EXPERIMENTAL STUDY OF A BOLT-BUSHING CONNECTION SYSTEM FOR STRUCTURAL COMPOSITE LUMBER

by

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ABSTRACT

The results of an experimental study are presented on the use of polyurethane lined bushings in bolted connections of structural composite lumber. Monotonic tension tests and cyclic axial tests were performed on 80 specimens of varying dimensions made with Douglas Fir parallel strand lumber. All the connections were made with a single fastener, which consisted of a 12 mm bolt, with or without bushing. The bushings consisted of an inner and outer steel ring with a mouldable polyurethane filling. Varying diameters and steel ring thicknesses were tested. To prevent brittle splitting failures of the connections, the end distance was varied and transverse reinforcement of the wood with threaded dowels was introduced. Material tests were conducted on the structural composite lumber and the polyurethane filling.

The introduction of a polyurethane bushing in a single fastener connection served to increase the ductility of the connection under tension loading. A high degree of variability in capacity and ductility were observed, however, which can be attributed to a lack of filler material consistency in the fabrication process. Significant improvements in ductility and resistance were achieved when transversely placed treaded dowels were introduced as reinforcing elements of the structural composite lumber. This effect was most pronounced for connections with bolts only. For the connections with bushings, splitting failures still prevailed and a need for more elaborate reinforcements was identified. In the absence of reinforcing elements, it was found that the end distance of connectors has to be increased when bushings of a diameter larger than the bolt were introduced.

The cyclic behaviour of bushing connectors showed hysteresis loops with a significant amount of degradation under repeated cycles. Although cyclic compression tests on polyurethane cylinders exhibited stable hysteretic behaviour with significant energy absorption, the high deformation demand of the material in the bushings showed that a more suitable material needs to be found for application in bushing connections that are subjected to severe earthquake motions. The results from this study provide important information on the behaviour of polyurethane bushing connections and paves the way for refinements of innovative connection techniques that are suitable for structures in high risk seismic zones.

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1. INTRODUCTION

1.1. GENERAL

This experimental study has been initiated to satisfy an identified need of the construction industry for research and development of advanced connection methods for heavy timber construction. Of special interest are connections for composite wood members, which have not yet advanced to a stage where the enhanced properties of these newly developed materials are fully and efficiently utilized.

In the last decade, the pressure due to diminishing resources and environmental concerns has begun to push the forest products industry towards a transition from a mainly resource based to a manufacturing industry. This transition has an immediate impact on other industries such as the construction industry, due to an emphasis on the design and manufacture of prefabricated buildings using composite wood products.

Composite wood products have several advantages over sawn lumber members such as:

- The ability to produce high grade members from wood, which did not originate from old grown forests;
- The capacity to incorporate lower grade materials in a very efficient manner;
- A higher homogeneity, due to the reduction of variability normally associated with defects and knots in sawn lumber;
- Engineered material properties dedicated for specific applications;

These advantages make structural composite lumber competitive with steel and concrete for many applications, especially small to midsize structures. The use of these elements, characterized by better mechanical properties, is presently still restricted by inefficient design rules and lack of manufacturing technology for connections. By improving the efficiency of the connection design between composite wood members, the overall costs, which tends to be higher because of the higher costs of the elements, can be reduced.

The development of new types of ductile connections, simple and efficient, became a necessity in promoting composite wood members in large timber structures subjected to earthquake loading. This is because the traditional methods of connection design utilizing nails and bolts do not provide the most effective means of transferring loads between members and, as a result, the maximum potential strength of the members is not exploited resulting in design of structures with much larger members than might actually be required.

The objective of this experimental study was to investigate the strength and behaviour of bolted connections for parallel strand lumber (PSL). This product is currently marketed as Parallam®. PSL is manufactured by laminating long, narrow strands of either Douglas fir or Western Hemlock (referred to as "Western Species") or Southern pine or Yellow Poplar (referred to as "Eastern Species") veneer with the strands oriented along the length of the member. The strands are completely coated with an exterior-type adhesive (phenol formaldehyde), laid up and fed into a belt press under heat and pressure to form a continuous billet. The billet may then be cross-cut to any length up to 20 m. PSL is available up to a cross-section of 305 by 406 mm. Cross sections up to 305 by 610 mm are available through secondary lamination. Figure 1.1 illustrates a block of Parallam® PSL.

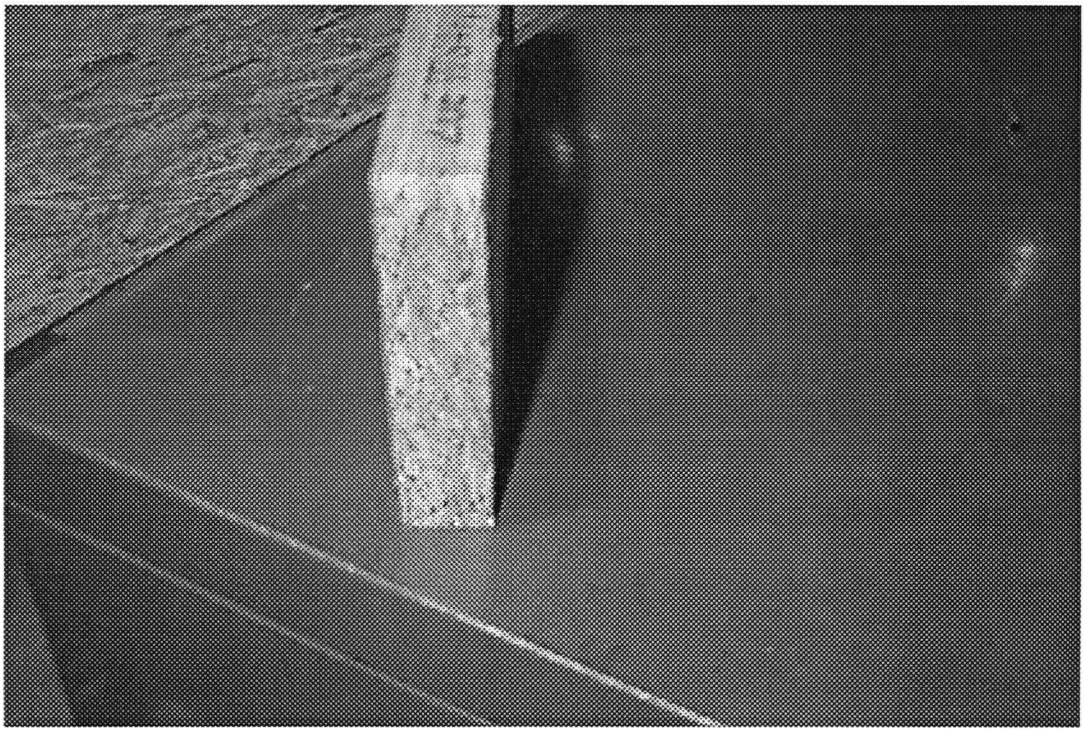


Fig. 1.1.: A block of Parallam® PSL

Parallam® PSL is permitted for use in residential and commercial construction as an alternative construction material for lumber, including studs, floor joists, rafters, beams, headers, lintels, columns, posts, sills, plates, and stair stringers. Parallam® PSL has to be designed in accordance with the requirements of Section 4.3 of the National Building Code of Canada 1990 and CAN3-086-M84, "Engineering Design in Wood (Working Stress Design)". For certain applications it is a particular suitable material due to its higher density and crushing strength.

The allowable design stresses given in Appendix A and the design loads in tables referenced above are applicable only to Parallam® PSL used in dry service conditions, where the maximum moisture content of the wood does not exceed 19%.

For now, values have not been fully calibrated for use in Limit States Design. Parallam® PSL used in heavy-timber construction must meet the minimum dimensions shown for glue laminated wood products in NBCC 1990 Article 3.1.4.6. Although the high crushing strength of Parallam® PSL will benefit the strength of bolted connections, the weak link is still the low perpendicular to grain tension strength, which is not much higher than that for sawn lumber. To devise efficient connections, it is necessary to consider non-traditional fastener methods that capitalize on the superior qualities of the product while avoiding stress conditions that lead to brittle failures.

One such innovative approach to enhance the connection strength is the use of prefabricated moulded polyurethane-steel bushings (Fig.1.2) introduced between the bolt and the wood member. The benefits that can be expected from such a connector are:

- Creation of an energy dissipating medium able to increase the overall ductility of the connection;
- Reduction of the pressure on the contact surface of the wood element to avoid premature splitting and crushing which could induce element failure;
- Reduction of stress concentration around the bolts;
- An easy-to-install connection entirely prefabricated, with high efficiency.

The bushings were made using one type of mouldable rubber (polyurethane), reinforced and unreinforced, of different thickness to obtain the optimum results. They were manufactured in the laboratory by pouring the mouldable rubber solution in between two concentric pipes, which acted as precision forms and as primary stress transmitters. The height of the bushing was always equal to the thickness of the wood member.

The testing sequence for the specimens, the description of the materials used and the manufacturing procedures are given in Chapter 2: "Experimental program" .

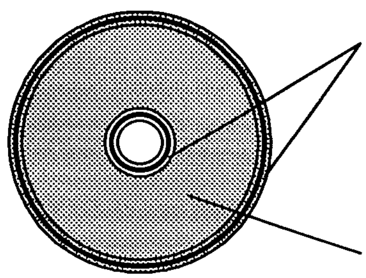


Fig.1.2.: Steel Polyurethane Bushing Shape

1.2. PREVIOUS RESEARCH

As mentioned earlier, the study of connections for composite wood elements is still at the infant stage. Numerous studies have been done for timber and glued laminated timber connections , but comparatively few for Parallam® PSL connections. There are some important results, however, which can be used for further research.

A study on the cyclic behaviour of dowel type connections of PSL [.Prion and Foschi, 1994] showed that the hysteretic behaviour of wood/metal connections can be accurately predicted with a finite element based analytical model. Mild steel tight fitting dowels were used, which resulted in a connection with good ductility.

Investigations by Wilkinson and Rowlands [1981], Moss [1984] and Rodd [1988] have shown that, for parallel to grain loading, the stress distribution around the joint depends on hole-bolt clearance, end distance and friction between the bolt and wood.

A comparative study [Patton-Mallory, 1989] between the yield theory of bolted connections and the current U.S. design criteria [NDS], showed that the yield theory can be adopted to predict working stress design loads and can result in an improvement of the present design criteria.

A joint configuration study [A. Kermani, H. Goh, 1994] showed good behaviour of connections made with welded steel gusset plates and dowels. Their performance was even better than the bolted connections of similar configuration, due to the tight fit of the dowels in timber.

An analysis of the stresses in bolted wood connections [Shih, Ju and Rowlands, 1994] showed that the stresses in the neighbourhood of the bolt-wood contact surface are affected by friction, and the nature of that effect is influenced by the relative geometry.

A study of glued laminated wood elements [Rodd and Pope, 1994] showed that joints made with resin injected dowels have good load carrying properties and a ductile mode of failure with minimal associated cracking.

Another study [Davalos and Pellicane, 1991] concluded that the load-deformation behaviour of bolted connections in wood structures can be described using a mathematical model. The average of normalized errors obtained was less than 15% and could still be reduced whenever a more rigorous fundamental theory of failure of the wood is developed.

A study presented to the International Wood Engineering Conference – New Orleans 1996 [Leitjen, 1996] shows that the use of low grade steel tubes in wood connections improves the capacity and ductility of the connection without causing too much damage in the surrounding material. Compared to joints with dowels, the stiffness is four to six times as high.

Another study [Werner, 1996] showed an increase in the load capacity by using tubing in wood bolted connections, as an intermediate stress transmitter between the wood material and the bolt.

A study by Kangas and Koponen [1996] presented the results obtained for joint tests of an engineered wood material – Kerto LVL – obtained by laminating 3 mm thick spruce veneers with the veneer face grain oriented along member length. The results showed that the load-carrying capacity is reduced significantly by diminished spacing and end distances. The moisture variation and drying did not affect the ultimate strength of the joints significantly.

The effects of bolt to hole clearance and changing the contact areas for bolted connections in anisotropic materials (including wood) have been studied by a number of researchers over the past 10 years [Rowlands et al. 1991, 1993]. They concluded that the ductility associated with the material nonlinearity in the wood grain direction significantly reduced the radial and shear stress around the hole.

Numerous analyses attempted to quantify the effects of friction in bolted connections in anisotropic materials. One first study [Shih, 1992] showed that the friction effects are primarily local to the contact region and may not be as significant as reported in earlier studies where only stresses along the hole boundary were evaluated. On the other hand, previous studies [Wilkinson and Rowlands 1981a] concluded that the effects of friction greatly influence the stresses and should be accounted for in any analysis. Another more recent study [Eriksson 1986, Hyer et al. 1987] showed that friction reduced the magnitude of radial stresses in the contact area, and shifted the point of maximum stress from the axis of symmetry. They reiterated the need to include the friction in the stress analysis.

From the above mentioned studies it can be concluded that:

- Connector to wood contact is a very important parameter to be considered.
- Ductility/flexibility of the connector has also an important role in the connection behaviour.
- Friction between the connector and the hole walls influence the stress distribution along the hole boundary.
- End distance and spacing can significantly influence the load carrying capacity of the connection.

Starting from these conclusions, the idea of a polyurethane bushing connector emerged with some interesting results as it can be seen in the following chapters.

1.3. CURRENT DESIGN PHILOSOPHY

There are no current design specifications for connections involving Parallam® PSL elements. For timber connections with bolts and dowels the approach in the Canadian standard seems to be very conservative compared to approaches in Europe and the United States of America. Therefore, connections involving bolts usually require a large number of fasteners and are thus excessively long and expensive.

Fundamental to the efficient utilization of bolted joints is an understanding of their mechanical behaviour under load. Particularly relevant are the effects of stress concentrations resulting from the presence of a load applied to a localized region in the member containing a hole. This behaviour is a function of material and geometric factors such as wood species, bolt diameter, end distance, edge distance, spacing and number of bolts.

Wood design was historically based on the allowable stress design (ASD) philosophy. In the last decade, the advancements in estimating the reliability indices (β) for wood connections made possible the adoption of load and resistance design criteria. In the United states the first draft Load and Resistance Factor Design (LRFD) code for engineered wood construction was published in 1988. In Canada the conversion to the limit states design was made in 1989.

The new LRFD code incorporates both the yield theory predictions of connection strength along with the new format. Where no new information existed to justify the changes, soft conversion from the ASD code was adopted in the LRFD code. One of these areas was bolt end distance and spacing requirements. The European unified code Eurocode 5 (EC5) contains end distance recommendations similar to the U.S. code (e/d = 7). The Canadian code requirements are more stringent (e/d = 10), to account for splitting failures in multiple-bolt connections tests that did not occur in single-bolt connection tests [Stieda, 1993; Masse, 1989]

To avoid premature splitting, the arrangement of fasteners in a connection is specified in the code in terms of end distance, edge distance and spacing as shown in the Figure below. The minimum distances in Figure 1.3, required by the Canadian code, are measured from the center of the bolt.

Concerning the bolt to hole clearance, it is necessary to manufacture a fastener hole slightly larger than the diameter of the bolt to ease installation and allow for small misalignment of members. Therefore, common practice in bolted wood connections is to manufacture the bolt holes not less than 1.0 mm nor more than 2.0 mm larger than the bolt diameter (0.8 - 1.6 mm in the United States).

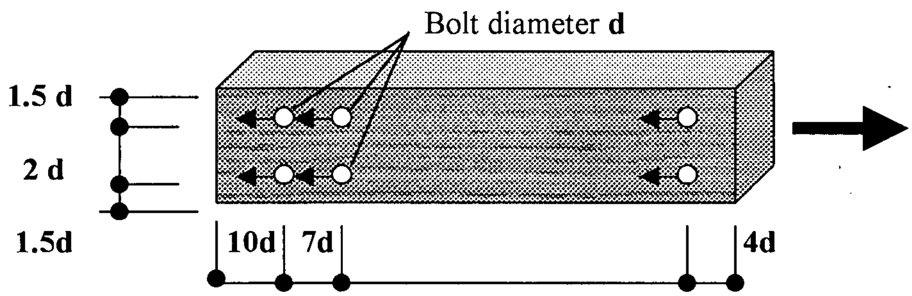


Fig.1.3.: Minimum Configuration Requirements of Fasteners in Terms of End Distance, Edge Distance and Spacing, According to CSA086.1

The direct effects of the bolt to hole clearance are:

- A smaller area of contact occurs with higher modulus materials.
- The bolt to hole clearance has a greater effect on shear and radial stresses along the hole boundary than do changes in the member elastic modulus.
- Radial stresses in the contact area increase when increasing the clearance (due to smaller contact area)
- The area of contact increases with decreasing bolt to hole clearance.
- Misalignment and low tolerance levels result in possibly uneven distribution among fasteners in multi-bolt connections. This may lead to premature failures when connectors lack ductility.

Experimental studies have also shown that significant frictional stresses exist on the bolt to hole contact region in a wood connection. Friction inhibits the free sliding of the wood along the bolt surface as the bolt is embedded into the wood when the connection deforms. There is a considerable disagreement among researchers on how friction affects critical stresses and connection behaviour, and there are no specific design specifications to take this phenomenon into account.

Design information provided in CAN/CSA-086.1-M95 is based on bolts conforming to the requirements of ASTM Standard A307. Threaded rods meeting the requirements of ASTM A307 are permitted to be used in lieu of bolts. A307 bolts are commonly available as either square headed machine bolts or, more commonly, as finished hexagon bolts. Bolts are generally available in imperial sizes. A307 threaded rod is sometimes used in place of bolts because it is readily available in long lengths and can easily be cut to the required size.

Yield Model and Beam on Deformable Foundation Model.

Models that predict the behaviour of both the wood and the bolt have been formulated as a beam resting on a deformable foundation with properties idealized as linear or nonlinear. The bolt is assumed to be elastic, perfectly plastic or elastic-perfectly plastic. The assumptions made when using beam on foundation type models include:

- Winkler foundation (ignores shear strain)
- The connector fits tightly in the hole (no clearance)
- No friction between members or along the bolt
- Small displacement theory is valid
- Failure is due to wood crushing beneath the bolt (no splitting)

- Constant material properties through the thickness
- Bolt ends are free to rotate

The shortfall of this model is prediction of linear load-displacement behaviour only. Observed behaviour of bolted connections is nonlinear even at low loads, therefore this model has only limited application.

The yield model of bolted connections developed by Johansen (1949) assumes perfectly plastic behaviour in the bolt and the wood. A series of failure modes were postulated for two-member and three-member connections. The principle of equilibrium was used to solve for the location of plastic hinges in the bolt. The original formulation assumed equal properties for all wood members in the connection. Johansen recommended a minimum end distance for developing the yield load: $e/d = 7$ for dowel connections and $e/d = 10$ for bolted connections. Larsen (1973) expanded the plastic model to describe bearing capacity (yield load) where wood members have different properties. The result was a yield load for each possible failure mode. The failure mode with the lowest load was selected to limit the connection strength. This model is often referred to as the "European yield model" because it describes how fastener yielding contributes to bolted wood connection strength. The model uses the connection geometry, bolt yield strength and the wood embedment strength to predict connection yield load. In the Canadian code, the wood density is used to calculate the effective embedment strength. The limitation of the model are:

- It only predicts a failure load with no description of connection stiffness or displacement at failure.

- The model does not consider fracture due to shear or perpendicular-to-grain tension stresses.
- The dowels have to fit the holes perfectly.
- Friction between members is ignored.
- Tension stiffening for bolted connections is ignored.

Although the current design rules are a significant improvement over the old prescriptive rules, by linking design values to specific connection behaviour, much work is still needed to establish rational design models that consider the entire spectrum of connection behaviour from linear elastic to failure. Recent attempts to consider all the parameters such as spacing, end distance and number of rows, have resulted in severe reductions in connection strength in the Canadian code, especially when compared to US and European codes. This reiterates the need for consistency and for comprehensive study on the interaction of all parameters governing the behaviour of dowel type connections.

2. EXPERIMENTAL PROGRAM

2.1. GENERAL

The purpose of the experimental program was to determine the behaviour of polyurethane bushing elements introduced between PSL wood member and the bolt or dowel, and to establish a database from which further analytical studies may be performed. The study is one of the preliminary steps in developing design specifications for connections in composite structural lumber elements. This material is new on the market and its behaviour is largely unknown in combination with other materials used in structural connections. The laboratory results will be compared to the current Canadian design specifications for sawn lumber and glulam during the next phases of the project, to determine the differences and to emphasize the importance of using the new engineered wood products and connections.

It was important to determine the ultimate load capacity of the members with different types and sizes of bushings, as well as the behaviour under cyclic and long term loading. To maintain a means of direct comparison between specimens, all of them had the same sectional properties for the same testing type.

The experimental program consisted of three different phases, described and designated as Type A: Pilot Tests, Type B: Traction Test and Type C: Cyclic Tests, preceded by a preliminary material testing program.

