.0000 | 0 | 0.51 | 0 | 16 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 143.3 | 0.0000 | 0.32 | 0.51 | 15.74 | 16 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 143.3 | 0.0000 | 0.51 | 0.51 | 16 | 16 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 143.3 | 0.0000 | 0.64 | 0.51 | 16 | 16 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 143.3 | 0.0000 | 1.27 | 0.51 | 14.96 | 16 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 143.3 | 0.0000 | 2.54 | 0.51 | 13.52 | 16 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 143.3 | 0.0000 | 5.08 | 0.51 | 10.58 | 16 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 143.3 | 0.0000 | 7.62 | 0.51 | 7.48 | 16 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 143.3 | 0.0000 | 10.16 | 0.51 | 4.64 | 16 |
| 61 | Defreese & Wollmann (2002) | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 143.3 | 0.0000 | 0 | 0.64 | 0 | 14.2 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 143.3 | 0.0000 | 0.32 | 0.64 | 13.93 | 14.2 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 143.3 | 0.0000 | 0.64 | 0.64 | 14.2 | 14.2 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 143.3 | 0.0000 | 1.27 | 0.64 | 13.98 | 14.2 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 143.3 | 0.0000 | 2.54 | 0.64 | 12.9 | 14.2 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 143.3 | 0.0000 | 5.08 | 0.64 | 11.35 | 14.2 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 143.3 | 0.0000 | 7.62 | 0.64 | 10.73 | 14.2 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 143.3 | 0.0000 | 10.16 | 0.64 | 9.2 | 14.2 |
| | | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.66 | 143.3 | 0.0000 | 12.7 | 0.64 | 9 | 14.2 |
| 62 | Okelo (2007) | CFRP | HB | HL | Confined | 10 | 36.9 | 6.075 | 3.80 | 160 | 0.0785 | 0 | 0.74 | 0 | 13.4 |
| | | CFRP | HB | HL | Confined | 10 | 36.9 | 6.075 | 3.80 | 160 | 0.0785 | 0.5 | 0.74 | 11.5 | 13.4 |
| | | CFRP | HB | HL | Confined | 10 | 36.9 | 6.075 | 3.80 | 160 | 0.0785 | 0.74 | 0.74 | 13.4 | 13.4 |
| | | CFRP | HB | HL | Confined | 10 | 36.9 | 6.075 | 3.80 | 160 | 0.0785 | 1 | 0.74 | 13.3 | 13.4 |
| | | CFRP | HB | HL | Confined | 10 | 36.9 | 6.075 | 3.80 | 160 | 0.0785 | 1.4 | 0.74 | 13.2 | 13.4 |
| | | CFRP | HB | HL | Confined | 10 | 36.9 | 6.075 | 3.80 | 160 | 0.0785 | 1.5 | 0.74 | 12.8 | 13.4 |
| | | CFRP | HB | HL | Confined | 10 | 36.9 | 6.075 | 3.80 | 160 | 0.0785 | 2 | 0.74 | 12.2 | 13.4 |
| | | CFRP | HB | HL | Confined | 10 | 36.9 | 6.075 | 3.80 | 160 | 0.0785 | 3 | 0.74 | 12 | 13.4 |
| | | CFRP | HB | HL | Confined | 10 | 36.9 | 6.075 | 3.80 | 160 | 0.0785 | 4 | 0.74 | 12.5 | 13.4 |
| | | CFRP | HB | HL | Confined | 10 | 36.9 | 6.075 | 3.80 | 160 | 0.0785 | 5 | 0.74 | 12.8 | 13.4 |
| | | CFRP | HB | HL | Confined | 10 | 36.9 | 6.075 | 3.80 | 160 | 0.0785 | 6.25 | 0.74 | 12.4 | 13.4 |
| | | CFRP | HB | HL | Confined | 10 | 36.9 | 6.075 | 3.80 | 160 | 0.0785 | 7.5 | 0.74 | 11.8 | 13.4 |
| 63 | Okelo (2007) | CFRP | HB | HL | Confined | 16 | 36.9 | 6.075 | 2.38 | 160 | 0.0491 | 0 | 1.45 | 0 | 7.7 |
| | | CFRP | HB | HL | Confined | 16 | 36.9 | 6.075 | 2.38 | 160 | 0.0491 | 1 | 1.45 | 7.1 | 7.7 |
| | | CFRP | HB | HL | Confined | 16 | 36.9 | 6.075 | 2.38 | 160 | 0.0491 | 1.45 | 1.45 | 7.7 | 7.7 |
| | | CFRP | HB | HL | Confined | 16 | 36.9 | 6.075 | 2.38 | 160 | 0.0491 | 1.5 | 1.45 | 7.7 | 7.7 |
| | | CFRP | HB | HL | Confined | 16 | 36.9 | 6.075 | 2.38 | 160 | 0.0491 | 2 | 1.45 | 4.5 | 7.7 |
| | | CFRP | HB | HL | Confined | 16 | 36.9 | 6.075 | 2.38 | 160 | 0.0491 | 3 | 1.45 | 3.5 | 7.7 |
| | | CFRP | HB | HL | Confined | 16 | 36.9 | 6.075 | 2.38 | 160 | 0.0491 | 4 | 1.45 | 3 | 7.7 |
| | | CFRP | HB | HL | Confined | 16 | 36.9 | 6.075 | 2.38 | 160 | 0.0491 | 5 | 1.45 | 2.8 | 7.7 |
| | | CFRP | HB | HL | Confined | 16 | 36.9 | 6.075 | 2.38 | 160 | 0.0491 | 6.25 | 1.45 | 2.4 | 7.7 |
| | | CFRP | HB | HL | Confined | 16 | 36.9 | 6.075 | 2.38 | 160 | 0.0491 | 7.5 | 1.45 | 2.2 | 7.7 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CFRP | HB | HL | Confined | 16 | 36.9 | 6.075 | 2.38 | 160 | 0.0491 | 8.75 | 1.45 | 2 | 7.7 |
| | | CFRP | HB | HL | Confined | 16 | 36.9 | 6.075 | 2.38 | 160 | 0.0491 | 10 | 1.45 | 1.8 | 7.7 |
| | | CFRP | HB | HL | Confined | 16 | 36.9 | 6.075 | 2.38 | 160 | 0.0491 | 11.25 | 1.45 | 1.6 | 7.7 |
| 64 | Okelo (2007) | CFRP | HB | HL | Confined | 10 | 39.3 | 6.269 | 3.80 | 200 | 0.0785 | 0 | 0.86 | 0 | 11.8 |
| | | CFRP | HB | HL | Confined | 10 | 39.3 | 6.269 | 3.80 | 200 | 0.0785 | 0.5 | 0.86 | 10.6 | 11.8 |
| | | CFRP | HB | HL | Confined | 10 | 39.3 | 6.269 | 3.80 | 200 | 0.0785 | 0.86 | 0.86 | 11.8 | 11.8 |