Preliminary Material Testing

During this phase, density and moisture content tests were performed on ten randomly chosen Parallam® PSL specimens, which were participants in the subsequent experimental program. Material tests were also performed on Parallam® PSL and polyurethane coupons, to obtain information on the load-deformation behaviour when subjected to monotonic and cyclic loading. Two Parallam® PSL coupons were subjected to tension parallel to grain loading and one to tension perpendicular to grain. One polyurethane cylinder was subjected to compression and one small polyurethane bushing was subjected to traction while in working position to obtain the load-displacement curves necessary for the cyclic testing calibration.

Type A: Pilot Tests

During this phase, a variety of different specimens were tested to determine the general behaviour of the connections before committing to more extensive tests in the next phases of the experimental program. Two specimens were tested under long term loading (test designated as **Type A1**). Another nine specimens, having different sizes and positions for the bushing, were tested in pure tension (designated as **Type A2**). Two specimens, having different bushing sizes, were tested under cyclic loading (designated as **Type A3**). Finally, six specimens with and without bushings, reinforced against premature splitting with 12 mm threaded rod dowels positioned in a plane perpendicular to the bolt axis, at different positions, were tested under pure tension (designated as **Type A4**).

a) Type A1: Long Term Loading

Two specimens with a length of 400 mm and polyurethane–steel bushings were tested for creep under a constant permanent load of 250 kg. The first one had an ordinary polyurethane-steel bushing, the second one had a reinforced polyurethane-steel bushing. The test length was two-weeks for each specimen at which point the displacements were

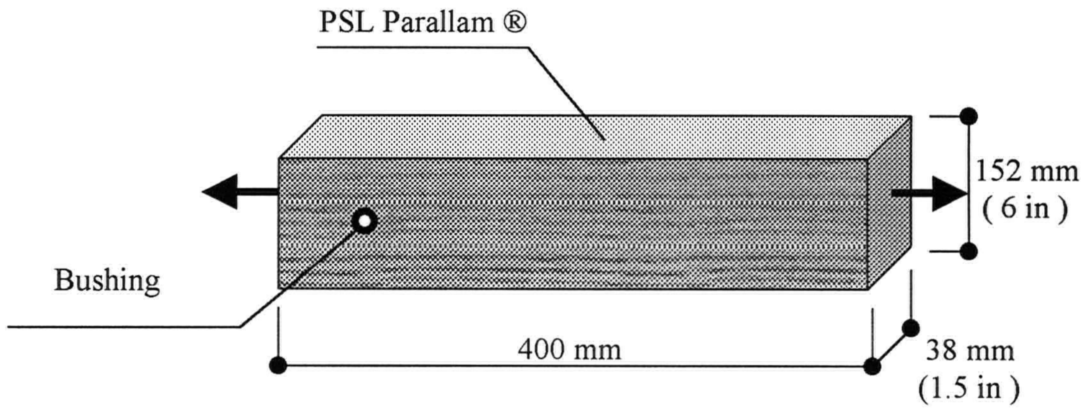


Fig. 2.1.: Specimen Properties

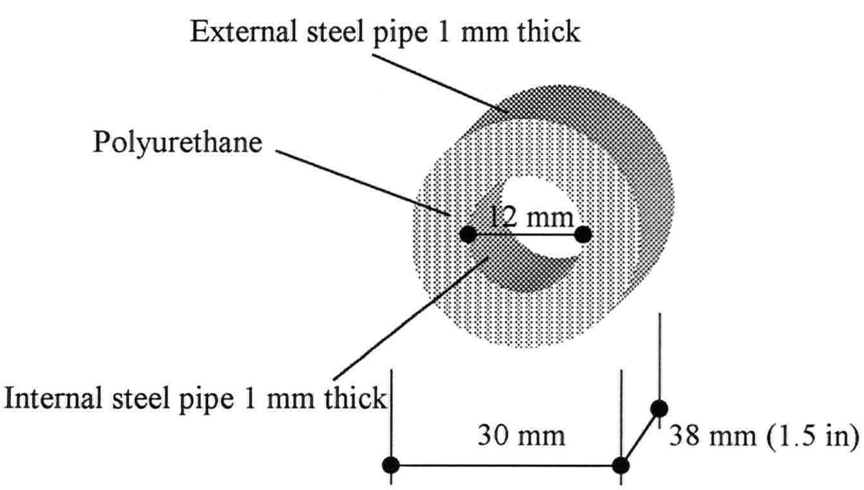


Fig. 2.2.: Small Polyurethane-Steel Bushing Properties

deemed to have stabilized. The specimen and bushing properties used for this test are presented in Figure 2.1.and 2.2.

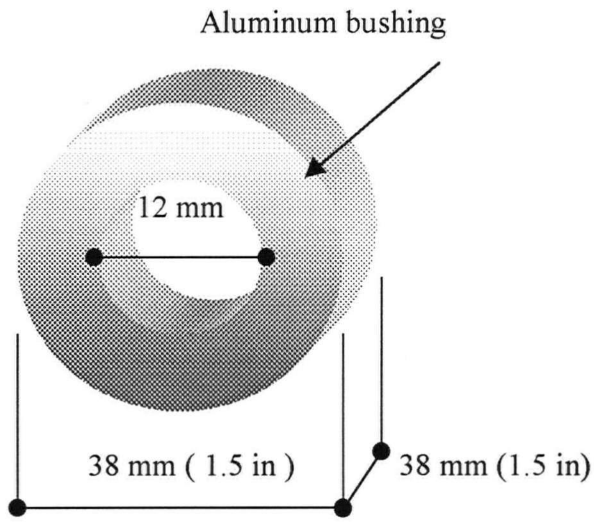
b) Type A2: Pure Tension

Nine specimens, 400 mm long as shown in Fig.2.1., with different bushing materials, positions and sizes were tested in pure tension. The load – deformation curves were obtained and the failure modes were observed. The pattern of fracture was studied for each specimen, to determine the optimal size and position of the bushings.

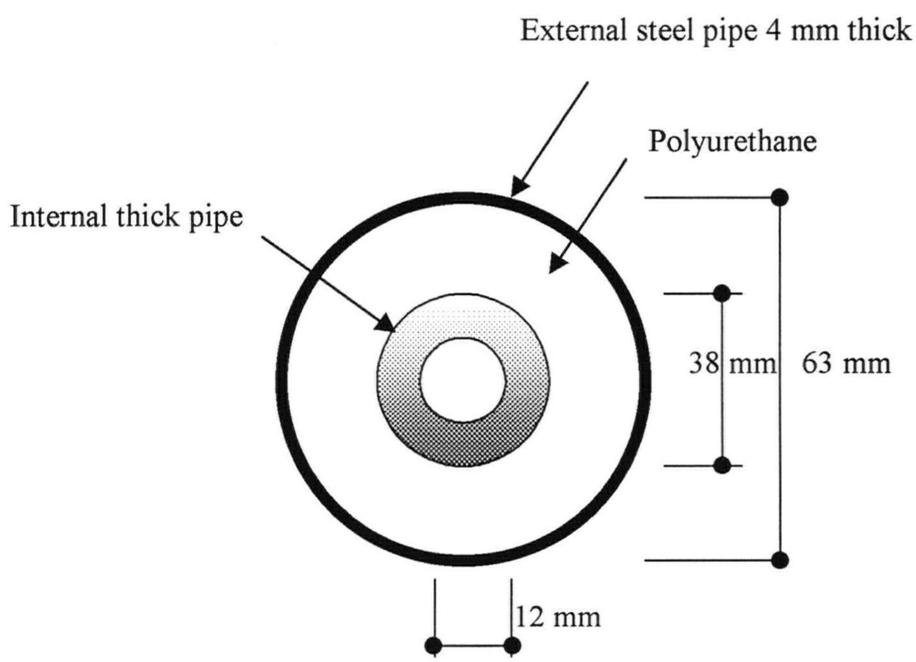
Three specimens had small polyurethane-in-steel bushings, with the dimensions shown in Fig. 2.2., having different positions with respect to the member end (84 mm, 100mm and 120 mm, respectively). This test series, designated as **Type A2 [a]**, was aimed at obtaining preliminary information about the optimal position of the bushing which would avoid premature splitting, yet maintain the compactness of the connection.

Two of the specimens had solid aluminum bushings, with 12 mm (0.5 in) internal diameter and 38 mm (1.5 in) external diameter - Fig. 2.3(a) - glued into the Parallam® PSL member at 84 mm (7 d) and 120 mm (10 d) from the edge, respectively (designated as **Type A2 [b]**). This test intended to offer some information about the behaviour of connections made with bushings of solid material. Note that the end distance is consistently given as a multiple of the connector bolt diameter (12 mm in this case).

With the end distance chosen as recommended in the design code (e = 10 d), four other specimens were tested for different types and sizes of bushings: one bushing, with dimensions as in Fig.2.2., but reinforced with wire mesh to restrain the lateral flow of the plastic polyurethane; two other bushings, with the external diameter increased to 63 mm (2.5 inch), one of them reinforced with wire mesh; one other bushing, with the external



a)



b)

Fig. 2.3.: Dimensions of: a) Aluminum bushing; b) Large Polyurethane Bushings

diameter increased to 63 mm and 13 mm thick internal pipe, as shown in Fig.2.3 (b). This test series, designated as **Type A2 [c]**, was intended to obtain preliminary information about the influence of the size of the bushing and of the polyurethane reinforcement on the general behaviour of the connection, and to determine the optimal shape and material of the bushing for maximum ductility.

c) Type A3: Cyclic loading

Two specimens, shaped as in Fig.2.1, one with small and the other with big bushing, were tested under cyclic loading to find the hysteretic response of the connection, and the capacity to dissipate energy. The specimens were subjected to calibrated cyclic displacements in a servo controlled MTS testing machine, using the revised (30.06.97) cyclic protocol as shown in Appendix A. This test series, designated as **Type A3 [a]** was intended to provide information about the influence of the size of the bushing on the energy dissipation capacity of the connection.

During this phase, two polyurethane cylindrical coupons were also tested under cyclic compression to obtain information about the load-deformation characteristics of this material and its ability to dissipate energy (designated as **Type A3 [b]**).

Then two small bushings, placed in a thick steel plate, were tested under calibrated cyclic loading to obtain information about the behaviour of these elements only, when subjected to cyclic loading (designated as **Type A3 [c]**). The calibration was possible after one traction test abridged in Appendix A.

d) Type A4: Reinforced Wood – Pure Traction

The reinforcement of the PSL Parallam® specimens was necessary after investigation of the characteristic failure mode: brittle fracture due to sudden splitting along the glue lines. Up to now, the experimental study provided information about the optimal size and positioning of the bushings. These tests were done using narrower specimens, with dimensions as shown in Fig.2.4.

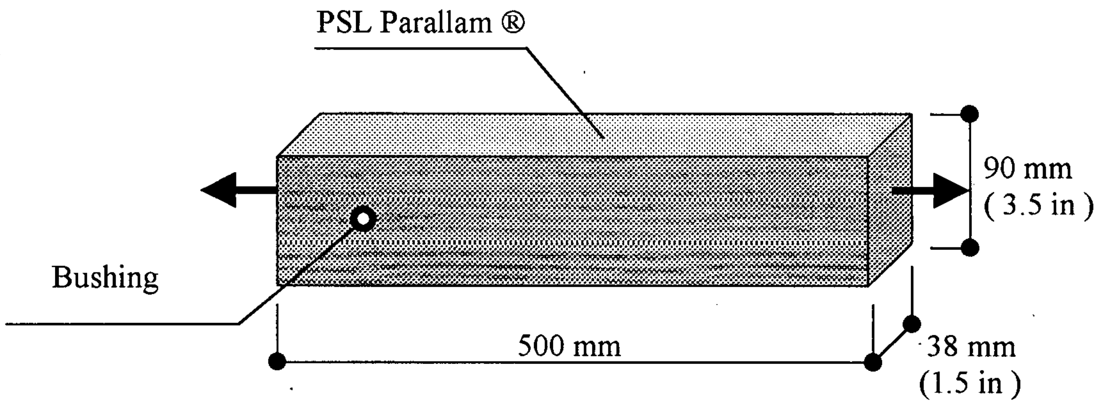


Fig. 2.4.: Test Type B - Specimen Properties

Six specimens reinforced with 12 mm threaded rod dowels were tested: the first two, with and without bushing, had the threaded rod dowel placed beneath the bolt position, practically in contact with the bolt (bushing) body acting like a support for the bolt (bushing) during the test (Figure 2.5.a). The next two, with and without bushing, had two threaded rod dowels placed beneath the bolt position, one practically in contact with the bolt (bushing) body, the other situated at 50 mm from the bolt towards the free end (Figure 2.5.b). Finally, the last two, with and without bushing, had the threaded rod dowel situated beneath the bolt position, at a distance of 50 mm center to center (Figure 2.5.c).

__Type B: Tension Tests__

Using the information collected during the first phase of the project (designated as **Test Type A**), forty specimens were tested under tension to determine the characteristic load – displacement curves, P - Δ. Ten of them were without any bushing (test designated as **Type B1**), another ten with small bushings, which were found to have a better behaviour in the connection (test designated as **Type B2**). The next twenty specimens were reinforced against premature splitting with one threaded dowel situated at 50 mm from the bolt axis: ten of them without bushing (designated as **Type B3**), the other ten with small bushings (test designated as **Type B4**). The wood specimens, made from PSL Parallam ®, were shaped as shown in Fig. 2.4. The end distance was 120 mm (10 d) and the threaded rod diameter was 12 mm (0.5 inch) for all specimens.

<u>Type C: Cyclic Loading Tests</u>

Twenty specimens, shaped as in Fig.2.4, five without bushings (designated as **Type C1**), five without bushings but reinforced with dowels (designated as **Type C3**), five with small bushings (designated as **Type C2**) and five with small bushings reinforced with dowels (designated as **Type C4**), were tested under cyclic loading to find the hysteretic response of the connection, and the energy dissipation capacity. All the reinforcements were done with one dowel, 50 mm from the bolt. The specimens were subjected to cyclic displacements in a servo controlled MTS testing machine, using the revised (30.06.97) cyclic protocol as shown in Appendix A. The results of the test also provided information on the failure mechanism, which occurred in the bushing material during the dissipation process.

2.2. SPECIMEN PREPARATION

Two PSL beams 3800 mm long, 300 mm wide and 38 mm thick and ten other beams of 2100 mm length, 90 mm width, 38 mm thickness were donated by the local

Parallam® factory (Trus Joist MacMillan). The wood species used for these beams was Douglas fir, grade 2.0E. The factory allowable design stresses for these beams are given in Appendix A.

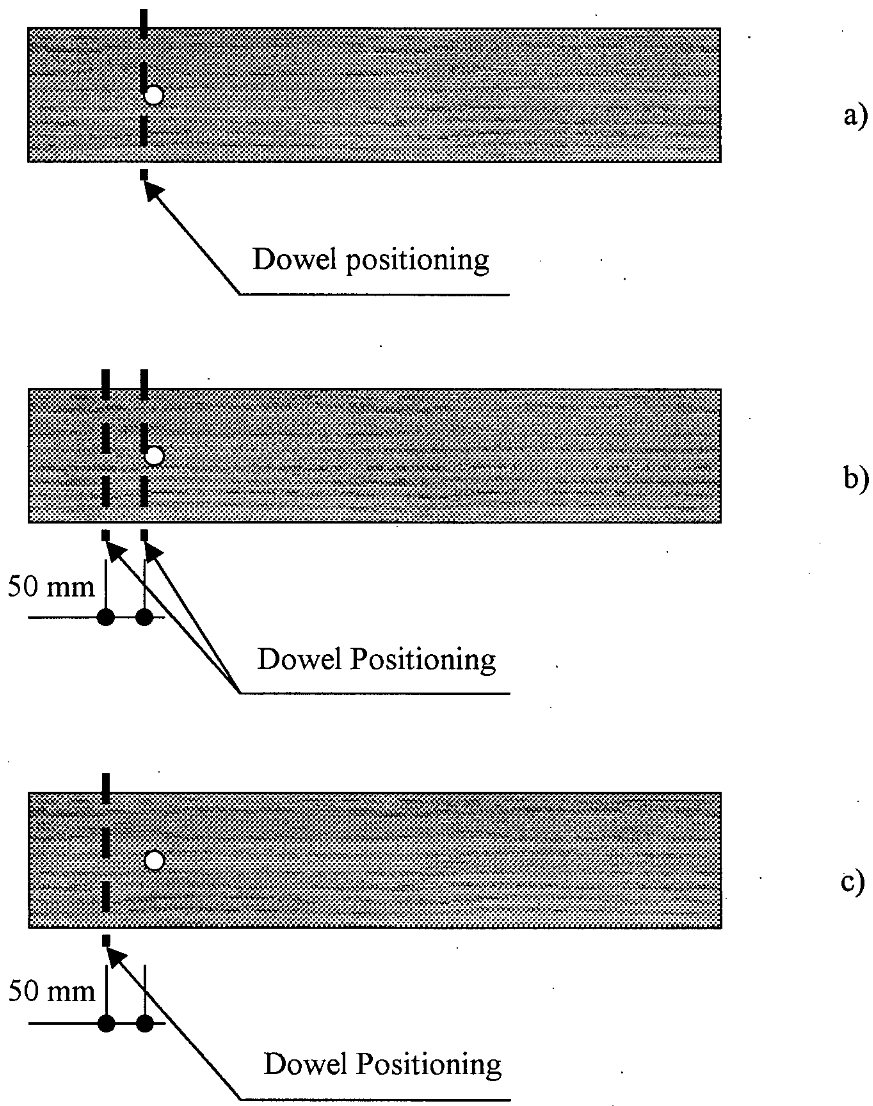


Fig.2.5.: Reinforcement Dowel Positions

Each of these beams was cut into small specimens, 13 being 400 mm length, 150 mm wide and 38 mm thick, and 66 being 500 mm length, 90 mm wide and 38 mm thick. The remainder of the material was used to perform tension tests parallel and perpendicular to the grain. The resulting force-displacement curves are presented in Appendix A.

After cutting the specimens, holes for the bolts which connect the specimen to the testing machine (three, in a triangular distribution) at one end, and for the bushings at the other end (one, with variable position and size) were drilled. The drilling was done using steel templates, for maximum precision in positioning.

The bushings were made one by one, using steel pipes purchased from a local tube supplier, and liquid polyurethane, obtained from a local vibration absorber supplier. Only one quality of polyurethane was used for all the bushings namely Flexan 94, the characteristics of which are given in Appendix A. The bushings were made using a casting form in order to obtain a good precision of the shape. The polyurethane in each bushing achieved the full mechanical characteristics after a seven days curing period. For the bushings made with reinforced polyurethane, a steel mesh was used, with the properties given in Appendix A.

The polyurethane cylinders were made by pouring the rubber mixture into a plastic tubing, which acted as a form. After curing, the pipe was cut in three parts of equal length, the form was broken and the polyurethane cylinders were obtained.

To test the small bushing behaviour under calibrated cyclic loading, it was necessary to make a steel specimen, 38 x 60 x 400 mm, with a hole of 16 mm (5/8 in) at one end and 30 mm, to permit the bushing placement, at the other end. This was done to maintain the same test layout on the MTS machine.

2.3. INSTRUMENTATION

2.3.1. Test Type A1

The two specimens which were tested for creep under 'long term' loading, were instrumented with a dial gauge, located at the bottom end of the suspended member, as seen in Fig.2.6. The dial gauge measured the long term displacement of the free end of the specimen, due to the creep of the bushing elasto-plastic material. The data acquisition was done by reading the gauge once an hour during the first day, then at least once a day for a period of two weeks, at which point the creep had stabilized.

2.3.2. Test Type A2, A3, A4, B, C

All the traction and cyclic tests were done in a MTS universal testing machine with three data controllers (Figure 2.7.). The first two controllers of the MTS machine kept track of the load signal and of the actuator stroke signal and provided feedback control of the machine. As a characteristic for all the tests done on the MTS machine, each of them was instrumented with one LVDT (Linear Variable Differential Transformer) connected to the third controller, to accurately measure the local connection displacement. The load signal was obtained from the load cell placed on the test frame's hydraulic ram. The instrumentation for these tests is presented in Fig. 2.8.