| | | CFRP | HB | HL | Confined | 10 | 39.3 | 6.269 | 3.80 | 200 | 0.0785 | 1 | 0.86 | 11.8 | 11.8 |
| | | CFRP | HB | HL | Confined | 10 | 39.3 | 6.269 | 3.80 | 200 | 0.0785 | 2 | 0.86 | 10.7 | 11.8 |
| | | CFRP | HB | HL | Confined | 10 | 39.3 | 6.269 | 3.80 | 200 | 0.0785 | 3 | 0.86 | 10 | 11.8 |
| | | CFRP | HB | HL | Confined | 10 | 39.3 | 6.269 | 3.80 | 200 | 0.0785 | 3.5 | 0.86 | 7.5 | 11.8 |
| | | CFRP | HB | HL | Confined | 10 | 39.3 | 6.269 | 3.80 | 200 | 0.0785 | 4 | 0.86 | 7.4 | 11.8 |
| | | CFRP | HB | HL | Confined | 10 | 39.3 | 6.269 | 3.80 | 200 | 0.0785 | 5 | 0.86 | 7.3 | 11.8 |
| | | CFRP | HB | HL | Confined | 10 | 39.3 | 6.269 | 3.80 | 200 | 0.0785 | 7.5 | 0.86 | 6.8 | 11.8 |
| | | CFRP | HB | HL | Confined | 10 | 39.3 | 6.269 | 3.80 | 200 | 0.0785 | 10 | 0.86 | 6.2 | 11.8 |
| | | CFRP | HB | HL | Confined | 10 | 39.3 | 6.269 | 3.80 | 200 | 0.0785 | 12.5 | 0.86 | 5.7 | 11.8 |
| | | CFRP | HB | HL | Confined | 10 | 39.3 | 6.269 | 3.80 | 200 | 0.0785 | 15 | 0.86 | 5 | 11.8 |
| | | CFRP | HB | HL | Confined | 10 | 39.3 | 6.269 | 3.80 | 200 | 0.0785 | 17.5 | 0.86 | 4.8 | 11.8 |
| 65 | Okelo (2007) | CFRP | HB | HL | Confined | 16 | 39.3 | 6.269 | 2.38 | 320 | 0.0491 | 0 | 0.79 | 0 | 9.2 |
| | | CFRP | HB | HL | Confined | 16 | 39.3 | 6.269 | 2.38 | 320 | 0.0491 | 0.5 | 0.79 | 8.2 | 9.2 |
| | | CFRP | HB | HL | Confined | 16 | 39.3 | 6.269 | 2.38 | 320 | 0.0491 | 0.79 | 0.79 | 9.2 | 9.2 |
| | | CFRP | HB | HL | Confined | 16 | 39.3 | 6.269 | 2.38 | 320 | 0.0491 | 1 | 0.79 | 9.2 | 9.2 |
| | | CFRP | HB | HL | Confined | 16 | 39.3 | 6.269 | 2.38 | 320 | 0.0491 | 1.5 | 0.79 | 7.3 | 9.2 |
| | | CFRP | HB | HL | Confined | 16 | 39.3 | 6.269 | 2.38 | 320 | 0.0491 | 2 | 0.79 | 5.5 | 9.2 |
| | | CFRP | HB | HL | Confined | 16 | 39.3 | 6.269 | 2.38 | 320 | 0.0491 | 3 | 0.79 | 5.5 | 9.2 |
| | | CFRP | HB | HL | Confined | 16 | 39.3 | 6.269 | 2.38 | 320 | 0.0491 | 4 | 0.79 | 5.3 | 9.2 |
| | | CFRP | HB | HL | Confined | 16 | 39.3 | 6.269 | 2.38 | 320 | 0.0491 | 5 | 0.79 | 5.2 | 9.2 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CFRP | HB | HL | Confined | 16 | 39.3 | 6.269 | 2.38 | 320 | 0.0491 | 7.5 | 0.79 | 5.1 | 9.2 |
| | | CFRP | HB | HL | Confined | 16 | 39.3 | 6.269 | 2.38 | 320 | 0.0491 | 10 | 0.79 | 5 | 9.2 |
| | | CFRP | HB | HL | Confined | 16 | 39.3 | 6.269 | 2.38 | 320 | 0.0491 | 12.5 | 0.79 | 4.8 | 9.2 |
| | | CFRP | HB | HL | Confined | 16 | 39.3 | 6.269 | 2.38 | 320 | 0.0491 | 15 | 0.79 | 4.7 | 9.2 |
| | | CFRP | HB | HL | Confined | 16 | 39.3 | 6.269 | 2.38 | 320 | 0.0491 | 17.5 | 0.79 | 4.5 | 9.2 |
| | | CFRP | HB | HL | Confined | 16 | 41.5 | 6.442 | 2.38 | 320 | 0.0491 | 20 | 0.79 | 4.2 | 9.2 |
| 66 | Okelo (2007) | GFRP | HB | HL | Confined | 19 | 41.5 | 6.442 | 2.00 | 150 | 0.0413 | 0 | 3.35 | 0 | 6.9 |
| | | GFRP | HB | HL | Confined | 19 | 41.5 | 6.442 | 2.00 | 150 | 0.0413 | 2.5 | 3.35 | 6.9 | 6.9 |
| | | GFRP | HB | HL | Confined | 19 | 41.5 | 6.442 | 2.00 | 150 | 0.0413 | 3.35 | 3.35 | 6.9 | 6.9 |
| | | GFRP | HB | HL | Confined | 19 | 41.5 | 6.442 | 2.00 | 150 | 0.0413 | 4 | 3.35 | 6.9 | 6.9 |
| | | GFRP | HB | HL | Confined | 19 | 41.5 | 6.442 | 2.00 | 150 | 0.0413 | 5 | 3.35 | 6 | 6.9 |
| | | GFRP | HB | HL | Confined | 19 | 41.5 | 6.442 | 2.00 | 150 | 0.0413 | 6.25 | 3.35 | 5.5 | 6.9 |
| | | GFRP | HB | HL | Confined | 19 | 41.5 | 6.442 | 2.00 | 150 | 0.0413 | 7.5 | 3.35 | 4.5 | 6.9 |
| | | GFRP | HB | HL | Confined | 19 | 41.5 | 6.442 | 2.00 | 150 | 0.0413 | 10 | 3.35 | 2.7 | 6.9 |
| | | GFRP | HB | HL | Confined | 19 | 41.5 | 6.442 | 2.00 | 150 | 0.0413 | 12.5 | 3.35 | 1.7 | 6.9 |
| 67 | Okelo (2007) | CFRP | HB | HL | Confined | 10 | 41.5 | 6.442 | 3.80 | 150 | 0.0785 | 0 | 1.39 | 0 | 15.9 |
| | | CFRP | HB | HL | Confined | 10 | 41.5 | 6.442 | 3.80 | 150 | 0.0785 | 0.5 | 1.39 | 15.3 | 15.9 |
| | | CFRP | HB | HL | Confined | 10 | 41.5 | 6.442 | 3.80 | 150 | 0.0785 | 1 | 1.39 | 15.5 | 15.9 |
| | | CFRP | HB | HL | Confined | 10 | 41.5 | 6.442 | 3.80 | 150 | 0.0785 | 1.3 | 1.39 | 15.9 | 15.9 |
| | | CFRP | HB | HL | Confined | 10 | 41.5 | 6.442 | 3.80 | 150 | 0.0785 | 1.39 | 1.39 | 15.9 | 15.9 |
| | | CFRP | HB | HL | Confined | 10 | 41.5 | 6.442 | 3.80 | 150 | 0.0785 | 1.5 | 1.39 | 11 | 15.9 |
| | | CFRP | HB | HL | Confined | 10 | 41.5 | 6.442 | 3.80 | 150 | 0.0785 | 2 | 1.39 | 12 | 15.9 |
| | | CFRP | HB | HL | Confined | 10 | 41.5 | 6.442 | 3.80 | 150 | 0.0785 | 3 | 1.39 | 12.4 | 15.9 |
| | | CFRP | HB | HL | Confined | 10 | 41.5 | 6.442 | 3.80 | 150 | 0.0785 | 4 | 1.39 | 10.5 | 15.9 |
| | | CFRP | HB | HL | Confined | 10 | 41.5 | 6.442 | 3.80 | 150 | 0.0785 | 5 | 1.39 | 8 | 15.9 |
| | | CFRP | HB | HL | Confined | 10 | 41.5 | 6.442 | 3.80 | 150 | 0.0785 | 7.5 | 1.39 | 7 | 15.9 |

| Beam | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_i$ (mm) | $s_m$ (mm) | $\tau_i$ (MPa) | $\tau_m$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CFRP | HB | HL | Confined | 10 | 41.5 | 6.442 | 3.80 | 150 | 0.0785 | 10 | 1.39 | 6.5 | 15.9 |
| | | CFRP | HB | HL | Confined | 10 | 41.5 | 6.442 | 3.80 | 150 | 0.0785 | 12.5 | 1.39 | 6 | 15.9 |
| | | CFRP | HB | HL | Confined | 10 | 41.5 | 6.442 | 3.80 | 150 | 0.0785 | 15 | 1.39 | 5.4 | 15.9 |
| | | CFRP | HB | HL | Confined | 10 | 41.5 | 6.442 | 3.80 | 150 | 0.0785 | 17.5 | 1.39 | 5.2 | 15.9 |
| | | CFRP | HB | HL | Confined | 10 | 41.5 | 6.442 | 3.80 | 150 | 0.0785 | 20 | 1.39 | 5.4 | 15.9 |
| 68 | Okelo (2007) | CFRP | HB | HL | Confined | 16 | 41.5 | 6.442 | 2.38 | 240 | 0.0491 | 0 | 2.26 | 0 | 11.9 |
| | | CFRP | HB | HL | Confined | 16 | 41.5 | 6.442 | 2.38 | 240 | 0.0491 | 0.5 | 2.26 | 10.8 | 11.9 |
| | | CFRP | HB | HL | Confined | 16 | 41.5 | 6.442 | 2.38 | 240 | 0.0491 | 1 | 2.26 | 11.6 | 11.9 |
| | | CFRP | HB | HL | Confined | 16 | 41.5 | 6.442 | 2.38 | 240 | 0.0491 | 2 | 2.26 | 11.7 | 11.9 |
| | | CFRP | HB | HL | Confined | 16 | 41.5 | 6.442 | 2.38 | 240 | 0.0491 | 2.1 | 2.26 | 11.8 | 11.9 |
| | | CFRP | HB | HL | Confined | 16 | 41.5 | 6.442 | 2.38 | 240 | 0.0491 | 2.2 | 2.26 | 11.9 | 11.9 |
| | | CFRP | HB | HL | Confined | 16 | 41.5 | 6.442 | 2.38 | 240 | 0.0491 | 2.26 | 2.26 | 11.9 | 11.9 |
| | | CFRP | HB | HL | Confined | 16 | 41.5 | 6.442 | 2.38 | 240 | 0.0491 | 2.3 | 2.26 | 11.9 | 11.9 |
| | | CFRP | HB | HL | Confined | 16 | 41.5 | 6.442 | 2.38 | 240 | 0.0491 | 2.4 | 2.26 | 10 | 11.9 |
| | | CFRP | HB | HL | Confined | 16 | 41.5 | 6.442 | 2.38 | 240 | 0.0491 | 2.5 | 2.26 | 10 | 11.9 |
| | | CFRP | HB | HL | Confined | 16 | 41.5 | 6.442 | 2.38 | 240 | 0.0491 | 2.6 | 2.26 | 10 | 11.9 |