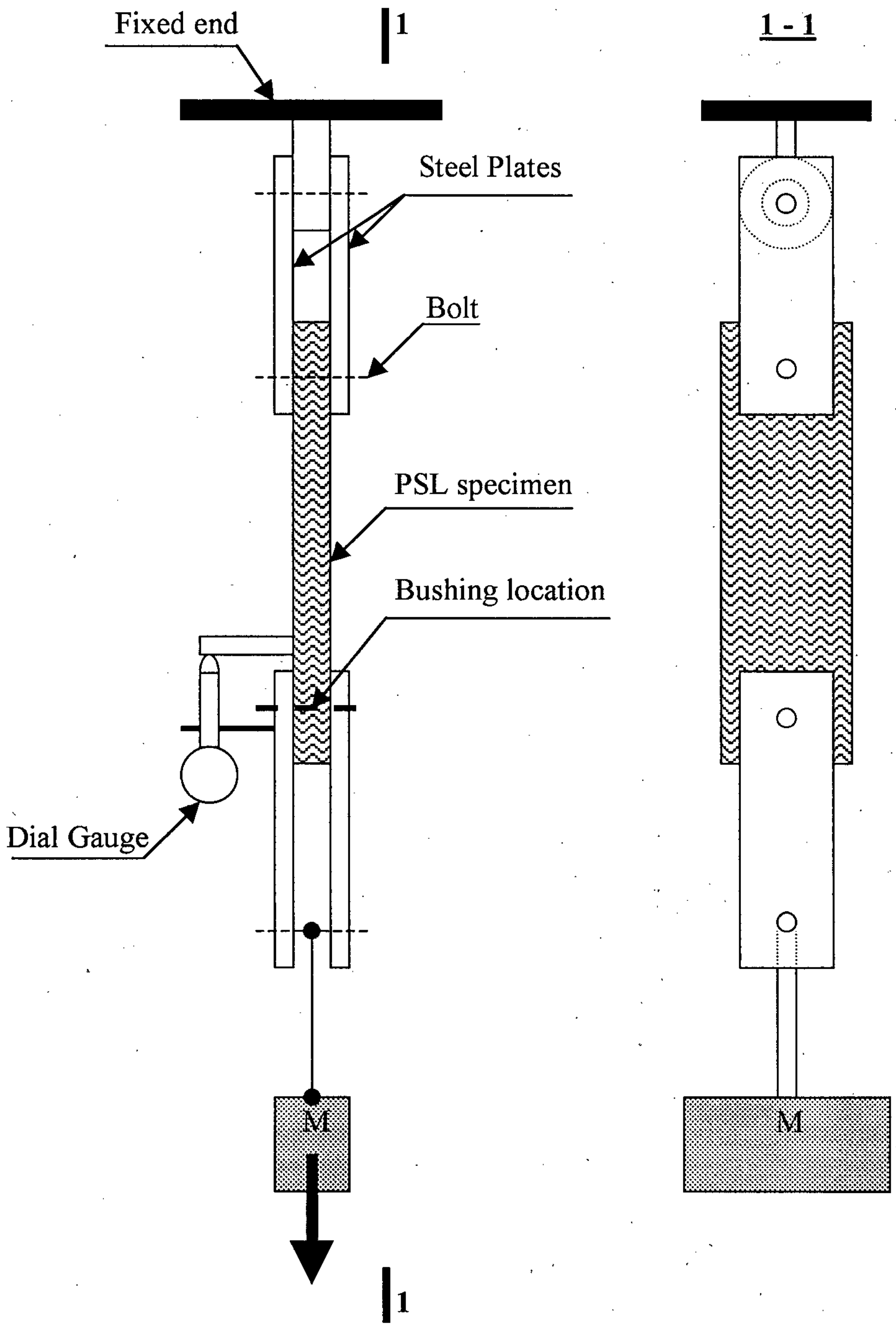


Fig 2.6.: Type A1- Test Layout and Instrumentation

2.4. LOAD APPLICATION

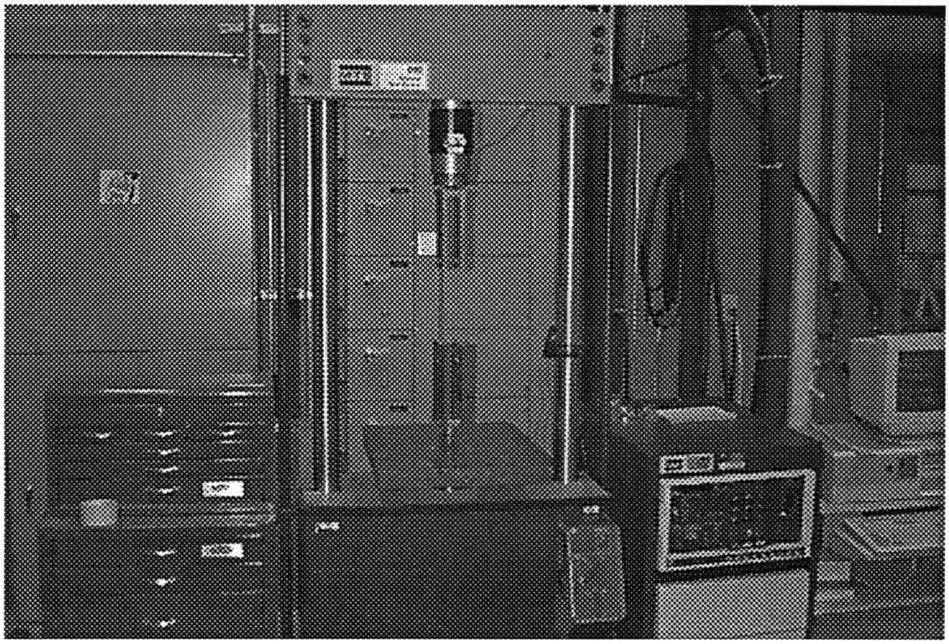
2.4.1 Test Type A1

The axial load for the long term tests was applied as a gravitational load and was applied using a cable suspended weight. The layout for this test type is presented in Fig.2.6. For the first test in this category, the weights were hooked up using the crane. As the data acquisition could begin only after the full load was in place and the specimen was perfectly vertical, the initial elastic deformation could not be obtained. For the second test, the load was applied from beneath, using a hydraulic hoist, so the initial elastic deformation could be read on the dial gauge.

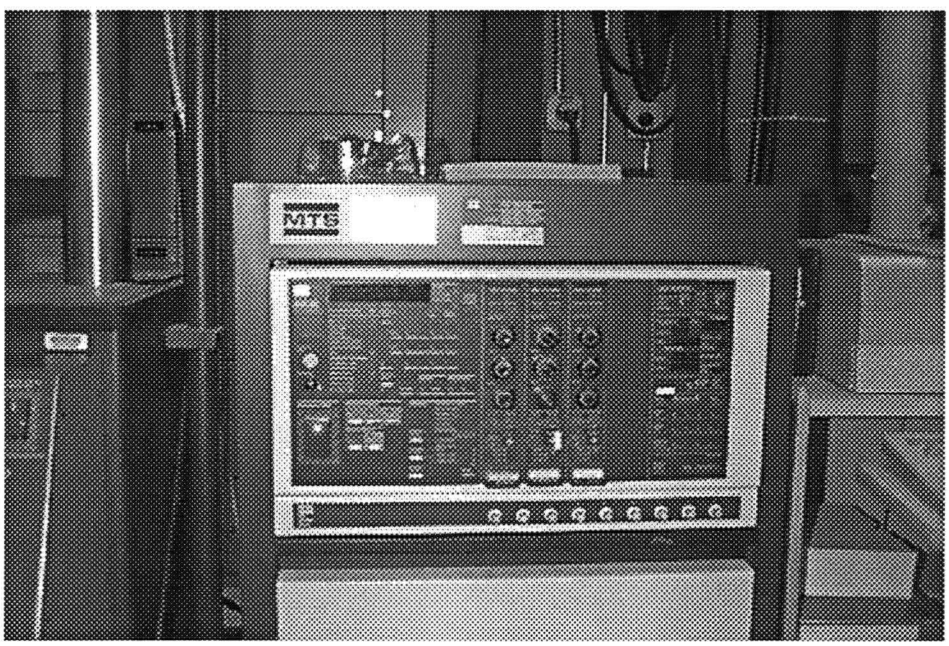
2.4.2. Test Type A2, A3, A4, B, C

The axial load was applied on all the specimens under displacement control, using the MTS universal testing machine in the Wood Products Laboratory at the University of British Columbia. A devise made of gusset plates with a three 16 mm (5/8 in) hole pattern was fixed with threaded studs to the fixed frame of the MTS, and another one having one 12 mm hole (1/2 in) was fixed to the mobile table of the MTS. The specimens were attached to the gusset plates with proper bolts. The templates used in preparing the specimens provided a perfect match of the holes, thereby assuring uniaxial loading of the specimens.

The loading protocol for the traction tests was driven by a desktop computer program developed at the University of British Columbia. For the cyclic tests, the loading protocol was programmed in the MTS machine and the computer was used only for recording the test data.



a)



b)

Fig. 2.7.: a) Type A2, A3, A4, B, C - Test layout; b) Controllers Unit

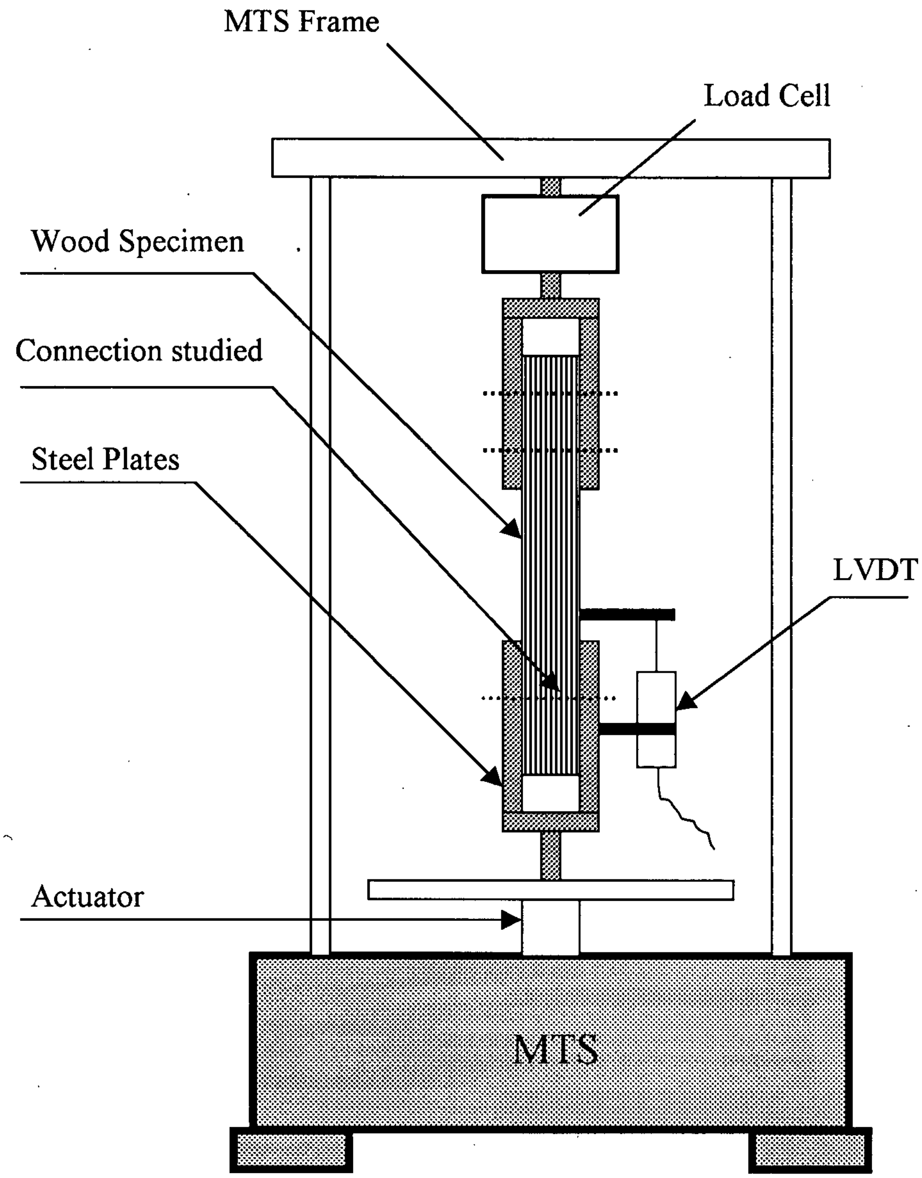


Fig. 2.8.: Type A2, A3, A4, B, C – Test Instrumentation

2.5. DATA ACQUISITION

Data were recorded using an automatic acquisition system which was driven by a desktop computer (IBM-PC). The loading procedure continued without interruption while data were being recorded. The data scanning rate for each set of readings was about 10 readings per second. As the loading rate was not very fast, for all practical purposes readings could be regarded as being instantaneous.

3. EXPERIMENTAL BEHAVIOUR AND RESULTS

3.1. GENERAL

In this chapter, the test results are presented and noticeable trends are discussed. The abridged versions of the test data sets of specimen behaviour can be found in Appendix B where the data sets were plotted for each specimen and test type.

3.2. MATERIAL PROPERTIES

3.2.1. Parallam® PSL

In order to verify the allowable design stresses published by the manufacturer (see Appendix A) and to obtain information about the specific failure modes, two tensile coupon tests were performed on Parallam® PSL for loading parallel to grain and one for loading perpendicular to the grain using a MTS universal testing machine equipped with tensile grips. The coupons were cut from the remaining material obtained after manufacturing the connection specimens. The cross sectional dimensions (15 x 25 mm) were dictated by the grip capacity of the MTS machine. For the coupons tested in traction parallel to the grain, the length was chosen equal to the specimens in the experimental program, namely 500 mm. For the coupon tested in traction perpendicular to the grain, the length was dictated by the maximum height of the PSL beam: 300 mm. The tests can at best be considered informative due to the high sectional defect rate of the Parallam® PSL material which is obtained whenever the sectional dimensions are small. The traction parallel to the grain results are shown in Appendix A. For both coupons tested, there is a nonlinear region of behaviour at the beginning of the test which is due to the initial slip in the grip of the MTS machine. The failure mode was brittle in both cases, although somewhat different for each. The first case showed visible degradation of the stiffness before fracture, the second had a brittle partial fracture, after which the load increased again until general failure. For both tests the maximum load obtained (11kN and 15 kN) was significantly higher than the design load (7.5 kN). The perpendicular to the grain test was characterized by brittle fracture and high non-linearity. The fracture for this coupon happened at a lower load value (0.42 kN) than the design load (1.2 kN). The results of the perpendicular to grain test are presented in Appendix A.

In addition to these tests, density and moisture content tests were performed on a representative number of specimens used in the experimental program. Ten specimens were measured and weighted, then dried 24 hours in the oven and weighted again. The mass density and the moisture content were obtained for each specimen and averaged. The mean mass density was 626.5 kg/m^3 and the mean moisture content was 6.93%. The value of the mean moisture content was lower than the one released by the manufacturer as a production value. The individual results for these tests are presented in Appendix A.

3.2.2. Polyurethane

To obtain information on the energy dissipation capacity of the polyurethane material which was used in the bushings, three cylindrical specimens were fabricated and tested. The cylinders, 45 mm in diameter and 85 mm in length, were made by pouring the liquid mixture into a polyethylene pipe mould.

Before establishing the cyclic behaviour and energy dissipation for the material used, one specimen was tested under compression and the load-displacement curve was obtained (see Appendix A). The remaining two specimens were subjected to cyclic compression loading and the load-displacement curves were obtained (Appendix B – Test Type A3[b]). The results showed good dissipation characteristics and behavioural uniformity.

To obtain information on the energy dissipation and load-deflection behaviour of the small polyurethane bushings, three specimens were tested. The bushings specimens were installed in a thick steel plate and tested to obtain the bushing behaviour only.

One of the bushings was tested in tension and the load-displacement curve was obtained (see Appendix A), then the other two bushings were tested under cyclic loading (Appendix B – Test Type A3[c]). The cyclic test curves showed also good uniformity in behaviour and good energy dissipation characteristics. Due to the fabrication tolerances, a small amount of slack in the connection resulted in a horizontal translation at zero load between the traction and compression portions of the curve.

3.3. SPECIMEN BEHAVIOUR

3.3.1. Pilot Tests (Type A)

3.3.1.1. Test Type A1 – Creep Testing

These tests provided preliminary information about the long term loading behaviour of the small bushing connection and about the effect of the wire mesh reinforcing on the creep behaviour of the polyurethane. The behaviour of both specimens is characterized by a nonlinear creep rate in the first 100 hours of loading followed by a stabilized plateau. The creep rate for the reinforced bushing was slightly smaller than for the unreinforced bushing, due to the wire mesh confinement of the polyurethane.

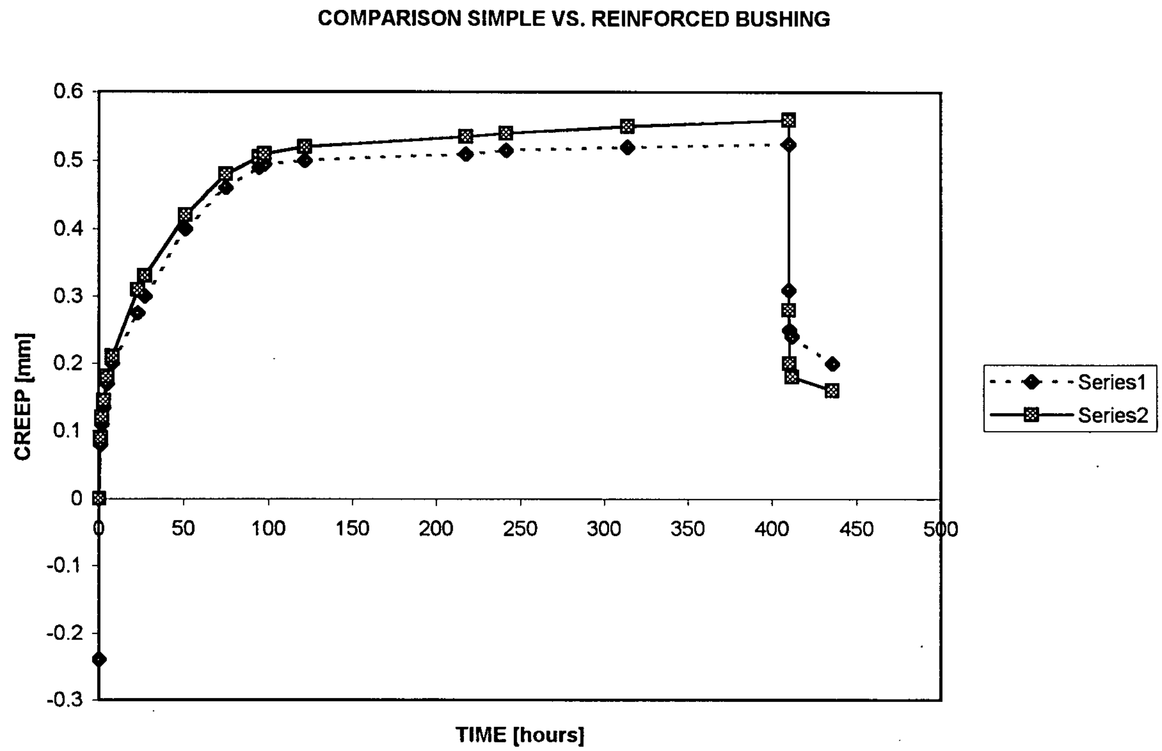


Fig. 3.1.: Comparison Simple vs. Reinforced Bushing under Long Term Loading

This was also confirmed during the unloading phase. The comparison of the values is shown in Figure 3.1. In the Figure, series 1 represent the reinforced bushing behaviour and series 2 represent simple bushing behaviour. The total creep displacement over a two week loading period was less than 0.6 mm although was still increasing slowly and linearly with time.

3.3.1.2. Test Type A2 - Pure Tension

This test series provided information about the influence of the position, size and material used for the bushing on the strength and failure mode of the connection.

As far as the positioning is concerned, the test results showed a significant variability in the polyurethane behaviour due to the difficulty in controlling the homogeneity of the liquid mixture in the manual process of manufacturing the bushings. Nevertheless the optimal end distance seemed to be in agreement with the code prescribed value of ten times the bolt diameter (120 mm). The wood behaviour at ultimate was characterized by brittle fracture due to splitting. The results of these tests are presented in Appendix B (Test A2[a]) and the failure mode is presented in the photo section abridged in the same Appendix.

The next phase of the pilot testing provided information about the behaviour of the connection made with aluminum bushings. As these bushings would not allow the same amount of stress redistribution, a bigger diameter was chosen to compensate for this. The results showed similar values of strength as obtained for the small polyurethane bushings. The failure of the connections was brittle, due to multiple splitting of the wood element (double split pattern). The difference was in the maximum displacement which did not exceed 3.5 mm in this case compared to an average of 8 mm obtained for the polyurethane bushings. Also, when the bushing was positioned at 84 mm (7 d) from the bolt axis to the member end, the load-displacement curve shows that some cracking occurred in the specimen before general failure. The results are presented in Appendix B – Test Type A2 [b].

In the third phase of the pilot test, some information was obtained about the influence of the size and the reinforcement of the bushings. A good correlation of results was observed between small bushings and small reinforced bushings where the pattern of behaviour was similar between the two cases; however, a slightly higher displacement was obtained for the reinforced bushing for the same load step. In the case of the big bushing series, the variability in the polyurethane behaviour was significant; the failure was brittle and reached about 50% of the strength of the small bushing connection. The behaviour of the reinforced polyurethane bushing was significantly better. All the big bushing connections failed in a brittle manner, by wood multiple splitting. The results of all the connection with 120 mm end distance are shown in Fig.3.2.