# Appendix C

**Table C.1 Database of beam-type specimens for deriving slip corresponding to peak bond stress of FRP rebars in concrete**

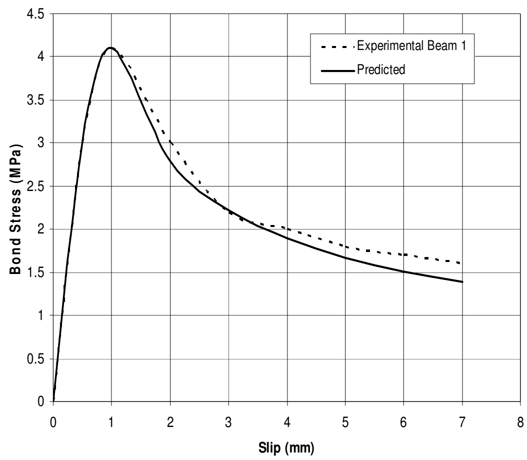
| SI | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f'_c$ (MPa) | $\sqrt{f'_c}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_m$ (mm) | $\frac{s_m}{l_{embed}}$ | Failure Type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Daniali (1990) | GFRP | HB | HL | Confined | 11.2 | 31 | 5.568 | 3.402 | 305 | 0.04 | 1.016 | 0.0033 | Pullout |
| 2 | Daniali (1990) | GFRP | HB | HL | Confined | 11.2 | 31 | 5.568 | 3.402 | 305 | 0.025 | 1.016 | 0.0033 | Pullout |
| 3 | Daniali (1990) | GFRP | HB | HL | Confined | 11.2 | 31 | 5.568 | 3.402 | 305 | 0.029 | 0.94 | 0.0031 | Pullout |
| 4 | Daniali (1990) | GFRP | HB | HL | Confined | 19.94 | 31 | 5.568 | 2.229 | 508 | 0.014 | 3.302 | 0.0065 | Pullout |
| 5 | Daniali (1990) | CFRP | HB | HL | Confined | 10 | 32.4 | 5.692 | 3.8 | 150 | 0.051 | 0.86 | 0.0057 | Pullout |
| 6 | Daniali (1990) | CFRP | HB | HL | Confined | 10 | 31.3 | 5.595 | 3.8 | 200 | 0.051 | 0.99 | 0.005 | Pullout |
| 7 | Daniali (1990) | CFRP | HB | HL | Confined | 10 | 36.9 | 6.075 | 3.8 | 100 | 0.051 | 0.74 | 0.0074 | Pullout |
| 8 | Daniali (1990) | CFRP | HB | HL | Confined | 16 | 36.9 | 6.075 | 2.375 | 160 | 0.032 | 1.45 | 0.0091 | Pullout |
| 9 | Daniali (1990) | CFRP | HB | HL | Confined | 10 | 41.4 | 6.434 | 3.8 | 150 | 0.051 | 1.39 | 0.0093 | Pullout |
| 10 | Daniali (1990) | CFRP | HB | HL | Confined | 10 | 39.3 | 6.269 | 3.8 | 200 | 0.051 | 0.86 | 0.0043 | Pullout |
| 11 | Daniali (1990) | GFRP | HB | HL | Confined | 19 | 33.3 | 5.771 | 2 | 190 | 0.027 | 2.13 | 0.0112 | Pullout |
| 12 | Daniali (1990) | CFRP | HB | HL | Confined | 16 | 41.5 | 6.442 | 2.375 | 240 | 0.032 | 2.26 | 0.0094 | Splitting |
| 13 | Makitani *et al.* (1993) | CFRP | HB | SC | Confined | 10 | 33.7 | 5.805 | 5 | 100 | 0.079 | 0.05 | 13.8 | Pullout |
| 14 | Makitani *et al.* (1993) | AFRP | HB | SC | Confined | 10 | 30.1 | 5.486 | 5 | 100 | 0.079 | 0.15 | 19 | Pullout |
| 15 | Makitani *et al.* (1993) | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.145 | 95.4 | 0.049 | 0.33 | 0.0035 | Pullout |
| 16 | Makitani *et al.* (1993) | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.937 | 127 | 0.062 | 0.3 | 0.0024 | Pullout |
| 17 | Makitani *et al.* (1993) | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.145 | 159 | 0.049 | 0.85 | 0.0053 | Pullout |
| 18 | Makitani *et al.* (1993) | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.937 | 203 | 0.062 | 0.25 | 0.0012 | Pullout |
| 19 | Makitani *et al.* (1993) | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.145 | 306 | 0.049 | 0.75 | 0.0025 | Pullout |
| 20 | Makitani *et al.* (1993) | GFRP | HB | HL | Confined | 25.4 | 31 | 5.568 | 1.969 | 254 | 0.03 | 1.5 | 0.0059 | Pullout |
| 21 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 10 | 28 | 5.292 | 1 | 38 | 0 | 0.47 | 0.0124 | Splitting |
| 22 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 10 | 28 | 5.292 | 2 | 38 | 0 | 0.63 | 0.0166 | Pullout |