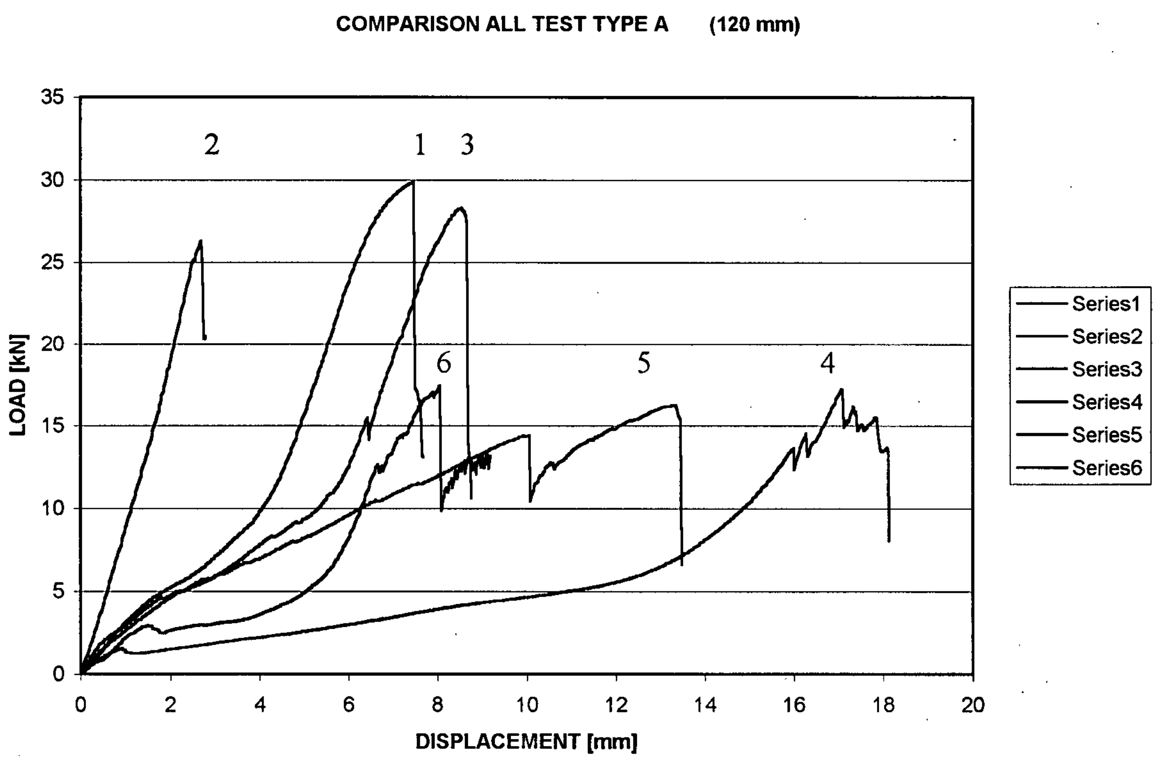


Fig. 3.2.: Comparison between Connection Types with 120 mm End Distance

In Fig. 3.2 Series 1 represent the behaviour of the small bushing connection, Series 2 the behaviour of the aluminum bushing, Series 3 the behaviour of the reinforced small bushing, Series 4 the behaviour of the big normal bushing, Series 5 the behaviour of the big reinforced bushing and Series 6 the behaviour of the big bushing with thick internal pipe. The data for these tests is also shown in Appendix B.

3.3.1.3. Test Type A3 – Cyclic Loading

This test series provided information on the energy dissipation capacity of the polyurethane material and the connection. The results of these tests are shown in Appendix B. In general it can be seen that under cyclic loading there was a moderate amount of energy dissipation. The material degraded relatively soon and after a few cycles there was significant slack in the connection when the displacement was reversed.

When the polyurethane cylinders were subjected to cyclic compression loading, good energy dissipation characteristics were evident with significant plastic displacement. Between the two tests there was less variability compared to the bushing tests, which can be attributed to better homogeneity of the material in the manufacturing process.

3.3.1.4. Test Type A4 – Reinforced Wood Pure Traction

As a result of the preliminary tests, the big bushings were eliminated from subsequent test series. The prevalence of brittle failure patterns also reiterated the necessity of reinforcement of the wood members to avoid premature splitting. Several reinforcement patterns using threaded dowels were used with positive results. Reinforcement with one dowel, situated immediately beneath the bolt, which acted as a direct support for the bolt, showed a significant increase in the strength and ductility for the simple bolt connections. The strength increase was about 80% and the failure pattern was semi-brittle. In the case of the small bushing connection, there was no significant increase in strength, but the overall behaviour was more ductile. When the reinforcement was done with two dowels, the improvement in the strength was more significant – 90% for simple bolt connections and 40% for bushing connections. The ductility improved in the simple bolt connections, but not for the bushing connection, where the brittle fracture pattern still prevailed. When the reinforcement was done with one dowel at 50 mm from the bolt axis, there was a very small increase in strength for both the simple bolt and bushing connections. In terms of ductility, the simple bolt connection behaved well, while the bushing connection still experienced splitting which led to a brittle failure. The results of all these tests are shown in Appendix B – Test Type A4.

3.3.2. Tension Tests (Type B)

3.3.2.1. Test Type B1 – Simple Bolt

The pattern of failure observed showed significant crushing of the wood beneath the bolt before splitting for most of the specimens. A high variability was also observed in the maximum displacement and therefore, the displacement ductility. Although two specimens had a significantly lower stiffness than the others, the maximum load value was relatively consistent for all the specimen tested, with an average of 24 kN. The failure generally occurred by splitting along glue lines in the wood member. Although most specimens showed significant plastic deformations before failure of the wood by splitting, one specimen failed soon after reaching the maximum load. This premature failure seemed to have been related to the presence of defective areas in the Parallam® PSL element. The experimental data are plotted in Appendix B for each of the ten specimens. Figure 3.3 shows all the tests while the average loading curve for this test type is presented in Figure 3.4..

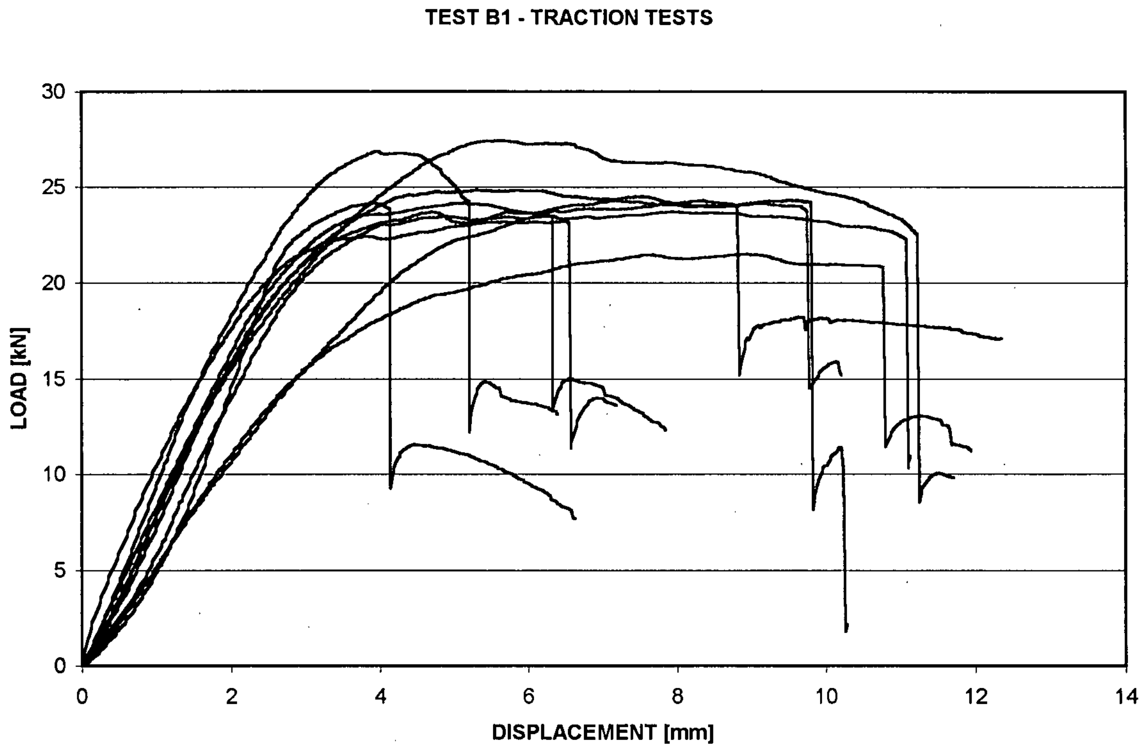


Fig.3.3.: Load-Displacement Curves for Simple Bolt Connection Tension Tests (Series B1)

The mean load-displacement curve (Figure 3.4.) is characterized by several steps, due to the different ultimate displacement cut-off values. Since the ultimate displacement from monotonic test results is required to establish the cyclic test protocol amplitude, it was important to establish a reasonable means to determine the post-ultimate behaviour. It was therefore decided to calculate the mean value of the ultimate displacement by using two different methods. The first method is by averaging the ultimate displacement values as obtained for every specimen individually. The second method is by using the average curve in Fig.3.4 and determine the ultimate displacement as outlined in Appendix A (Cyclic Loading Protocol). The two values for δ_u are presented in Table 3.1.

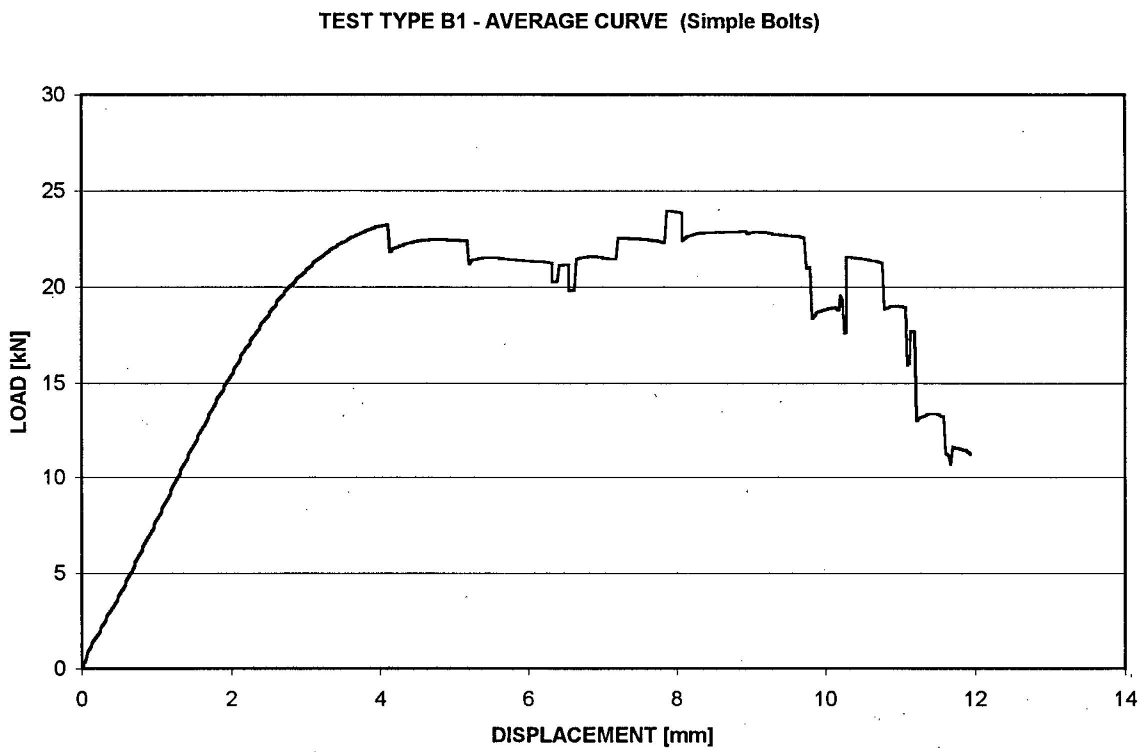


Fig.3.4.: Averaged Load – Displacement Curve for Simple Bolt Connections (Series B1)

δ_u (obtained by averaging the individual values)	δ_u (obtained using the average curve)
8.47 mm	**9.90 mm**

Table 3.1.: Calculated Ultimate Displacement Values for Simple Bolt Connection (Series B1)

Because of the discontinuities in the averaged load-displacement curve and the difficulty to clearly establish the "ultimate" point on the curve, it was decided to use for the cyclic tests the value obtained by averaging the individual values, as it better reflects the average behaviour of the specimens.

3.3.2.2. Test Type B2 – Small Bushings

The general behaviour observed for the tension tests of the simple small bushing connections can be characterized as brittle fracture at a higher load level than the simple bolt connections. Due to the inherent variability in material homogeneity, for both the bushing polyurethane and the wood element in the connection area, the behaviour of the simple small bushing connection showed a significant variation of stiffness between specimens.

Also noticeable is a significant increase in the maximum load resistance for most of specimens (about 25%), which can be attributed to better distribution of stresses along the edge of the bushing. A few specimens, however, did not fare as well, both in stiffness and strength, which might have been due to a high incidence of internal defects in the Parallam® PSL element in the connection area.

Failures occurred generally by splitting along the glued lines in the wood elements, which constituted a brittle fracture. The maximum displacement level was comparable to the one obtained using simple bolts for the connection, so there was no significant increase in displacement ductility. The variability of this parameter was much lower, however, so the usage of the bushings resulted in a higher uniformity in the ultimate displacement.

The experimental data are plotted in Appendix B for each of the ten specimens tested. Figure 3.5 presents all the tests, and Fig. 3.6 presents the averaged curve for this test type.

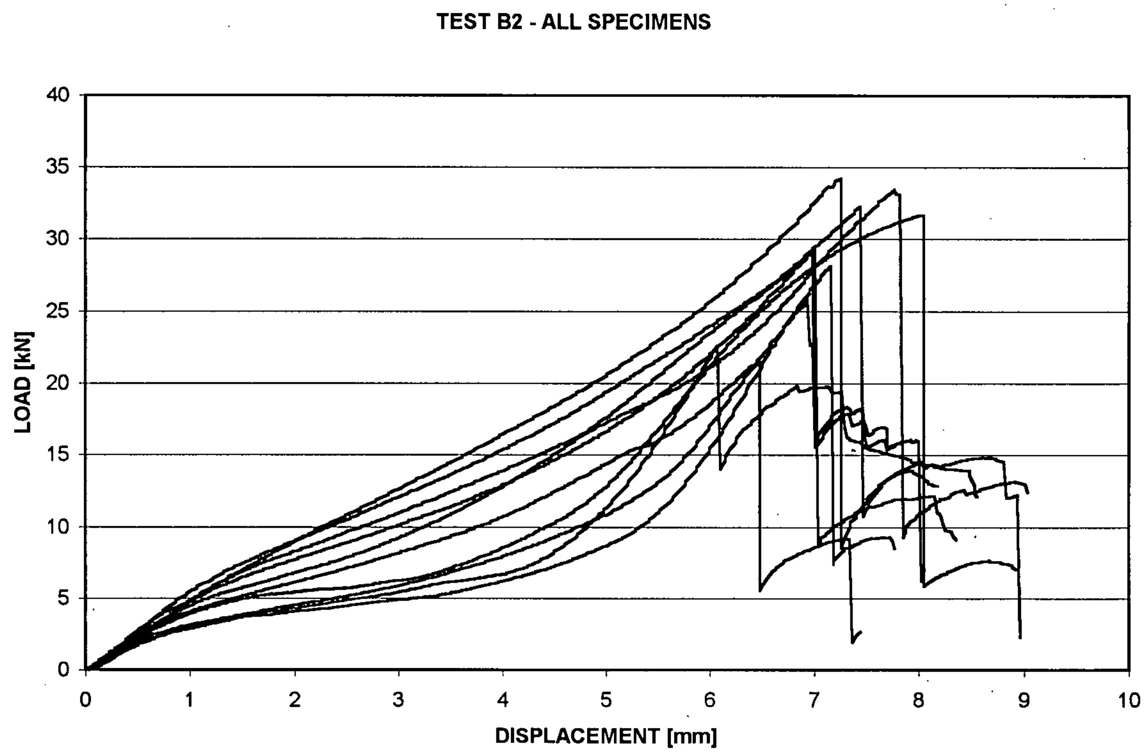


Fig. 3.5.: Load-Displacement Curves for Simple Bushing Connection Tension Tests (Series B2)

The mean load-displacement curve presented in Fig.3.6 is more uniform than the one obtained for the simple bolt connection, due to the higher uniformity of the ultimate displacements. The mean ultimate displacement is computed as for the previous test type, using two methods: the first, by averaging the individual values of the ultimate displacement obtained for each of specimens tested; the second, by using the average curve in Fig. 3.6. The values are virtually identical for both methods, as presented in Table 3.2.

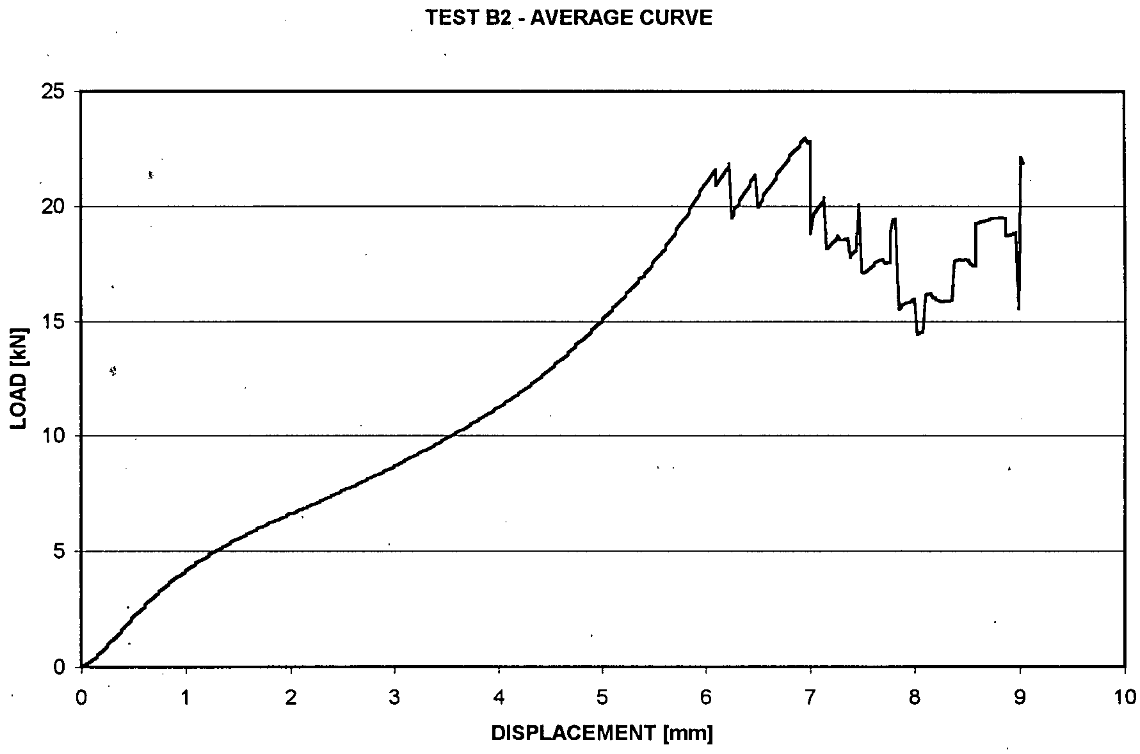


Fig. 3.6.: Averaged Load – Displacement Curve for Simple Bushing Connections (Series B2)

δ_u (obtained by averaging the individual values)	δ_u (obtained using the average curve)
7.17 mm	7.16 mm

Table 3.2.: Calculated Ultimate Displacement Values for Simple Bushing Connection (Series B2)

The value obtained by averaging the individual values will be used further for the cyclic testing.

3.3.2.3. Test Type B3 –Bolt Connections Reinforced With Dowels

The behaviour of these connections showed a good uniformity both in the maximum load resistance and the ultimate displacement. Whereas the failure in the case of simple bolts occurred by splitting along the glued lines, this was essentially prevented by the threaded rods situated at 50 mm from the bolt axis. The pattern of the failure for this series showed extensive crushing of the wood resulting in a good displacement ductility. As the ultimate displacement is defined as the lower of either 25 mm or the displacement at 80% of the maximum load, all the traction tests were terminated after reaching a 25 mm displacement. At this point all specimens showed a drop of more of 30% in the load resistance.

The experimental data are plotted individually in Appendix B for all the specimens tested. In Figure 3.7 a summary of all the tests is presented, while Figure 3.8 shows the average loading curve.

In comparison with test series B1 and B2, the average load-displacement curve (Figure 3.8) is very smooth, which is due to the high consistency of the results.

The ultimate displacement values were computed using the methods described earlier, and the mean values obtained are presented in Table 3.3. Again, the average value as computed from individual curves, was used for the cyclic protocol.

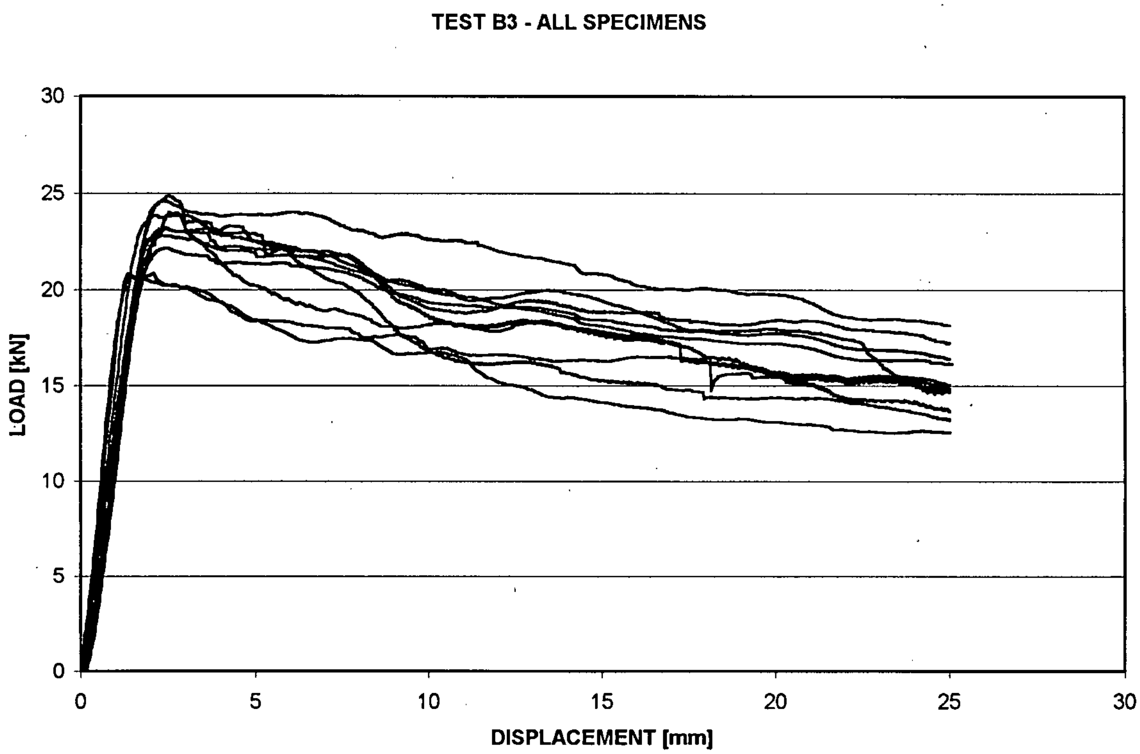


Fig.3.7.: Load-Displacement Curves for Bolt with Dowel Connection Tension Tests

(Series B3)

δ_u (obtained by averaging the individual values)	δ_u (obtained using the average curve)
13.24 mm	15.84 mm

Table 3.3.: Calculated Ultimate Displacement Values for Bolt with Dowel Connection

(Series B3)

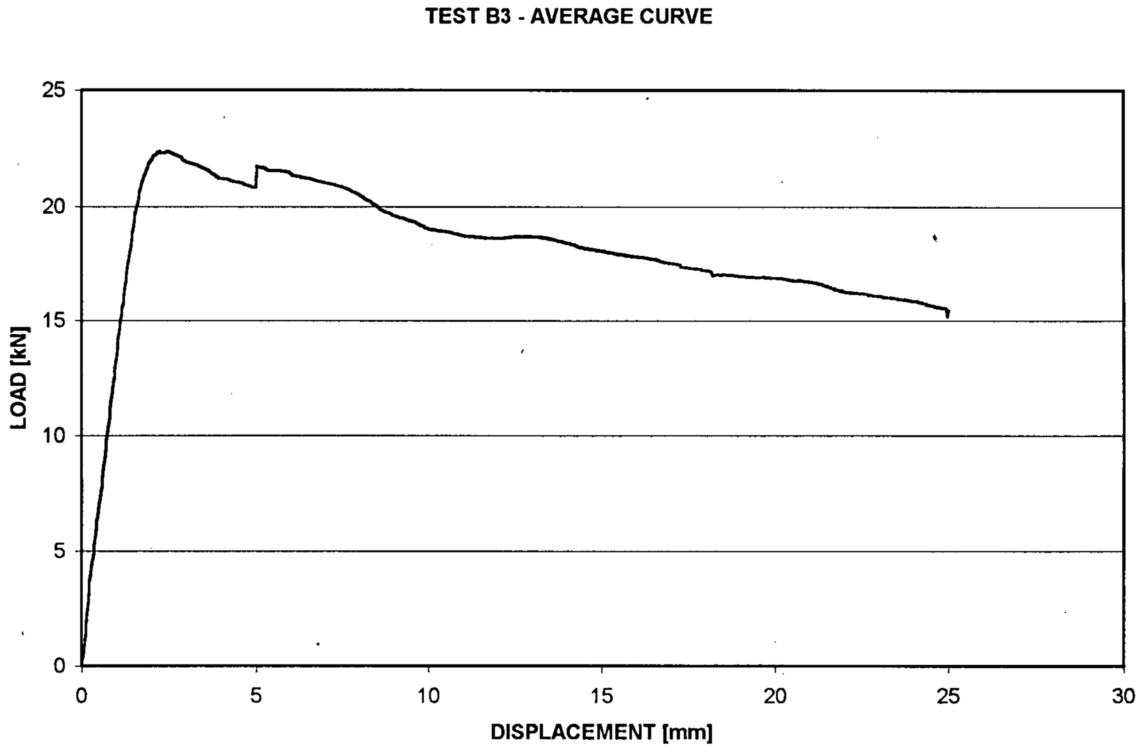


Fig. 3.8.: Averaged Load-Displacement Curve for Bolt with Dowel Connection

(Series B3)

3.3.2.4. Test Type B4 – Bushing Connections Reinforced With Dowels

The fracture pattern for this test series indicated that the presence of the threaded rod was not very efficient in restraining the splitting of the wood. The failure showed a certain improvement compared to the one observed in case of simple bushing connections but still had brittle characteristics. A significant variation in the behaviour was observed, in both the maximum load resistance and in the ultimate displacement. The initial elastic phase is also characterized by significant variability, which may be attributed to the existence of defects in the wood and air inclusions in the polyurethane.

Fracture of the specimens occurred by wood element splitting, which precipitated a sudden decrease in load resistance. The overall behaviour was very similar to the simple bushings without any reinforcement. The only significant difference was the higher consistency in post fracture behaviour.

The experimental data are plotted in Appendix B for each of the ten specimens tested. In Figure 3.9 all the tests are presented, while Figure 3.10 presents the average load-displacement curve for this test type. The ultimate displacement were calculated as before and is shown in Table 3.4.

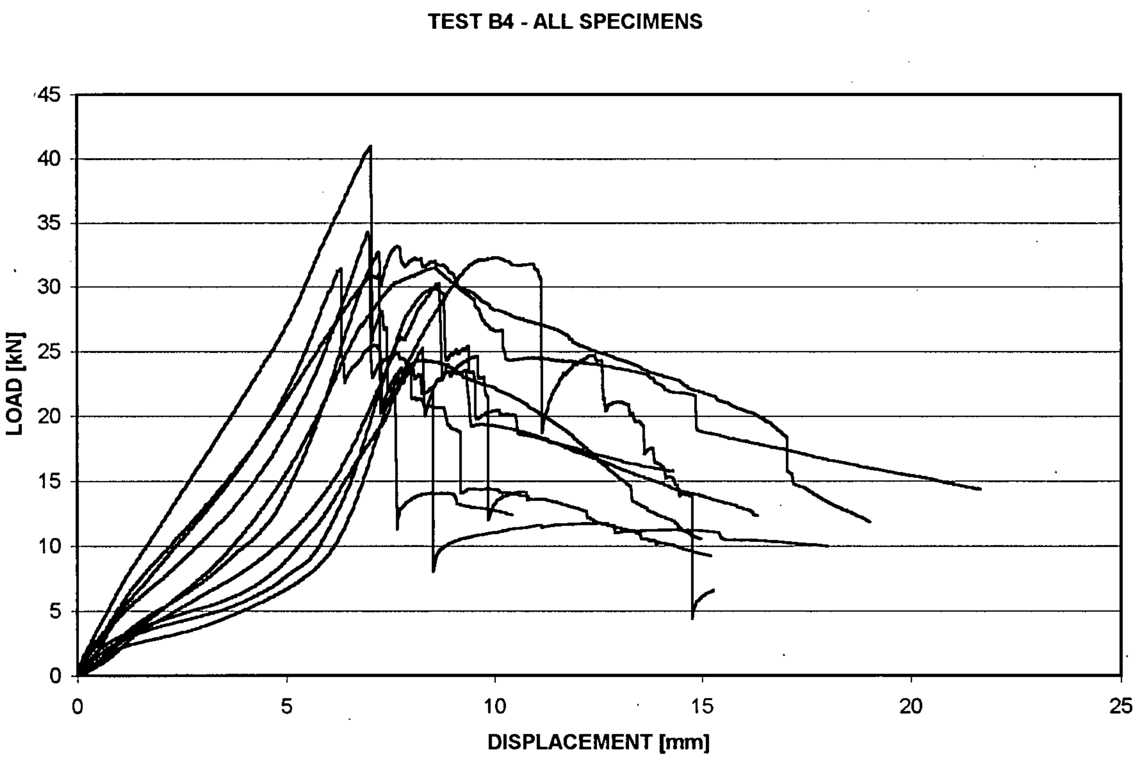


Fig. 3.9.: Load-Deformation Curves for Tension Tests of Bushing Connections with Dowel Reinforcement (Series B4)

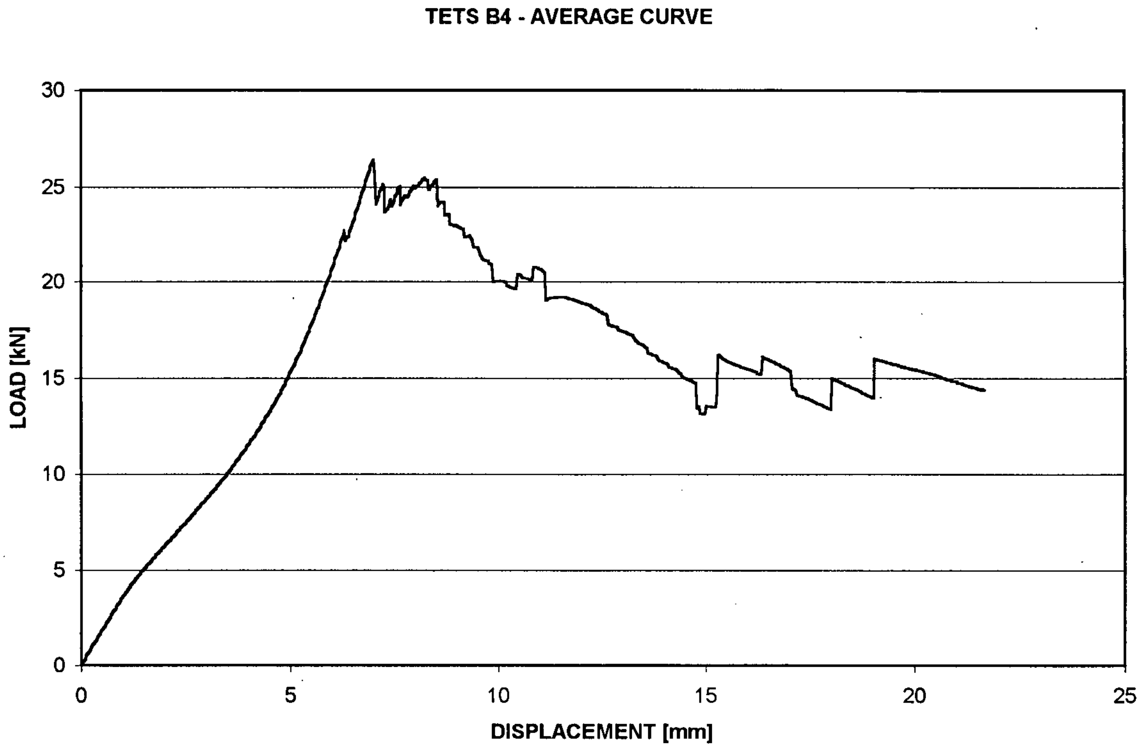


Fig. 3.10.: Averaged Load-Displacement Curve for Bushing Connections with Dowel Reinforcement (Series B4)

δ_u **(obtained by averaging the individual values)**	δ_u **(obtained using the average curve)**
8.71 mm	**9.88 mm**

Table 3.4.: Calculated Ultimate Displacement Values for Bushing Connections with Dowel Reinforcement (Series B4)

3.3.3. Cyclic Loading Tests (Type C)

3.3.3.1. Test Type C1 – Simple Bolt

The results were characterized by good behavioural uniformity, but a relatively fast degradation of the connections under cyclic loading. One of the specimens (specimen no.2) showed a better ductile behaviour, with a lower rate of resistance degradation. All the other specimens tested were characterized by a brittle fracture between 25 and 50% of the maximum displacement, resulting in a high rate of resistance degradation. For cycles with the same amplitude, a significant stiffness degradation occurred after the first cycle.

The values of the load obtained in the compression cycles were very close to the ones obtained in the tension cycles, which implies that the end distance was adequate. The behavioural pattern in the compression domain showed a slower degradation rate than in the tension domain, which can be attributed to the higher transverse strength of the PSL Parallam® element.

Also due to the fabrication tolerances (see Appendix A) the transfer between compression and tension in all the curves was accomplished through a nonlinear central zone.

3.3.3.2. Test Type C2– Simple Bushing

These tests were characterized by better uniformity in energy dissipation in each series of cycles (stiffness degradation after the first cycle in each series is not as high as for the simple bolt connections). There were, however, significant differences between the compression cycles and the tension ones: the compression cycles were characterized by ductile behaviour, while the tension cycles showed brittle fractures with fast resistance degradation. There was also a significant difference in maximum load capacity in compression and in tension, which showed that the connection might have been positioned too close to the end of the wood specimen.

These tests were also characterized by an important compression-tension transfer nonlinear zone due to the high fabrication tolerances (see Appendix A).

After brittle fractures occurred in the tension cycle, the load capacity was significantly diminished and the elements failed. One of the specimens (specimen 3) showed a good ductility in both tension and compression as the brittle tensile fracture did not occur.

3.3.3.3. Test Type C3 – Bolt Connections Reinforced With Dowels

These connections were characterized by high behavioural uniformity and good overall ductility. The load values and the curve symmetry showed a good positioning for the connection and dowels (no significant differences between compression and tension cycles).

The presence of the transverse reinforcement (threaded dowels) both sides of the bolt, at 50 mm centre to centre, was beneficial, as brittle fracture did not occur. In addition, each time the direction of loading changed, there was significant friction between the bolt and the hole walls which improved the energy dissipation.

Some negative characteristics were still present, such as rapid stiffness degradation after the first cycle, for cycles having the same amplitude. Also the nonlinear transfer between compression and tension, due to fabrication tolerances, was maintained. The tolerances were similar to the ones for the simple bolt connections.

3.3.3.4. Test Type C4 – Bushing Connections Reinforced With Dowels

This test type was characterized by a better ductility compared to the bushing unreinforced connection, since the premature fracture was prevented by the dowel reinforcement. There was still a difference between the load level in tension and compression, which suggest that the position of the bushing should be further from the end of the wood member.

In tension there was a certain improvement compared to the simple bushing tests, but the brittle fracture could not be avoided. Due to the dowel, the degradation of stiffness after the fracture was smaller than the one present in the tests of simple bushing without dowel.

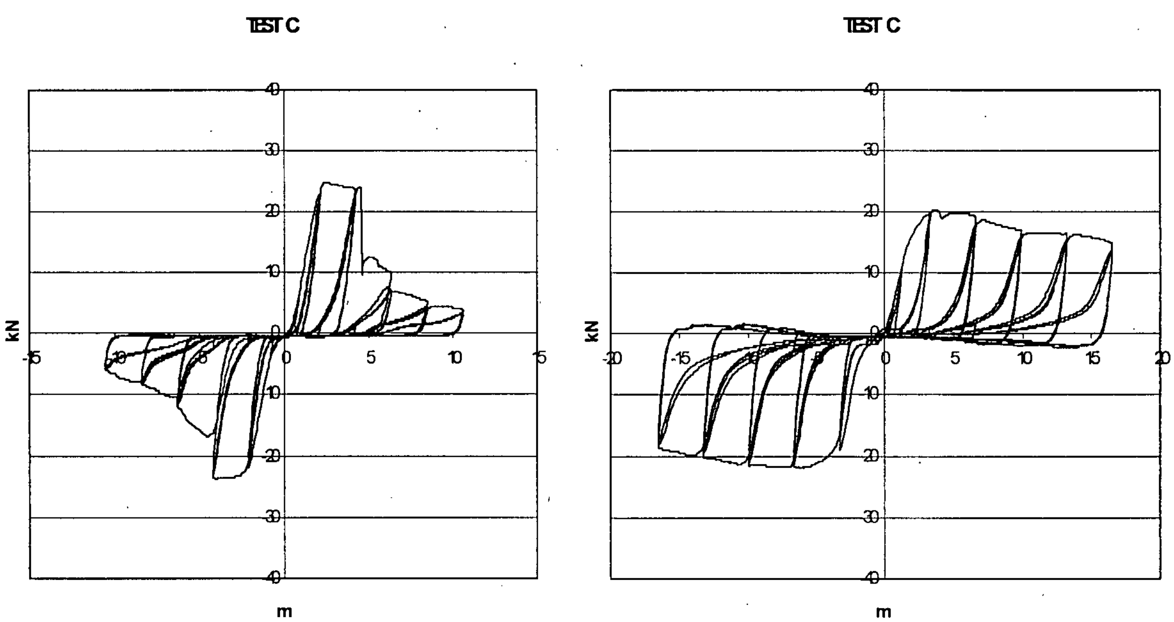


Fig. 3.11.: Cyclic Load-Deformation Curves for Simple Bolt and Simple Bolt Reinforced Connections

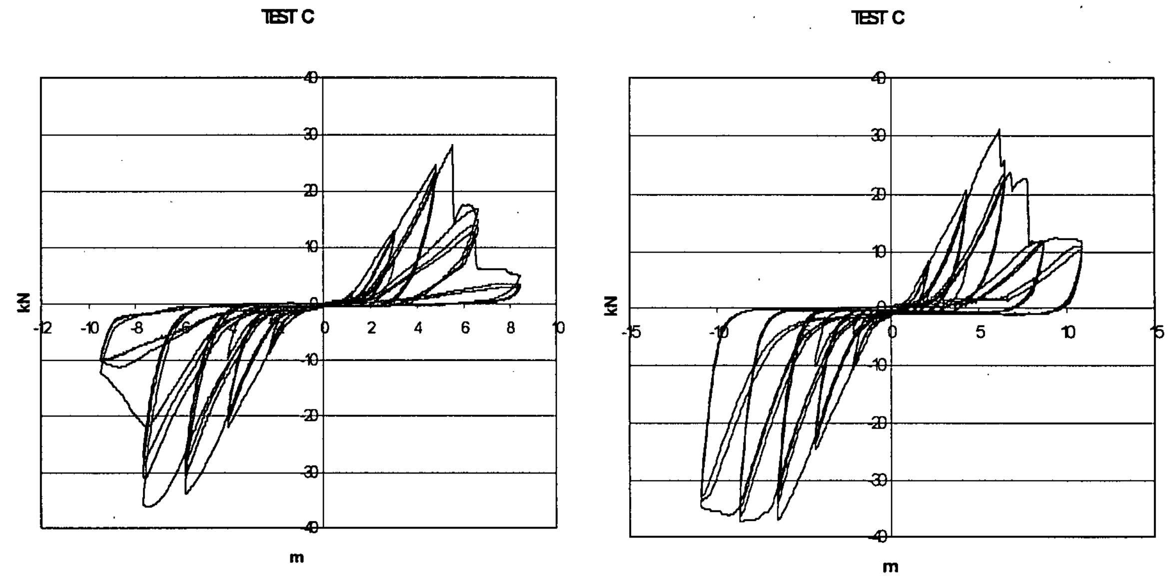


Fig.3.12.: Cyclic Load-Deformation Curves for Simple Bushing and Simple Bushing Reinforced Connections

The energy dissipation was improved in consecutive cycles because of the presence of the bushings. This improvement is characterized by a higher load level than without bushing, and a higher uniformity between cycles of same amplitude.

In Figure 3.11 and 3.12 comparisons between simple and reinforced connections for sample specimens are presented.

3.3.3.5. Energy Dissipation

The energy dissipation rate was plotted for each of the cyclic tests above. The plot was done by calculating the area of each cycle loop and shows the degradation which occurs in consecutive same amplitude cycles. The total number of cycles is 20 as in the cyclic testing protocol used. The energy dissipated in the simple and reinforced bushing connections (series 2 and 4 in Figure 3.13) was higher than in the simple bolt connection. The best dissipation capacity was obtained for reinforced bolted connections.