| SI | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_m$ (mm) | $\frac{s_m}{l_{embed}}$ | Failure Type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 23 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 10 | 28 | 5.292 | 2 | 76.2 | 0 | 0.68 | 0.0089 | Pullout |
| 24 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 19 | 28 | 5.292 | 1 | 76.2 | 0 | 1.33 | 0.0175 | Splitting |
| 25 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 19 | 28 | 5.292 | 1 | 76.2 | 0 | 1.62 | 0.0213 | Splitting |
| 26 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 19 | 28 | 5.292 | 2 | 76.2 | 0 | 1.15 | 0.0151 | Pullout |
| 27 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 19 | 28 | 5.292 | 2 | 76.2 | 0 | 1.25 | 0.0164 | Pullout |
| 28 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 19 | 28 | 5.292 | 2 | 152 | 0 | 1.21 | 0.0079 | Pullout |
| 29 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 19 | 39.2 | 6.258 | 2 | 305 | 0 | 1.53 | 0.005 | Pullout |
| 30 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 19 | 39.2 | 6.258 | 4 | 406 | 0 | 1.52 | 0.0037 | Pullout |
| 31 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 19 | 39.2 | 6.258 | 4 | 406 | 0 | 1.77 | 0.0044 | Pullout |
| 32 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 19 | 47.7 | 6.907 | 2 | 305 | 0 | 1.72 | 0.0056 | Pullout |
| 33 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 19 | 47.7 | 6.907 | 2 | 305 | 0 | 2.23 | 0.0073 | Pullout |
| 34 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 19 | 47.7 | 6.907 | 4 | 406 | 0 | 1.43 | 0.0035 | Pullout |
| 35 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 19 | 47.7 | 6.907 | 4 | 406 | 0 | 1.59 | 0.0039 | Pullout |
| 36 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 29 | 27.7 | 5.258 | 1 | 102 | 0 | 1.16 | 0.0114 | Splitting |
| 37 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 29 | 27.7 | 5.258 | 2 | 102 | 0 | 1.44 | 0.0142 | Pullout |
| 38 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 29 | 27.7 | 5.258 | 2 | 203 | 0 | 1.44 | 0.0071 | Pullout |
| 39 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 29 | 39.7 | 6.302 | 4 | 660 | 0 | 1.43 | 0.0022 | Pullout |
| 40 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 29 | 39.7 | 6.302 | 4 | 660 | 0 | 2.23 | 0.0034 | Pullout |
| 41 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 29 | 44.8 | 6.69 | 4 | 660 | 0 | 1.71 | 0.0026 | Pullout |
| 42 | Ehsani *et al.* (1993) | GFRP | IHB | HL | Unconfined | 29 | 44.8 | 6.69 | 4 | 660 | 0 | 1.37 | 0.0021 | Pullout |
| 43 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 1.923 | 300 | 0 | 0.75 | 0.0025 | Splitting |
| 44 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.115 | 300 | 0.016 | 1.25 | 0.0042 | Splitting |
| 45 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.115 | 300 | 0.031 | 1.25 | 0.0042 | Splitting |
| 46 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.115 | 300 | 0.046 | 1.1 | 0.0037 | Splitting |
| 47 | Kanakubo *et al.* (1993) | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.115 | 300 | 0 | 0.75 | 0.0025 | Splitting |
| 48 | Kanakubo *et al.* (1993) | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.115 | 300 | 0.016 | 1.5 | 0.005 | Splitting |
| 49 | Kanakubo *et al.* (1993) | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.115 | 300 | 0.031 | 2 | 0.0067 | Splitting |

| Sl | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_m$ (mm) | $\frac{s_m}{l_{embed}}$ | Failure Type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 50 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.115 | 300 | 0 | 1.5 | 0.005 | Splitting |
| 51 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.115 | 300 | 0.016 | 1.2 | 0.004 | Splitting |
| 52 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.115 | 300 | 0.031 | 1.7 | 0.0057 | Splitting |
| 53 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.115 | 300 | 0.027 | 1.7 | 0.0057 | Splitting |
| 54 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 1.923 | 300 | 0 | 0.75 | 0.0025 | Splitting |
| 55 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.115 | 300 | 0.016 | 1.25 | 0.0042 | Splitting |
| 56 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.115 | 300 | 0.031 | 1.25 | 0.0042 | Splitting |
| 57 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.115 | 300 | 0.046 | 1.1 | 0.0037 | Splitting |
| 58 | Kanakubo *et al.* (1993) | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.115 | 300 | 0 | 0.75 | 0.0025 | Splitting |
| 59 | Kanakubo *et al.* (1993) | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.115 | 300 | 0.016 | 1.5 | 0.005 | Splitting |
| 60 | Kanakubo *et al.* (1993) | GFRP | IHB | SW | Unconfined | 13 | 33.1 | 5.753 | 2.115 | 300 | 0.031 | 2 | 0.0067 | Splitting |
| 61 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.115 | 300 | 0 | 1.5 | 0.005 | Splitting |
| 62 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.115 | 300 | 0.016 | 1.2 | 0.004 | Splitting |
| 63 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.115 | 300 | 0.031 | 1.7 | 0.0057 | Splitting |
| 64 | Kanakubo *et al.* (1993) | CFRP | IHB | SW | Unconfined | 13 | 34.5 | 5.874 | 2.115 | 300 | 0.027 | 1.7 | 0.0057 | Splitting |
| 65 | Ehsani *et al.* (1996) | GFRP | HB | HL | Unconfined | 28.58 | 28 | 5.292 | 2 | 203 | 0 | 1.27 | 0.0063 | Pullout |
| 66 | Ehsani *et al.* (1996) | GFRP | HB | HL | Unconfined | 28.58 | 28 | 5.292 | 4 | 661 | 0 | 1.27 | 0.0019 | Pullout |
| 67 | Ehsani *et al.* (1996) | GFRP | HB | HL | Unconfined | 28.58 | 28 | 5.292 | 6.002 | 762 | 0 | 1.02 | 0.0013 | Pullout |
| 68 | Ehsani *et al.* (1996) | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.292 | 300 | 0 | 1.5 | 0.005 | Splitting |
| 69 | Ehsani *et al.* (1996) | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.292 | 300 | 0 | 1.5 | 0.005 | Splitting |
| 70 | Ehsani *et al.* (1996) | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.292 | 300 | 0 | 1.5 | 0.005 | Splitting |
| 71 | Ehsani *et al.* (1996) | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.292 | 300 | 0 | 3.2 | 0.0107 | Splitting |
| 72 | Ehsani *et al.* (1996) | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.292 | 300 | 0 | 4 | 0.0133 | Splitting |
| 73 | Tighiouart *et al.* (1998) | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.937 | 76.2 | 0.062 | 0.13 | 0.0017 | Pullout |
| 74 | Tighiouart *et al.* (1998) | GFRP | HB | SW | Confined | 15.9 | 31 | 5.568 | 3.145 | 95.4 | 0.049 | 0.33 | 0.0035 | Pullout |
| 75 | Tighiouart *et al.* (1998) | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.937 | 127 | 0.062 | 0.3 | 0.0024 | Pullout |
| 76 | Tighiouart *et al.* (1998) | GFRP | HB | SW | Confined | 12.7 | 31 | 5.568 | 3.937 | 203 | 0.062 | 0.25 | 0.0012 | Pullout |

| SI | Ref | FRP Type | Test Type | Bar Surface | Confinement | $d_b$ (mm) | $f_c'$ (MPa) | $\sqrt{f_c'}$ | $\frac{c}{d_b}$ | $l_{embed}$ (mm) | $\frac{A_{tr}}{snd_b}$ | $s_m$ (mm) | $\frac{s_m}{l_{embed}}$ | Failure Type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 77 | Cosenza *et al.* (1999) | GFRP | HB | HL | Unconfined | 12.7 | 37 | 6.083 | 5.906 | 63.5 | 0 | 0.5 | 0.0079 | Pullout |
| 78 | Cosenza *et al.* (1999) | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.906 | 63.5 | 0 | 0.25 | 0.0039 | Pullout |
| 79 | Cosenza *et al.* (1999) | GFRP | HB | HL | Unconfined | 12.7 | 40 | 6.325 | 5.906 | 127 | 0 | 0.22 | 0.0017 | Pullout |
| 80 | Cosenza *et al.* (1999) | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.292 | 300 | 0.017 | 1.5 | 0.005 | Splitting |
| 81 | Cosenza *et al.* (1999) | CFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.292 | 300 | 0.05 | 1.5 | 0.005 | Splitting |
| 82 | Cosenza *et al.* (1999) | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.292 | 300 | 0 | 1.5 | 0.005 | Splitting |
| 83 | Cosenza *et al.* (1999) | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.292 | 300 | 0.034 | 3.2 | 0.0107 | Splitting |
| 84 | Cosenza *et al.* (1999) | AFRP | IHB | HL | Unconfined | 12 | 33.1 | 5.753 | 2.292 | 300 | 0.029 | 4 | 0.0133 | Splitting |
| 85 | Defreese & Wollmann (2002) | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.5 | 63.5 | 0 | 0.15 | 0.0024 | Pullout |
| 86 | Defreese & Wollmann (2002) | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.5 | 63.5 | 0 | 0.32 | 0.005 | Pullout |
| 87 | Defreese & Wollmann (2002) | GFRP | IHB | HL | Confined | 12.7 | 23.4 | 4.837 | 5.5 | 95.3 | 0 | 0.64 | 0.0067 | Pullout |
| 88 | Defreese & Wollmann (2002) | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.393 | 79.5 | 0 | 0.64 | 0.0081 | Pullout |
| 89 | Defreese & Wollmann (2002) | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.393 | 79.5 | 0 | 0.51 | 0.0064 | Pullout |
| 90 | Defreese & Wollmann (2002) | GFRP | IHB | HL | Confined | 15.9 | 23.4 | 4.837 | 4.393 | 119 | 0 | 0.32 | 0.0027 | Pullout |
| 91 | Defreese & Wollmann (2002) | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.657 | 95.5 | 0 | 0.32 | 0.0034 | Pullout |
| 92 | Defreese & Wollmann (2002) | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.657 | 95.5 | 0 | 0.32 | 0.0034 | Pullout |
| 93 | Defreese & Wollmann (2002) | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.657 | 143 | 0 | 0.51 | 0.0036 | Pullout |
| 94 | Defreese & Wollmann (2002) | GFRP | IHB | HL | Confined | 19.1 | 23.4 | 4.837 | 3.657 | 143 | 0 | 0.64 | 0.0045 | Pullout |
| 95 | Aly (2007) | CFRP | S | SC | Confined | 9.5 | 40 | 6.325 | 4.211 | 800 | 0.012 | 3.44 | 3.28 | Splitting |
| 96 | Aly (2007) | CFRP | S | SC | Confined | 19.1 | 40 | 6.325 | 2.094 | 700 | 0.006 | 2.709 | 3.3 | Splitting |
| 97 | Aly (2007) | CFRP | S | SC | Confined | 19.1 | 40 | 6.325 | 2.094 | 800 | 0.009 | 2.36 | 3.74 | Splitting |

# Appendix D


Experimental Beam 1
Predicted
Bond Stress (MPa)
Slip (mm)
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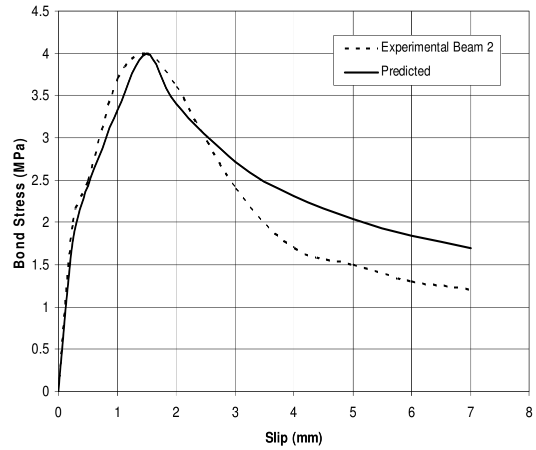
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0 1 2 3 4 5 6 7 8