In Figure 3.13, a comparative view among the energy dissipation capacities for the simple bolt (series 1), simple bushing (series 2), bolt reinforced with dowel (series 3) and bushing reinforced with dowel (series 4) specimens is presented.

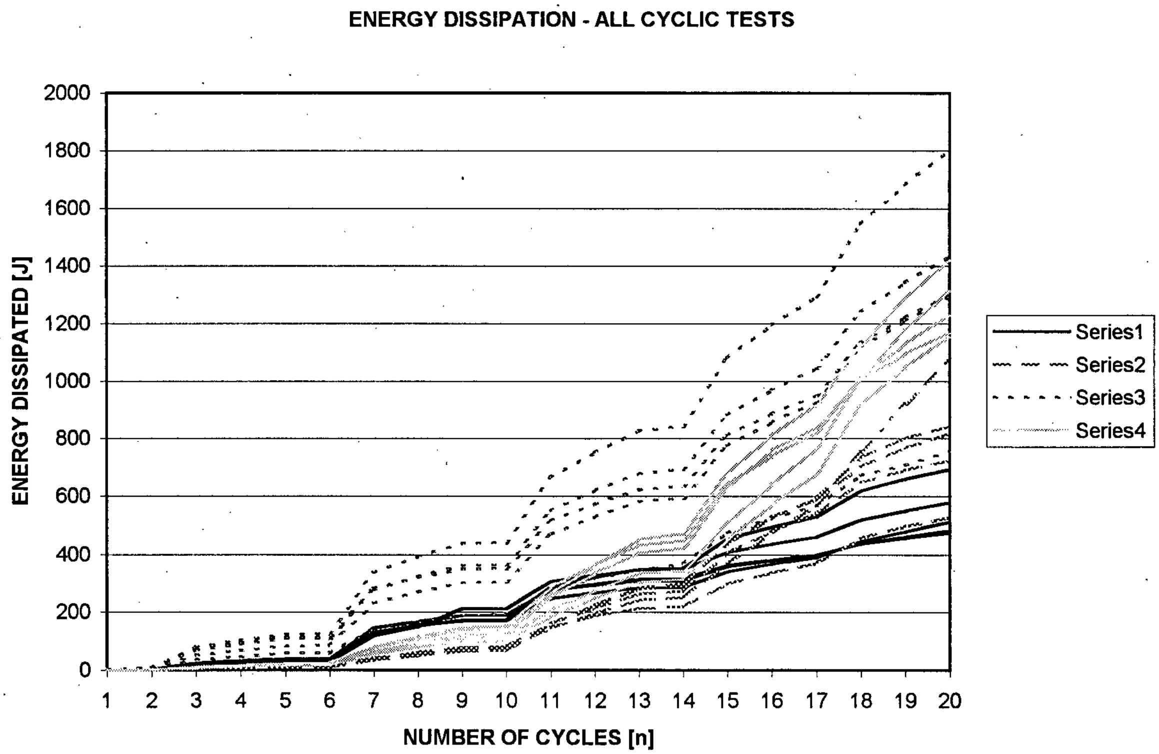


Fig.3.13.: Energy Dissipation Rate – Comparative View of All Tests

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. SUMMARY

The experimental investigation has shown promising results on the use of bushing type connectors and the benefits of reinforcing techniques as it affects the behaviour of the composite structural lumber bolted connections, both under monotonic and cyclic loading.

<u>Material Testing</u>

Tension tests of the Parallam® PSL coupons have shown large variability and brittle failure modes. This was more prevalent for loading perpendicular to the grain. This implies that the sectional dimensions are a very important factor in the overall behaviour of this material. For bigger sections the influence of the defects may be reduced because of a more even distribution of the defects.

Compression tests on the polyurethane material has shown high deformability and a significant plastic component in the total deformation. The material has limited suitability for energy dissipation, and has shown stable hysteresis loops under cyclic compression loading.

<u>Pilot Tests</u>

- There is no significant difference in the behaviour of reinforced and unreinforced bushings under long term loading.
- Larger diameter bushings were found to be less suitable for the proposed connection.

- Cyclic loading on small bushing connections has shown good energy dissipation characteristics, which was, however, accompanied by a high rate of degradation of the bushing material.
- There was significant variability in the behaviour of the polyurethane bushings because of non-homogeneities introduced during the manufacturing process.
- The behaviour of relatively large polyurethane coupons was characterized by good consistency, due to a more even defect distribution.
- Reinforcement of the composite structural lumber material has shown that an increase in strength of up to 90% can be realized when dowel reinforcement were used in contact with the bolt. A significant improvement in terms of ductility occurred when reinforcing dowels were placed 50 mm from the bolt. The brittle mode of failure for the polyurethane bushing connections still prevailed, however.

Tension Tests

- The simple bolt connection tests showed a high variability in the maximum displacement but were relatively consistent in the maximum load level. Failures typically occurred by splitting along glued lines and without much warning.
- The small unreinforced polyurethane bushing connections showed a significant variation in stiffness, which can be attributed to the variability in homogeneity of the material. There was an increase of about 25% of the maximum load resistance compared to the simple bolt connections. The general mode of failure was brittle fracture.
- Tests on simple bolt connections reinforced with dowel showed a high uniformity in the maximum displacement and the maximum load. Splitting of the wood was

restricted, so the failures occurred with significant crushing, which improved the displacement ductility.

- Tests on the small bushings, which were reinforced with a transverse dowel showed an improved behaviour compared with the case without reinforcement. The failure pattern was still of a brittle nature, however. In general, high variability in stiffness, maximum load resistance and maximum displacement were observed.

Cyclic Testing

- The simple bolt connections behaved very consistently and showed a high rate of degradation of the resistance and stiffness under cyclic loading. Because of montage tolerances, a transfer zone of zero resistance existed between the tension and compression zones.
- The simple polyurethane bushing connections showed a better energy dissipation uniformity under cyclic loading. The significant differences between the compression and the tension cycles suggested that additional improvements might be possible if the bushing end distance is increased. The montage tolerances induced a longer transfer zone between the compression and the tension zones, than in the case of simple bolt connections.
- The simple bolt connections reinforced with dowels exhibited very good ductility and uniformity when subjected to cyclic loading. Because the wood compression resistance provided the majority of the load resistance, significant stiffness degradation for consecutive cycles of same amplitude was observed as the bolt hole enlarged.

- The bushing connections reinforced with transverse dowels, showed a better ductility than the ones without reinforcement, under cyclic loading. Again, it can be concluded that improvements might be possible with increased end distances. The compression cycles showed a good ductile behaviour, with reasonable ductility in the tension cycles.

4.2. CONCLUSIONS

From this experimental study several important conclusions can be made about the behaviour of single fastener Parallam® PSL bolted connections, for sizes and proportions as tested:

1. The presence of a polyurethane bushing in a connection results in a significant increase of the maximum load resistance, as it assures a better stress distribution around the connection
2. Small diameter polyurethane bushings behave better than larger diameters.
3. The splitting fracture pattern, which was prevalent in the polyurethane bushing connections cannot be avoided, even using threaded dowel reinforcements for the structural composite lumber.
4. The presence of a polyurethane bushing in the connection results in a higher behavioural variability, due to the non-homogeneity of the bushing material which is a factor of fabrication procedures.
5. The presence of threaded dowel reinforcement has beneficial results on the behaviour of the connections studied, by increasing the maximum load resistance and the ductility.

6. The presence of the bushings improves the energy dissipation during consecutive cycles of loading.
7. For connections with bushings, an increase in end distance is suggested.

The results of the experimental study showed that the presence of an intermediate element between the bolt and the wall holes could result in higher connection strength and ductility. Also, it showed that transverse reinforcement of structural composite lumber is an efficient method to control splitting and improve the connection behaviour.

4.3. RECOMMENDATIONS

Although promising results were achieved, the viability of bushing connections depends largely on the bushing material. It is therefore recommended that different bushing materials be investigated and that bushing fabrication methods be improved. Also materials, which do not create gases in the process of curing, should be tested as bushing material.

To investigate the applicability of polyurethane bushing connections for different materials, tests with other types of structural composite lumber are necessary. Structural composite lumber with lower splitting sensitivity, such as laminated strand lumber (Timberstrand®), could show much more significant improvements in bushing connection behaviour.

As far as the positioning of the bushings is concerned, a study to determine the optimal position for the bushing is needed. If the asymmetry of the cyclic behaviour could be avoided, the energy dissipation could be significantly improved when using a bushing.

Further testing is necessary to investigate other types of reinforcement for the composite lumber around the connection, such as nail plates or fiberglass.

NOMENCLATURE

δ_u	=	Ultimate Displacement
d	=	Bolt Diameter
e	=	End Distance
$F_b^{2.5}$	=	Flexure
F_t	=	Tension Parallel to Grain
F_c	=	Compression Parallel to Grain
$F_{c\perp 1}$	=	Compression perpendicular to Grain, Parallel to wide face strand
$F_{c\perp 2}$	=	Compression Perpendicular to Grain, Perpendicular to Wide Face Strand
F_{V1}	=	Horizontal Shear, Parallel to Wide Face Strand
F_{V2}	=	Horizontal Shear, Perpendicular to Wide Face Strand
MOE	=	Modulus of Elasticity

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APPENDIX A

Appendix A contains material data and coupon test results for composite structural lumber and polyurethane used. Also the polyurethane reinforcement method, the revised (30.06.1997) cyclic protocol and the tolerance measurement are shown.

CONTENTS

A.1. MATERIAL DATA FOR PARALLAM® PSL

Table A.1.: Mass density and moisture content for the Parallam® PSL members

Specimen no.:	Volume x 10^{-3} [m^3]	Mass [kg]	Mass dry [kg]	Mass density [kg/m^3]	Moisture content [%]
1	1.76202	1.0892	1.0183	618.154	6.96
2	1.79010	1.1301	1.0552	631.306	7.10
3	1.76904	1.0927	1.0232	617.680	6.79
4	1.79712	1.1220	1.0515	624.332	6.70
5	1.79712	1.1194	1.0436	622.886	7.26
6	1.80414	1.1543	1.0833	639.806	6.55
7	1.79712	1.1343	1.0594	631.177	7.07
8	1.81467	1.1473	1.0760	632.236	6.62
9	1.78659	1.1113	1.0365	622.023	7.22
10	1.80414	1.1285	1.0547	625.506	7.00

Mean mass density : **626.511 kg/m^3**

Mean moisture content : **6.927 %**

The values in the table were obtained by sampling ten specimens of Parallam® PSL from the material used in the experimental program.

Table A.2.: Allowable Design Stresses [MPa] for Parallam® PSL

Species	Douglas fir		Southern Pine		Western Hemlock	Yellow Poplar
Grade	**2.0E**	**2.1E**	**2.0E**	**2.1E**	**2.0E**	**2.0E**
$F_b^{2.5}$	**20.0**	**21.4**	**20.0**	**21.4**	**20.0**	**20.0**
F_t	**16.5**	**16.5**	**16.5**	**16.5**	**16.5**	**16.5**
F_c	**20.0**	**20.0**	**20.0**	**20.0**	**20.0**	**20.0**
$F_{c\perp 1}$	**5.17**	**5.17**	**6.07**	**6.07**	**4.48**	**5.17**
$F_{c\perp 2}$	**3.31**	**3.31**	**3.62**	**3.62**	**3.31**	**4.62**
F_{V1}	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**
F_{V2}	**1.45**	**1.45**	**1.45**	**1.45**	**1.45**	**1.45**
MOE	**13790**	**14480**	**13790**	**14480**	**13790**	**13790**

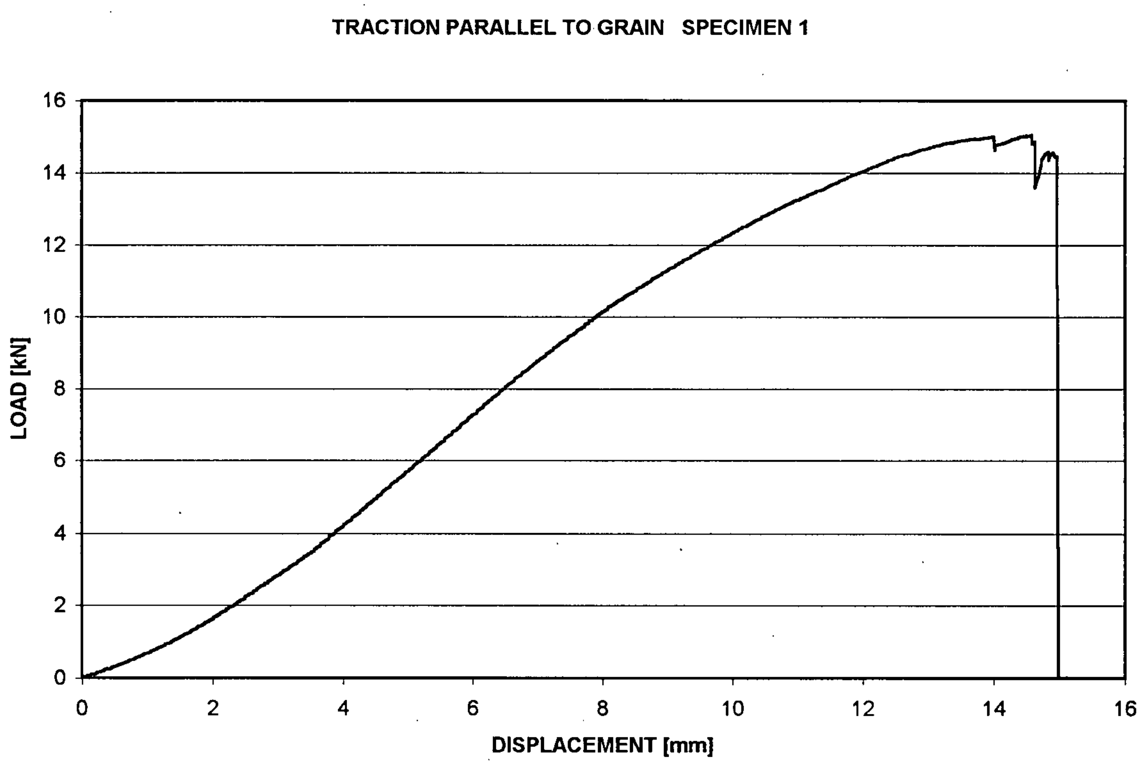
Note: The signification of the data in above table is given in the nomenclature.

A.2. MATERIAL PILOT TESTS

A.2.1. TRACTION PARALLEL TO GRAIN

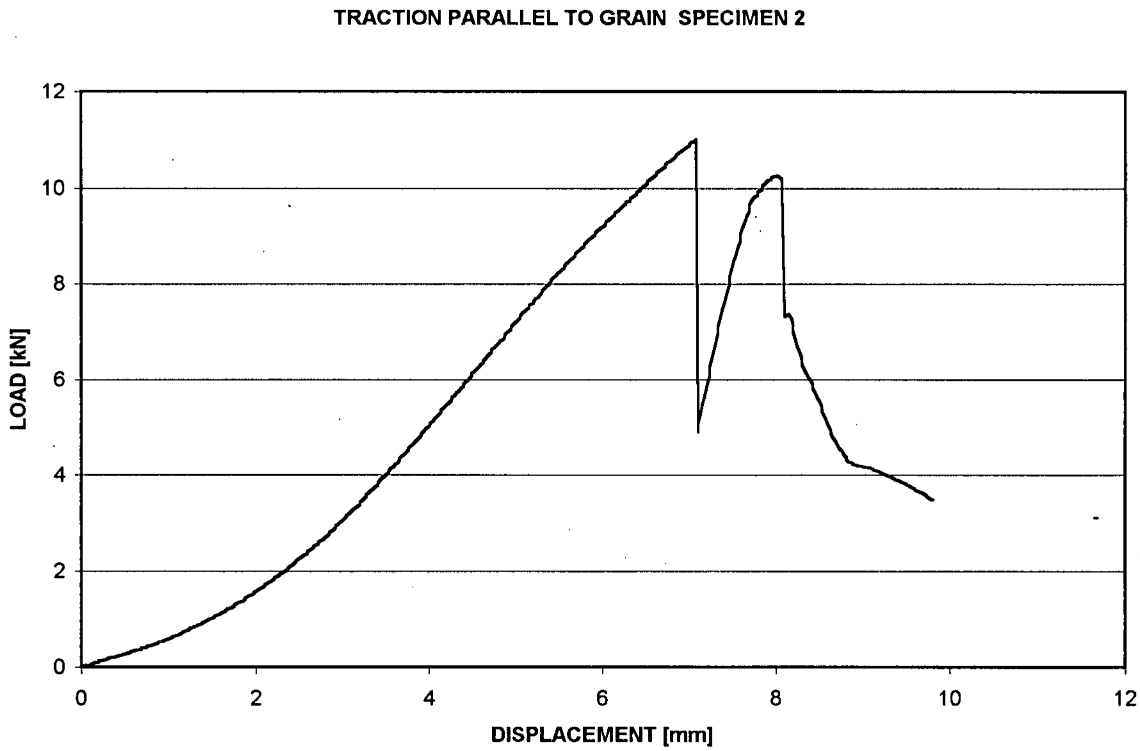
SPECIMEN 1 (15 x 25 x 500 mm)

Testing went ahead without difficulties and was terminated once the failure of the specimen occurred.



SPECIMEN 2 (15 x 25 x 500 mm)

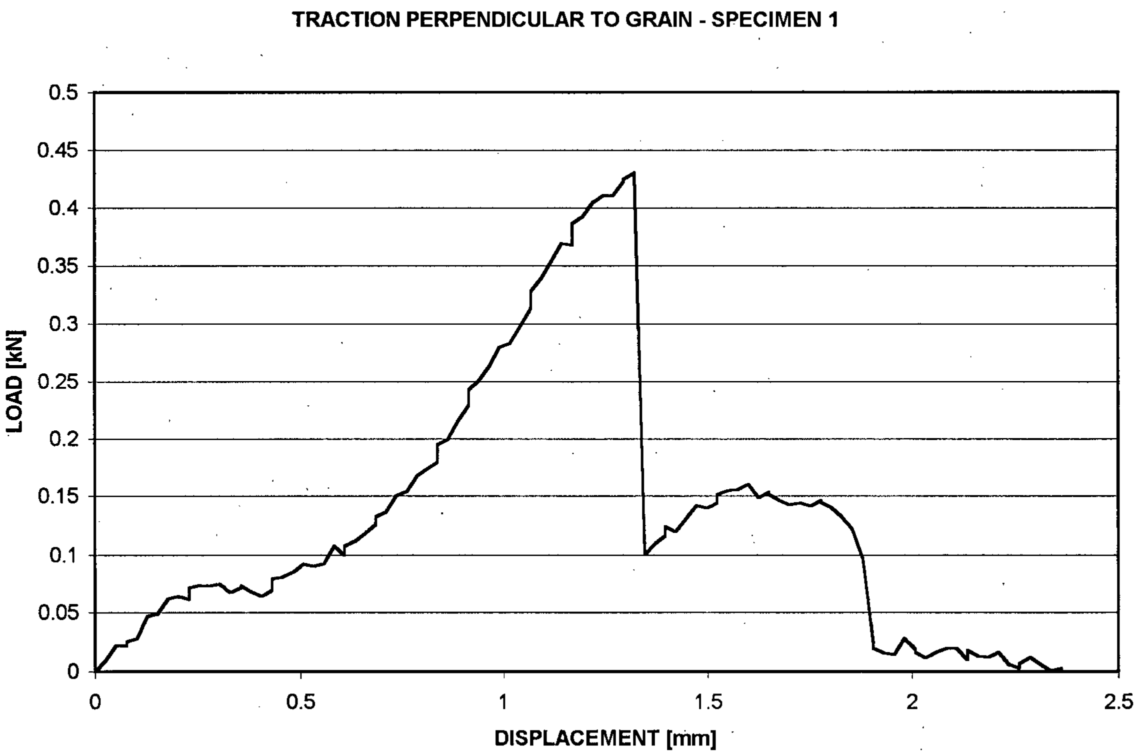
Testing went ahead without difficulties and was terminated once the failure of the specimen occurred.



A.2.2. TRACTION PERPENDICULAR TO GRAIN

SPECIMEN NO. 1 (15 x 25 x 300 mm)

Testing went ahead without any difficulties and it was terminated once the specimen failed.



A.3. CHARACTERISTICS FOR "FLEXANE 94" POLYURETHANE

Typical Properties:

• Mix ratio resin: curing agent, ratio % by weight:	69:31
• Mass density, kg/m^3	1050
• Cure shrinkage, mm/mm	0.0004
• Demoulding time, (hours)	5
• Operating temperature maximum °C	dry: 85; wet: 50
• Tensile Strength, MPa	19.5

General information:

Flexane liquids are ideal for casting parts in simple moulds. Moulds can be made from steel, aluminum, polypropylene and polyethylene. Porous materials such as wood must be sealed. Most Flexane parts will cure to a safely demouldable, rubbery solid overnight at 20°C, will reach 70%-95% strength in two days and achieve full properties in a week. Curing 100% may be achieved in 24 hours if heated to 65°C.