Experimental Beam 2
Predicted
Bond Stress (MPa)
Slip (mm)
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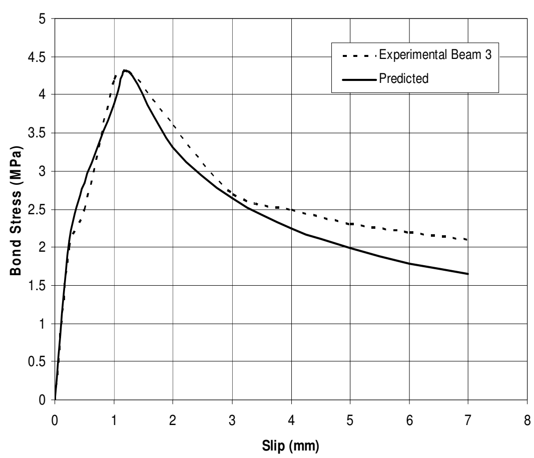
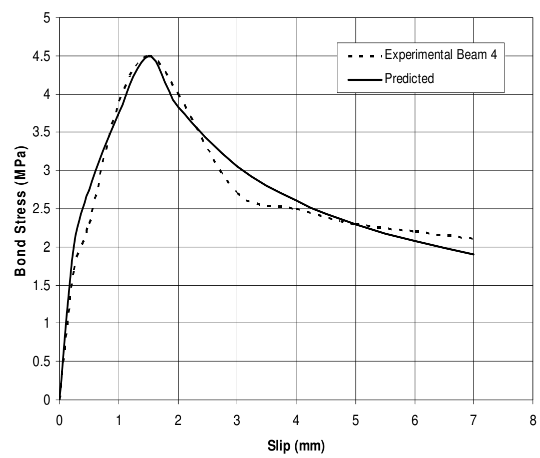
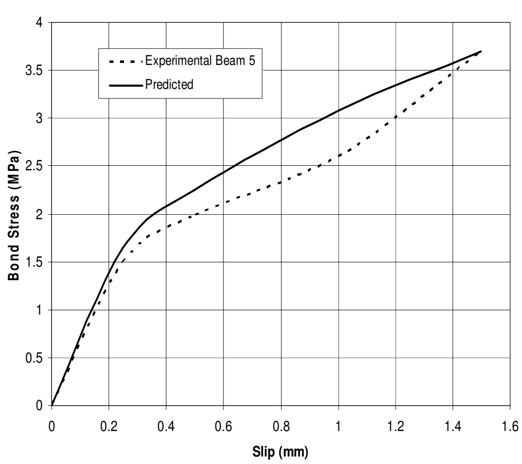
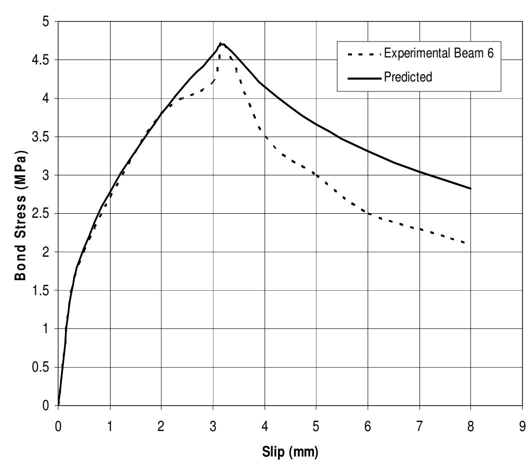
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0 1 2 3 4 5 6 7 8


Experimental Beam 3
Predicted
Bond Stress (MPa)
Slip (mm)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0 1 2 3 4 5 6 7 8


Experimental Beam 4
Predicted
Bond Stress (MPa)
Slip (mm)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0 1 2 3 4 5 6 7 8


Experimental Beam 5
Predicted
Bond Stress (MPa)
Slip (mm)
0
0.5
1
1.5
2
2.5
3
3.5
4
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6


Experimental Beam 6
Predicted
Bond Stress (MPa)
Slip (mm)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0 1 2 3 4 5 6 7 8 9

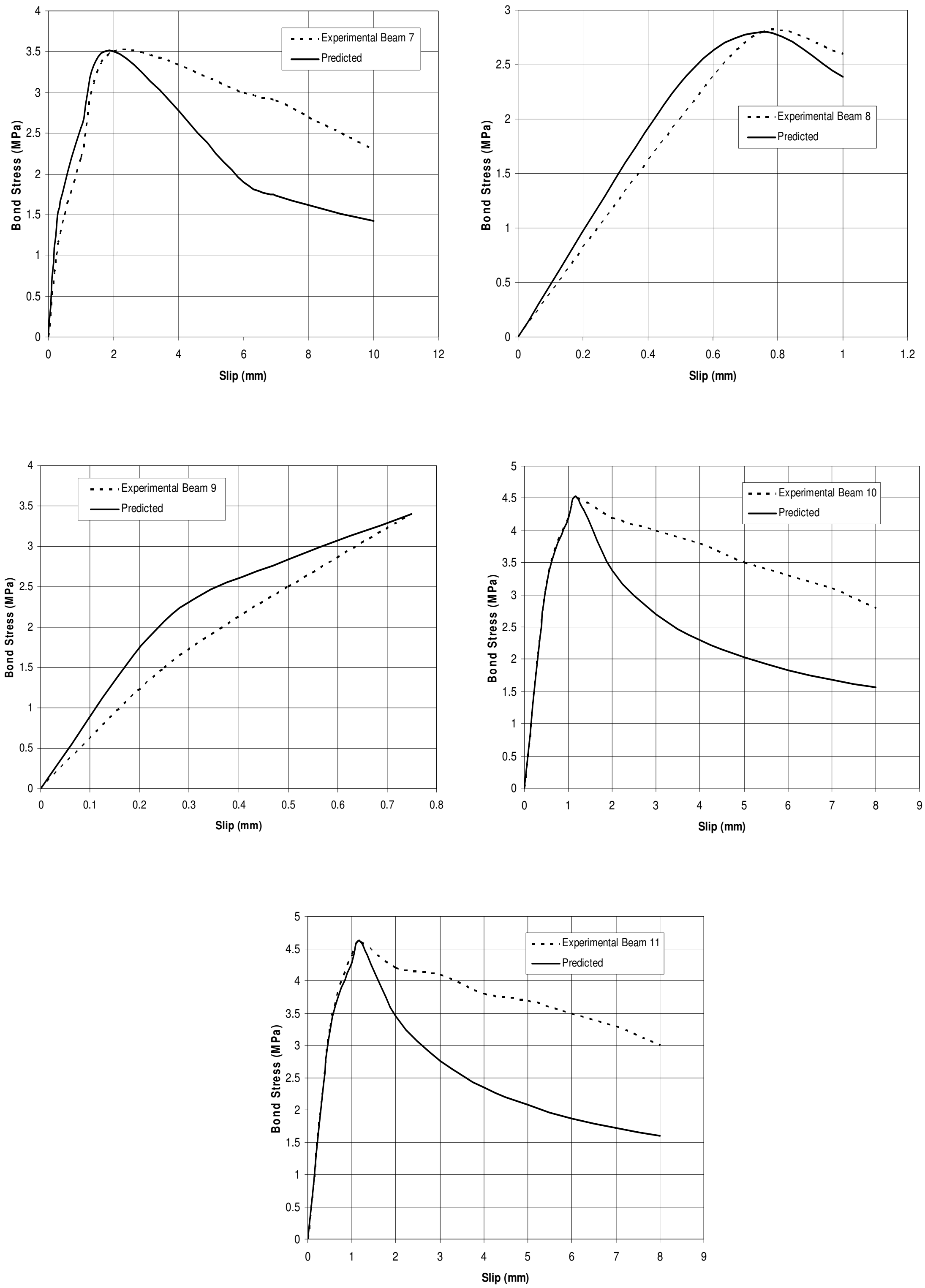
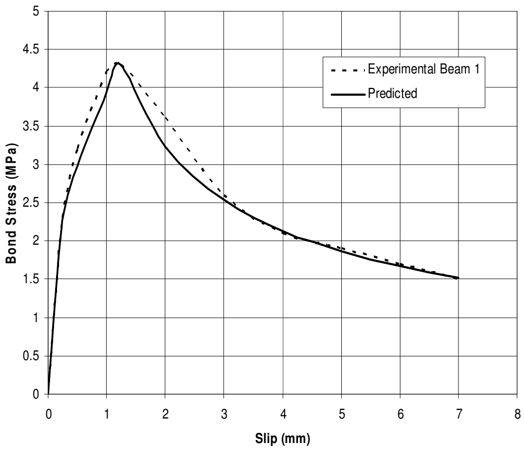
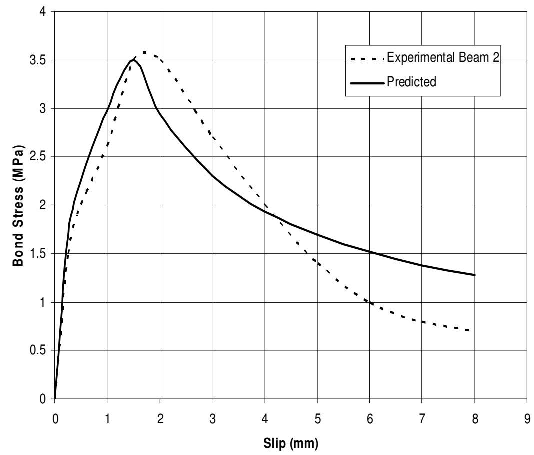
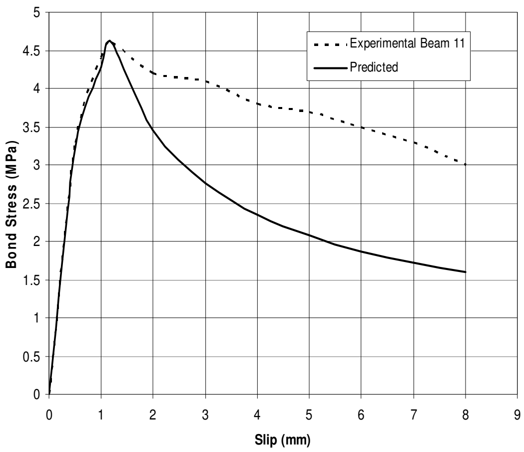
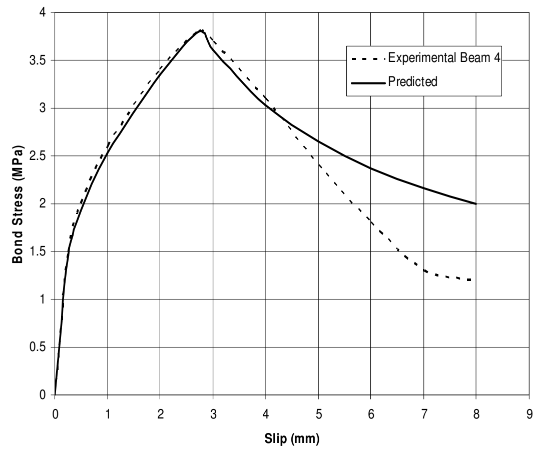