Proper mix ratios are essential to achieve the specified performance of Flexane. Mixing time is four minutes and the working time is about 10 minutes.

A.4. POLYURETHANE CYLINDER COMPRESION TEST

Type of Specimen : Polyurethane Cylinder ϕ 45 x 85 mm

Preset Displacement : 30 mm in compression (displacement conducted loading)

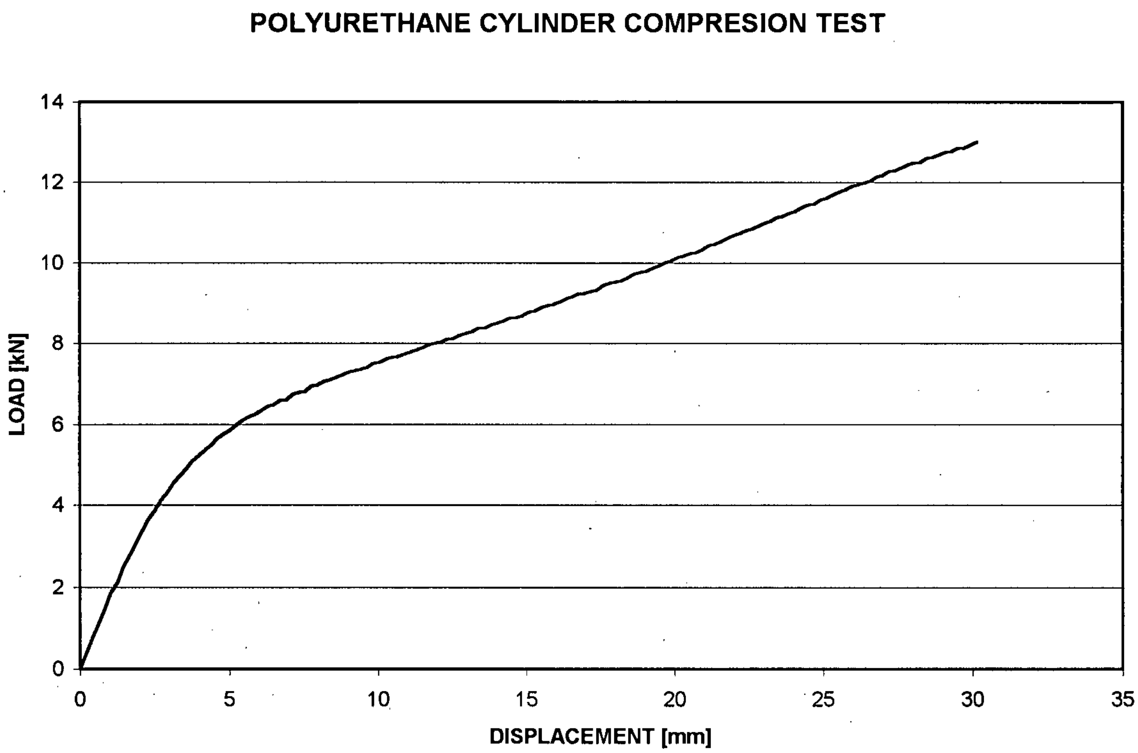


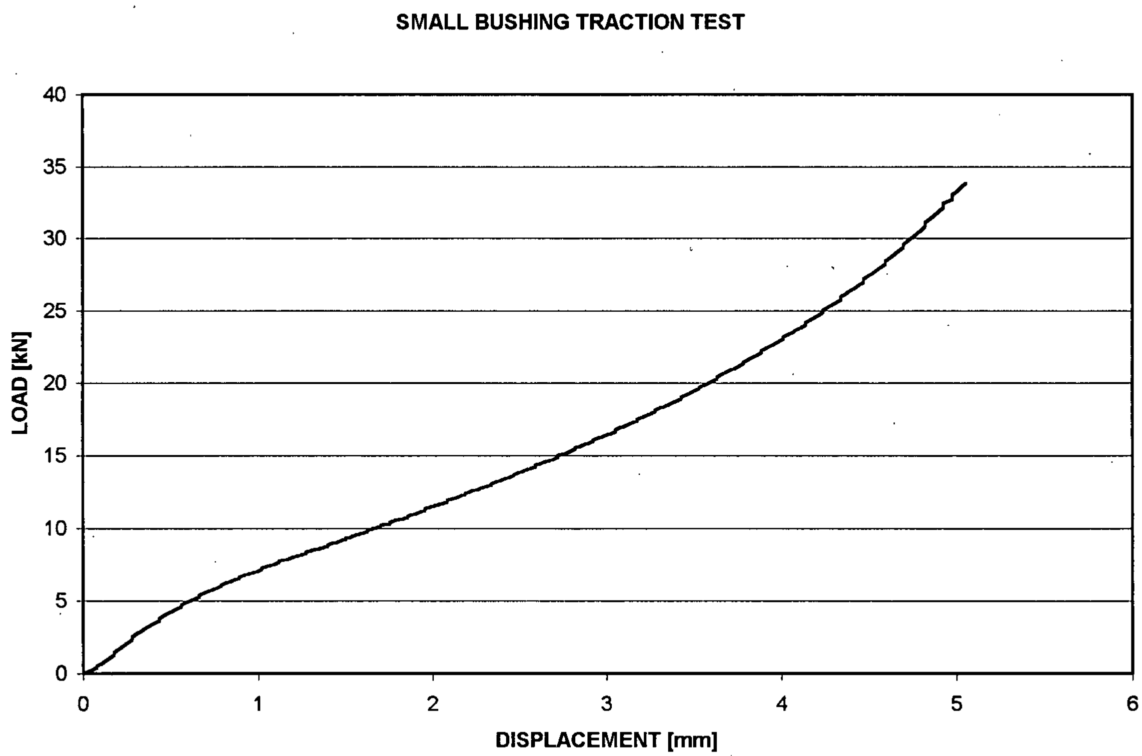
Fig. A.1.: Polyurethane Cylinder Before (right) and After (left) Compression Test

A.5. SMALL BUSHING TRACTION TEST

Type of Specimen : Small Bushing placed into a steel specimen

Preset Displacement : 5 mm in traction (displacement conducted loading)

NOTE: The testing was terminated once the preset displacement, set equal to the thickness of the polyurethane in the bushing, was reached.



A.6. POLYURETHANE REINFORCEMENT

The polyurethane material was reinforced in some bushings by using a fine welded mild steel wire mesh. The dimensions for the mesh are shown in Figure A.2.

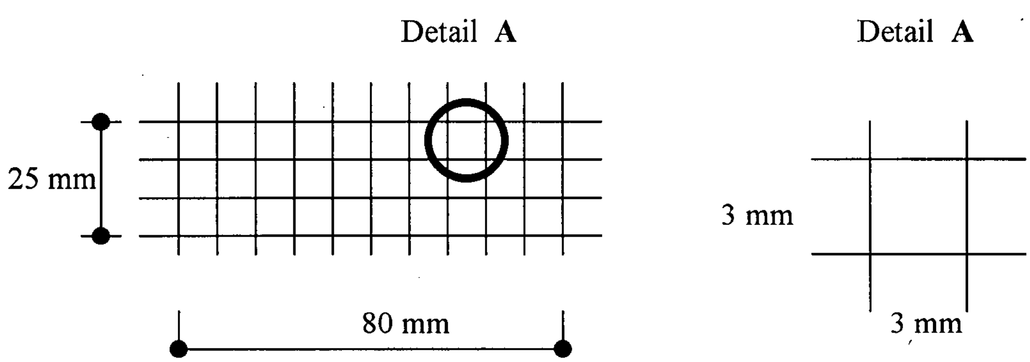


Fig.A.2.: Steel wire mesh used for reinforcement of the polyurethane in some bushings (wire diameter $\phi = 0.3$ mm)

The wire mesh was cut to the dimensions above, then shaped into a cylinder shell and introduced between the concentrically placed pipes of the bushing. The liquid polyurethane was then poured in the same space, becoming reinforced after the curing process. A welded wire mesh was chosen so it could provide resistance to the flow of the stressed polyurethane.

A.7. REVISED (30.06.1997) CYCLIC PROTOCOL

Cycles are a percentage of the ultimate displacement (δ_u) as shown in Figures A.3 and A.4 .

1) 1 cycle @ 5%

2) 1 cycle @ 10%

3) 3 cycles @ 25%

4) 1 cycle @ 10%

5) 3 cycles @ 50%

6) 1 cycle @ 25%

7) 3 cycles @ 75%

8) 1 cycle @ 50%

9) 3 cycles @ 100%

10) 3 cycles @ 125%

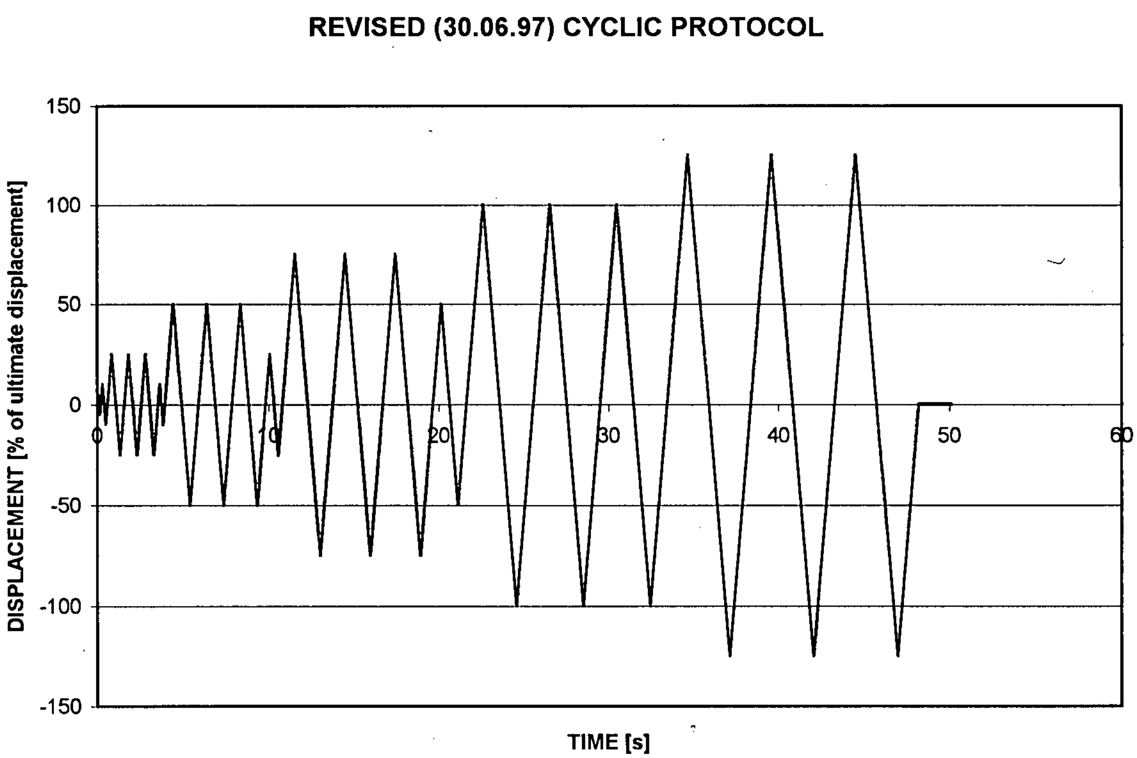


Fig.A.3.: Procedure for Cyclic Testing

A test velocity of 5 mm per second was used.

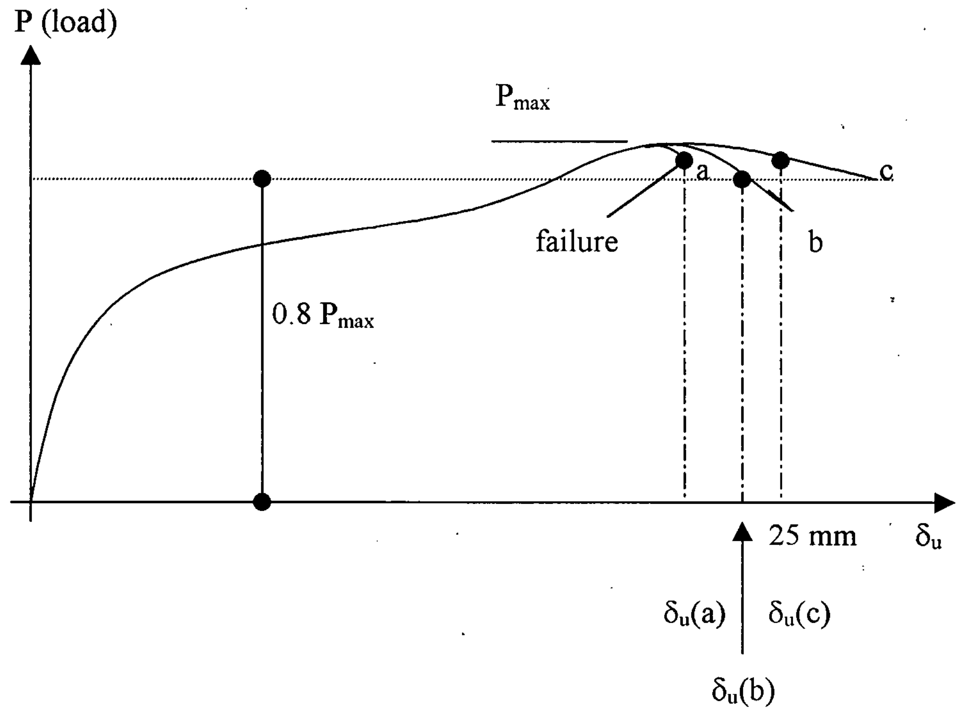
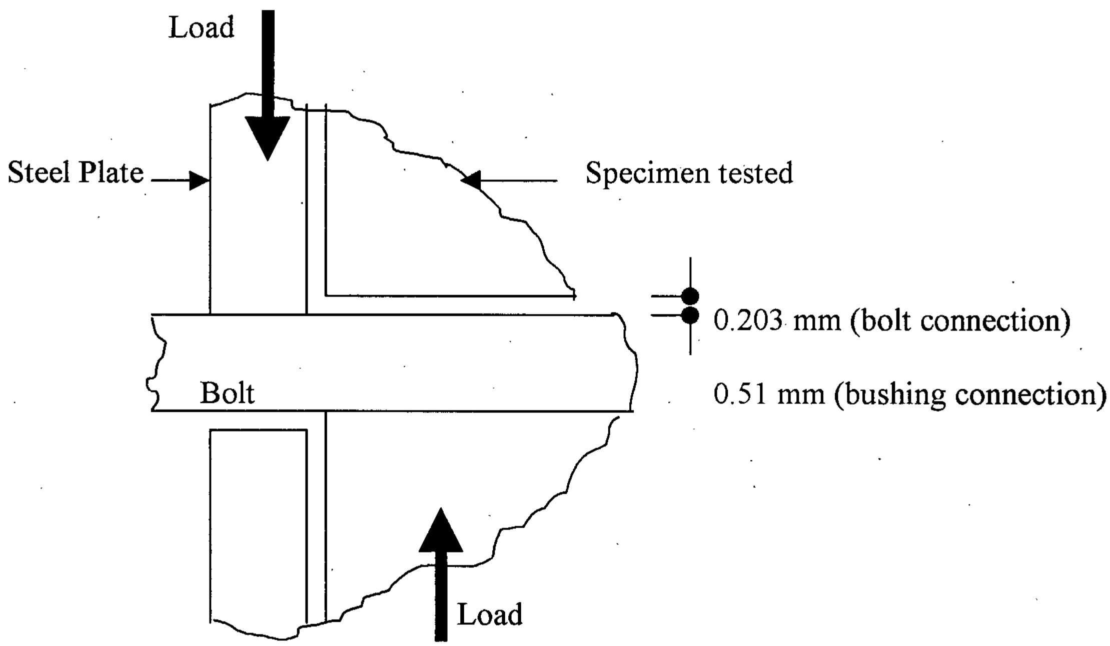


Fig. A.4.: Definition of ultimate displacement: δ_u corresponds to failure slip (case a) or 0.80 P_{max} slip (case b) or 25 mm slip (case c), whichever occurs first in the test.

A.8. TOLERANCE MEASUREMENT

Diameter ϕ	*Member*
12.57 mm (0.495")	Bolt
12.7 mm (0.500")	Steel Plates
12.65 mm (0.498")	PSL Member
12.95 mm (0.510")	Bushing

NOTE: The holes in the Composite Structural Lumber and in the Steel plates were made using a ½ inch drill. All the tolerances were smaller than the ones permitted by the Wood Design Manual (maximum 2 mm).



Tolerances have to be consumed before loading in each direction, meaning a transfer zone of 0.406 mm for bolt connections and 1.02 mm for bushing connections.

APPENDIX B

Appendix B contains abridged versions of the test data for all specimens tested, as described in Chapter 2 - Experimental Program. As well as showing the test data plots, a summary sheet is given for each specimen showing the loading conditions and any peculiarities that occurred during testing. Also, photographs of the failed specimens are included.

CONTENTS

B.1. PILOT TESTS

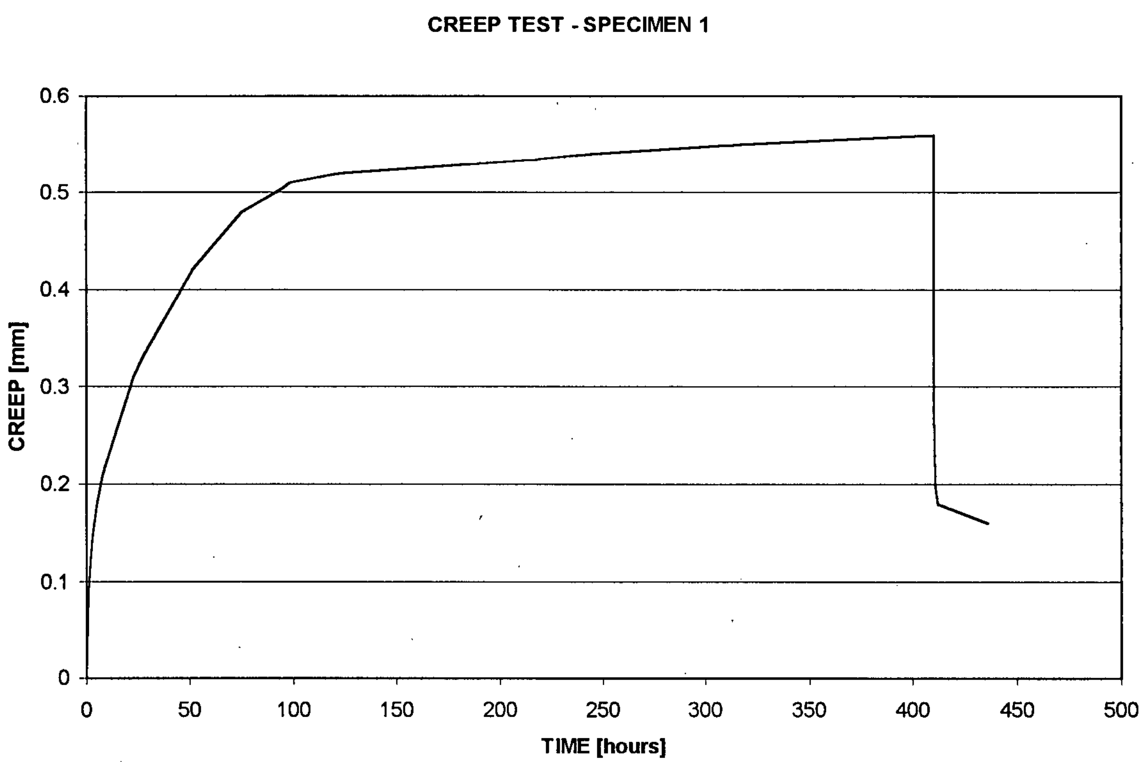
TEST TYPE A1

SPECIMEN NO. 1

- Bushing used : Small (Fig. 2.2)
- Long Term Load : 250 kg

NOTES:

Testing went ahead without any difficulties. The data acquisition began after the initial elastic deformation was consumed, as the dial gauge could be set after positioning the load (due to the lifting conditions)

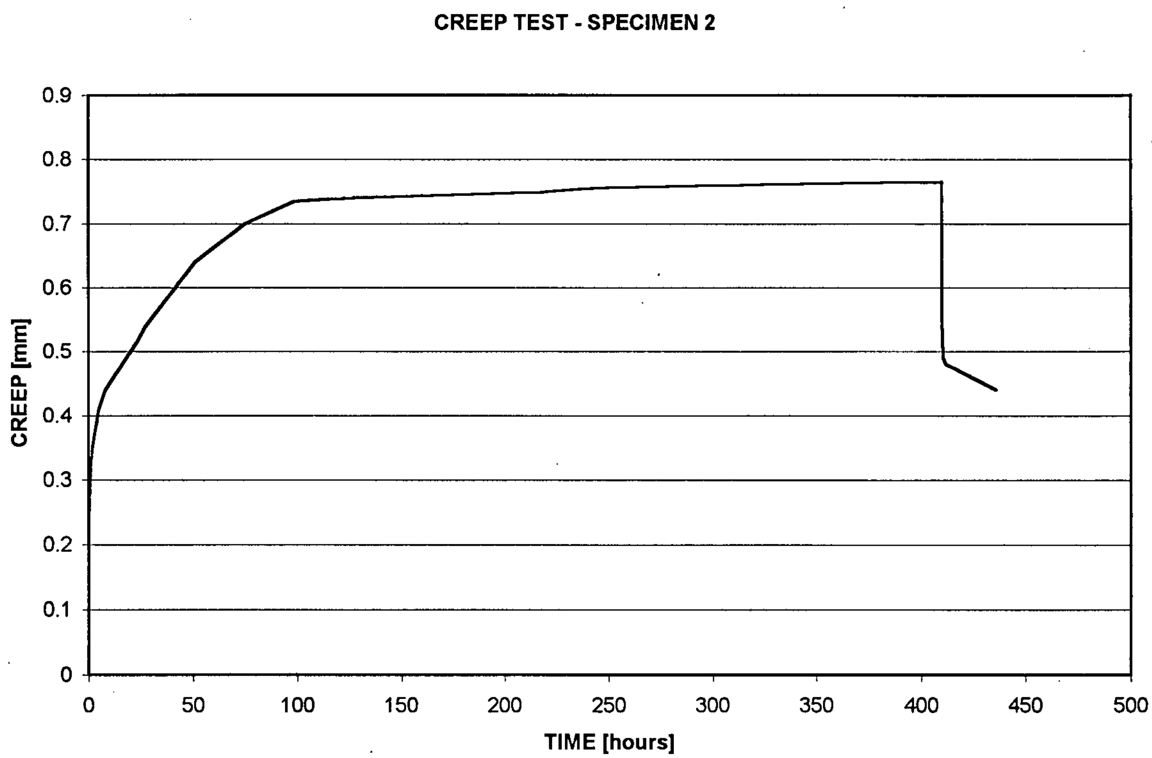


SPECIMEN NO. 2

- Bushing used : Small, reinforced with wire mesh (Fig. 2.2)
- Long term Load : 250 kg

NOTES:

Testing went ahead without any difficulties. For this test a different setting was used to capture the initial elastic deformation. The dial gauge was set to zero before the loading and the weights were put in place with a mobile high capacity jack.