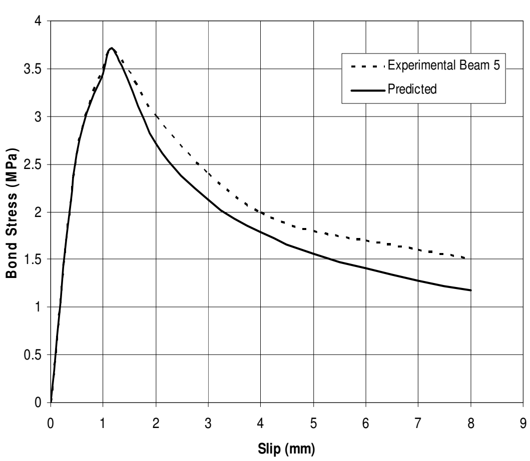

**Figure D.1 Predicted vs. experimental bond stress-slip curves for specimens with helical lugged FRP bars having splitting mode of failure.**

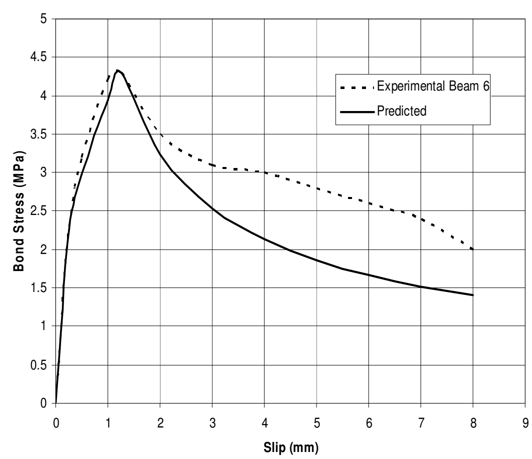

Bond Stress (MPa)
Slip (mm)
Experimental Beam 1
Predicted


Bond Stress (MPa)
Slip (mm)
Experimental Beam 2
Predicted


Bond Stress (MPa)
Slip (mm)
Experimental Beam 11
Predicted


Bond Stress (MPa)
Slip (mm)
Experimental Beam 4
Predicted


Bond Stress (MPa)
Slip (mm)
Experimental Beam 5
Predicted


Bond Stress (MPa)
Slip (mm)
Experimental Beam 6
Predicted

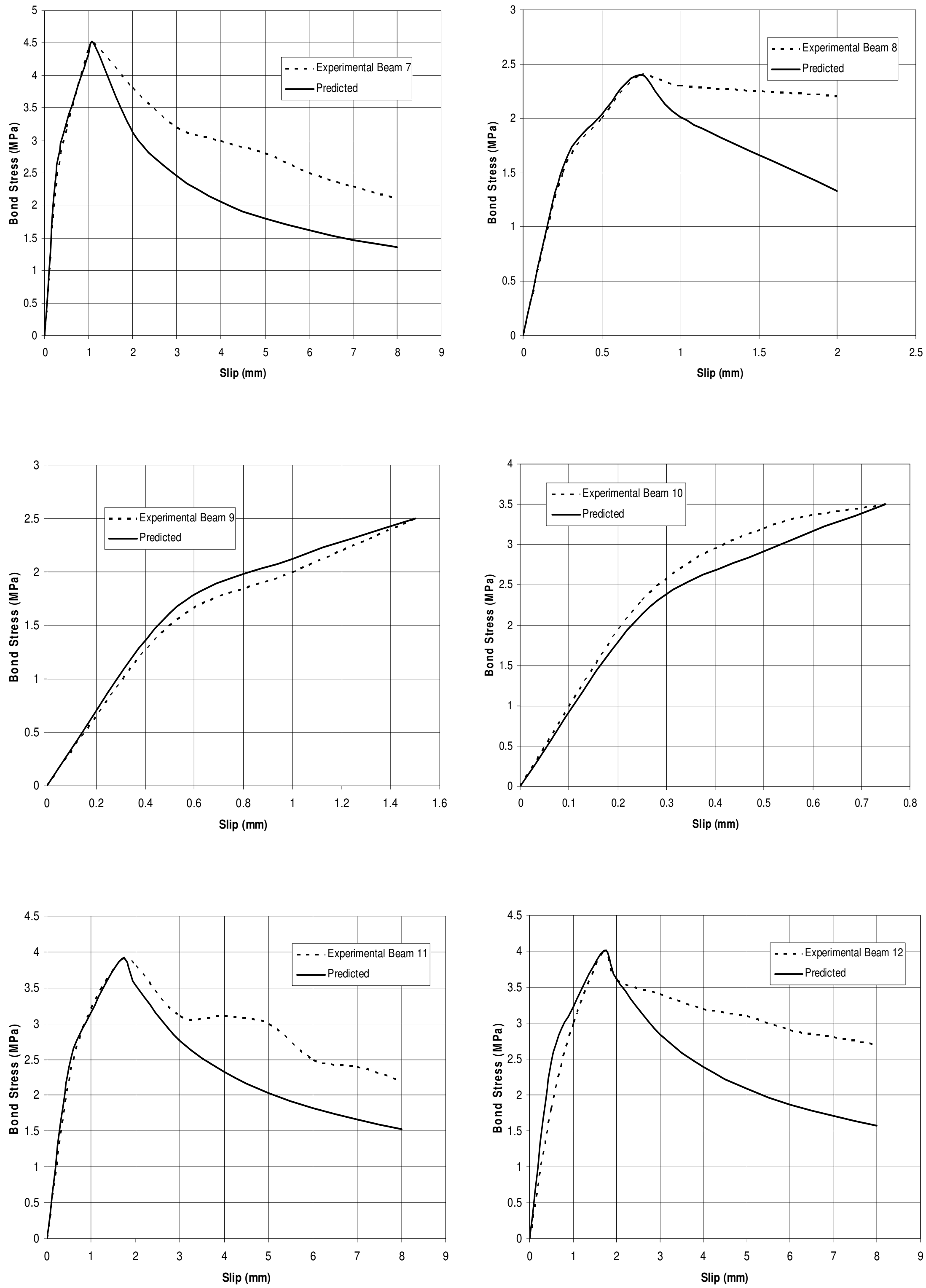



**Figure D.2 Predicted vs. experimental bond stress-slip curves for specimens with spiral wrapped FRP bars having splitting mode of failure.**

# Appendix E

**Table E.1 Values of $C_t$ from the finite element analysis of the 105 confined beam specimens failed by splitting of concrete**

| SI | Reference | Specimen | $C_t$ |
|---|---|---|---|
| 1 | Daniali (1990) | Sp-1 | 0 |
| 2 | | Sp-2 | 0 |
| 3 | | Sp-3 | 0 |
| 4 | | Sp-4 | 0 |
| 5 | | Sp-5 | 0 |
| 6 | Daniali (1991) | Sp-1 | 0 |
| 7 | | Sp-2 | 0 |
| 8 | | Sp-3 | 0 |
| 9 | | Sp-4 | 0 |
| 10 | Faza (1991) | Sp-1 | 3.7 |
| 11 | | Sp-2 | 3.7 |
| 12 | | Sp-3 | 2.9 |
| 13 | | Sp-4 | 2.9 |
| 14 | | Sp-5 | 0 |
| 15 | | Sp-6 | 0 |
| 16 | Tighiouart *et al.* (1998) | Sp-1 | 0 |
| 17 | | Sp-2 | 0 |
| 18 | | Sp-3 | 0 |
| 19 | | Sp-4 | 0 |
| 20 | | Sp-5 | 0 |
| 21 | | Sp-6 | 0 |
| 22 | | Sp-7 | 0 |
| 23 | | Sp-8 | 0 |
| 24 | | Sp-9 | 0.8 |
| 25 | | Sp-10 | 0.8 |
| 26 | | Sp-11 | 2.2 |
| 27 | | Sp-12 | 2.5 |

| SI | Reference | Specimen | $C_t$ |
|---|---|---|---|
| 28 | | Sp-13 | 1.7 |
| 29 | | Sp-14 | 1.8 |
| 30 | Tighiouart *et al.* (1999) | Sp-1 | 2.5 |
| 31 | | Sp-2 | 2.6 |
| 32 | | Sp-3 | 0.4 |
| 33 | | Sp-4 | 2.0 |
| 34 | | Sp-5 | 0 |
| 35 | | Sp-6 | 0 |
| 36 | | Sp-7 | 0 |
| 37 | | Sp-8 | 0 |
| 38 | | Sp-9 | 2.0 |
| 39 | | Sp-10 | 2.1 |
| 40 | | Sp-11 | 0.3 |
| 41 | | Sp-12 | 0.8 |
| 42 | | Sp-13 | 0.7 |
| 43 | | Sp-14 | 0.7 |
| 44 | Mosley (2000) | Sp-1 | 0 |
| 45 | | Sp-2 | 0 |
| 46 | | Sp-3 | 0 |
| 47 | | Sp-4 | 0 |
| 48 | | Sp-5 | 0 |
| 49 | | Sp-6 | 0 |
| 50 | | Sp-7 | 0 |
| 51 | | Sp-8 | 0 |
| 52 | | Sp-9 | 0 |
| 53 | Aly and Benmokrane (2005) | Sp-1 | 2.0 |
| 54 | | Sp-2 | 5.2 |
| 55 | | Sp-3 | 2.4 |
| 56 | | Sp-4 | 1.2 |

| SI | Reference | Specimen | $C_t$ |
|---|---|---|---|
| 57 | | Sp-5 | 5.2 |
| 58 | | Sp-6 | 2.9 |
| 59 | Aly *et al.* (2006) | Sp-1 | 3.9 |
| 60 | | Sp-2 | 3.7 |
| 61 | | Sp-3 | 3.5 |
| 62 | | Sp-4 | 4.0 |
| 63 | | Sp-5 | 3.1 |
| 64 | | Sp-6 | 4.4 |
| 65 | | Sp-7 | 4.7 |
| 66 | | Sp-8 | 4.8 |
| 67 | | Sp-9 | 4.6 |
| 68 | | Sp-10 | 4.7 |
| 69 | | Sp-11 | 4.5 |
| 70 | | Sp-12 | 4.7 |
| 71 | | Sp-13 | 2.9 |
| 72 | Aly (2007) | Sp-1 | 4.5 |
| 73 | | Sp-2 | 4.6 |
| 74 | | Sp-3 | 3.8 |
| 75 | | Sp-4 | 3.4 |
| 76 | | Sp-5 | 2.7 |
| 77 | | Sp-6 | 0 |
| 78 | | Sp-7 | 2 |
| 79 | | Sp-8 | 3.8 |
| 80 | | Sp-9 | 2.9 |
| 81 | | Sp-10 | 2 |
| 82 | | Sp-11 | 1.8 |
| 83 | | Sp-12 | 2.6 |
| 84 | Okelo (2007) | Sp-1 | 5.8 |
| 85 | Tharmin and Kaku (2007) | Sp-1 | 4.3 |

| SI | Reference | Specimen | $C_t$ |
|---|---|---|---|
| 86 | | Sp-2 | 5.2 |
| 87 | | Sp-3 | 6.0 |
| 88 | | Sp-4 | 0.3 |
| 89 | | Sp-5 | 2.3 |
| 90 | | Sp-6 | 3.1 |
| 91 | | Sp-7 | 3.1 |
| 92 | | Sp-8 | 0 |
| 93 | | Sp-9 | 5.1 |
| 94 | | Sp-10 | 2.4 |
| 95 | | Sp-11 | 2.9 |
| 96 | | Sp-12 | 0 |
| 97 | Mosley *et al.* (2008) | Sp-1 | 0 |
| 98 | | Sp-2 | 0 |
| 99 | | Sp-3 | 0 |
| 100 | | Sp-4 | 0 |
| 101 | | Sp-5 | 0 |
| 102 | | Sp-6 | 0 |
| 103 | | Sp-7 | 0 |
| 104 | | Sp-8 | 0 |
| 105 | | Sp-9 | 0 |

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