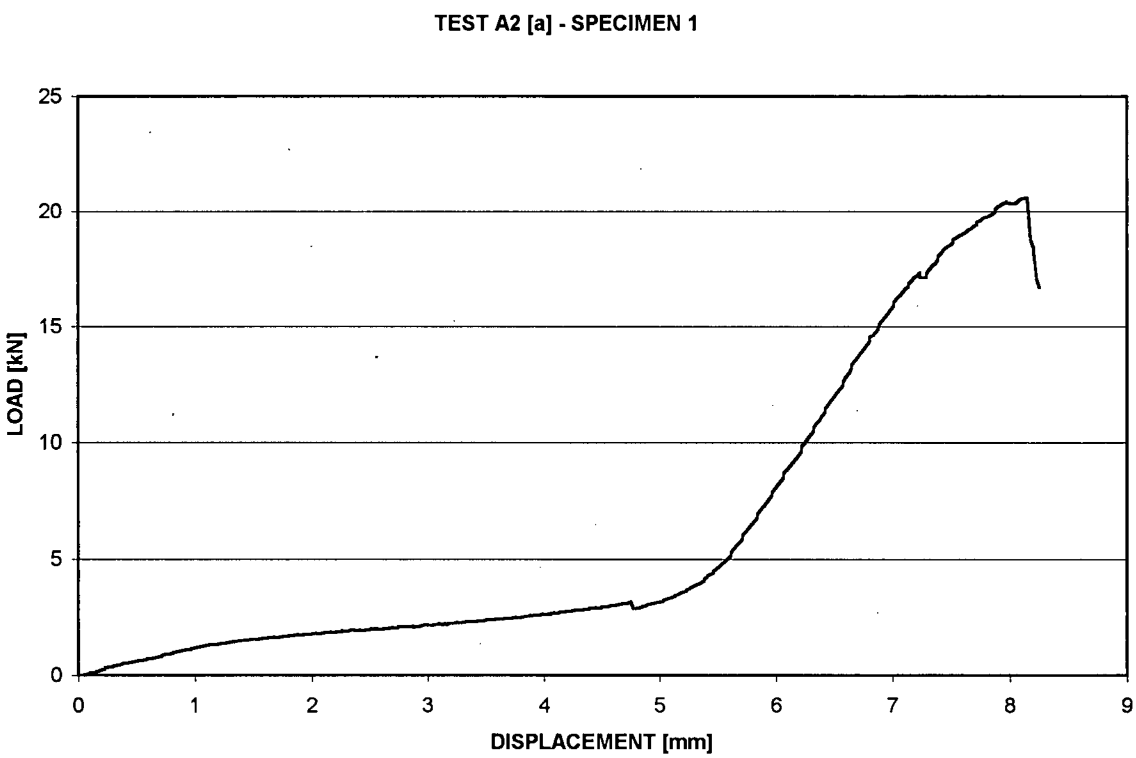
TEST TYPE A2 [a]

SPECIMEN NO. 1

- Wood Specimen : 38 x 150 x 400 mm (Fig. 2.1.)
- Bushing Type : Small (Fig.2.2.)
- Bushing Location : 84 mm, measured from the centroid of bushing to member end

NOTES:

Testing went ahead without any difficulties. Testing was terminated once the wood element failed due to splitting.

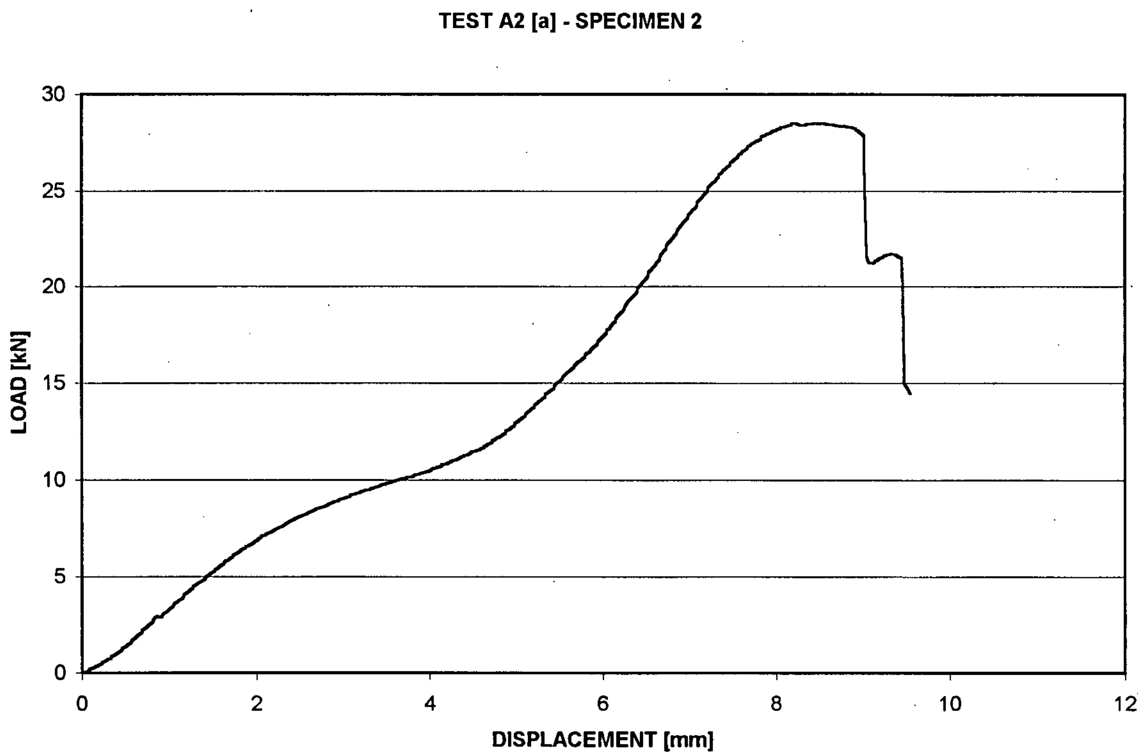


SPECIMEN NO. 2

- Wood Specimen : 38 x 150 x 400 mm (Fig. 2.1.)
- Bushing Type : Small (Fig.2.2.)
- Bushing Location : 100 mm, measured from the centroid of bushing to member end

NOTES:

Testing went ahead without any difficulties. Testing was terminated once the wood element failed due to splitting.

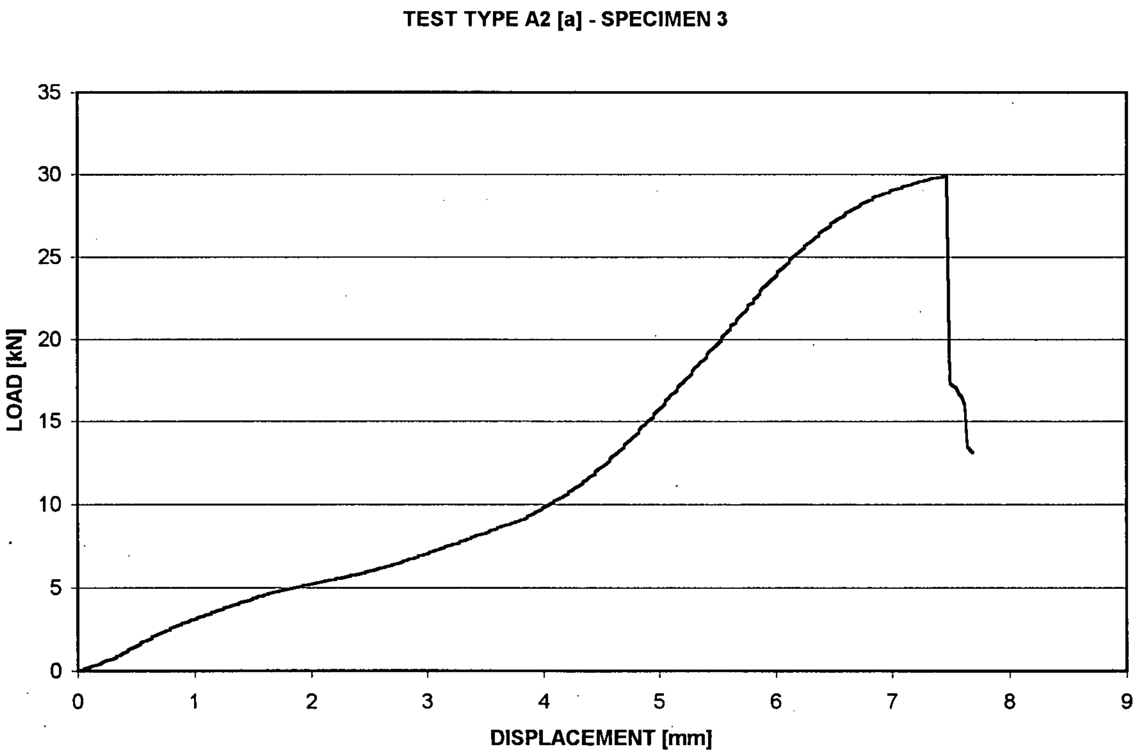


SPECIMEN NO. 3

- Wood Specimen : 38 x 150 x 400 mm (Fig. 2.1.)
- Bushing Type : Small (Fig.2.2.)
- Bushing Location : 120 mm, measured from the centroid of bushing to member end

NOTES:

Testing went ahead without any difficulties. Testing was terminated once the wood element failed due to splitting.



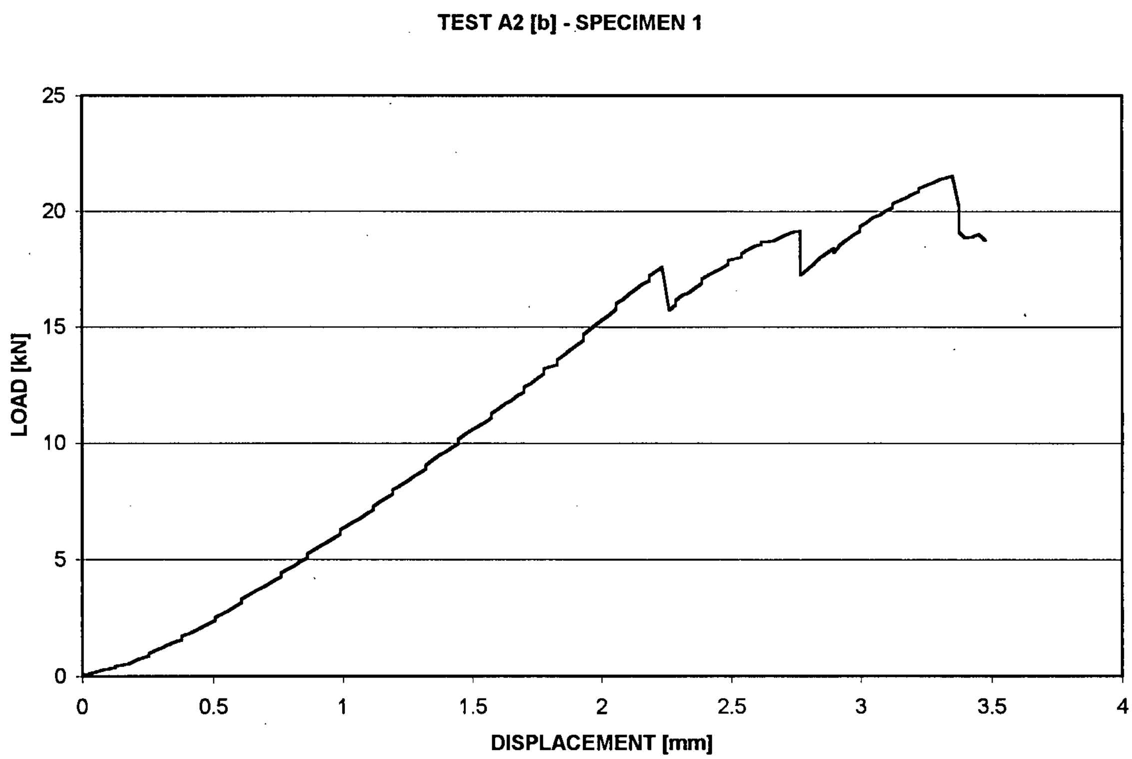
TEST TYPE A2 [b]

SPECIMEN NO. 1

- Wood Specimen : 38 x 150 x 400 mm (Fig. 2.1.)
- Bushing Type : Aluminum (Fig.2.3.a)
- Bushing Location : 84 mm, measured from the centroid of bushing to member end

NOTES:

Testing went ahead without any difficulties. The testing was terminated once the wood element failed by splitting.

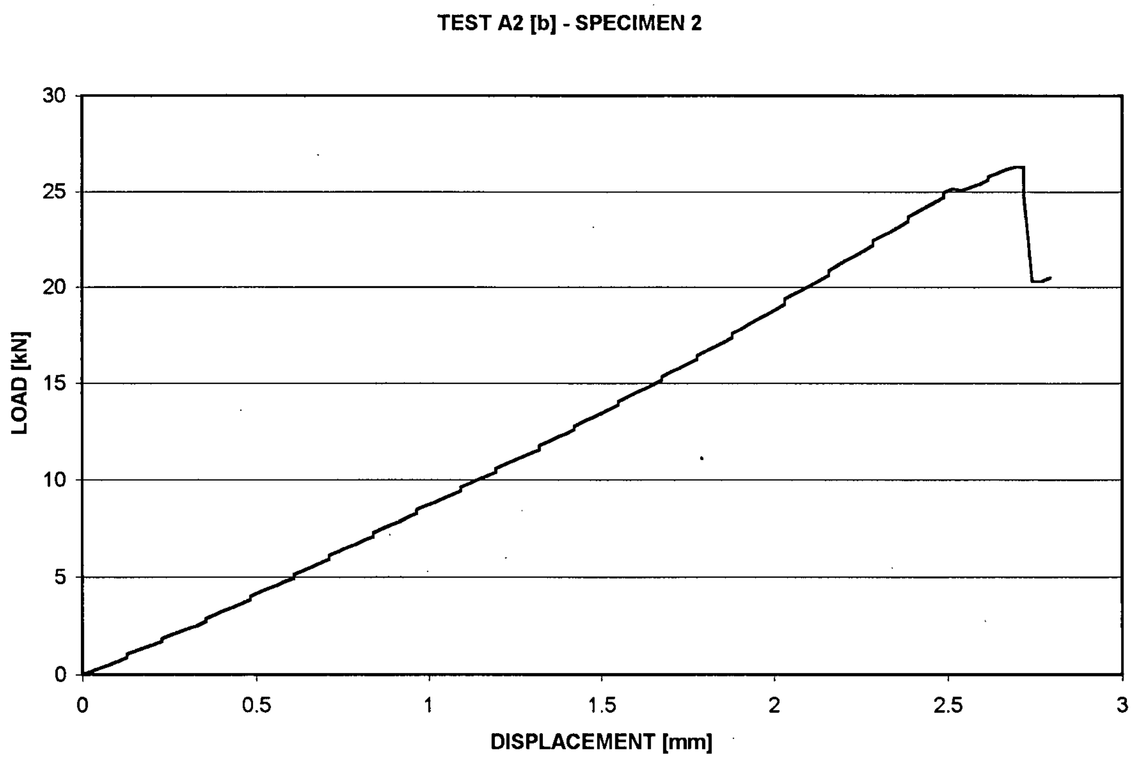


SPECIMEN NO. 2

- Wood Specimen : 38 x 150 x 400 mm (Fig. 2.1.)
- Bushing Type : Aluminum (Fig.2.3.a)
- Bushing Location : 120 mm, measured from the centroid of bushing to member end

NOTES:

Testing went ahead without any difficulties. Testing was terminated once the wood element failed by splitting.



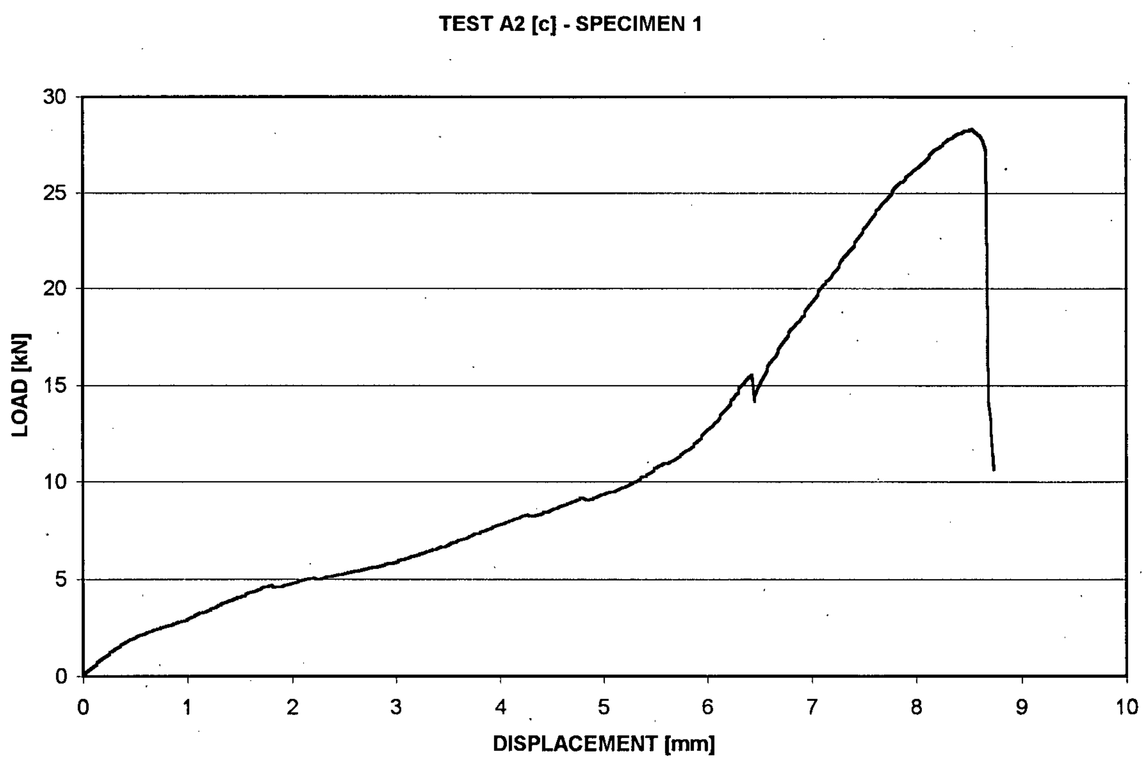
TEST TYPE A2 [c]

SPECIMEN NO. 1

- Wood Specimen : 38 x 150 x 400 mm (Fig. 2.1.)
- Bushing Type : Small, reinforced with wire mesh (Fig.2.2.)
- Bushing Location : 120 mm, measured from the centroid of bushing to member end

NOTES:

Testing went ahead without any difficulties.

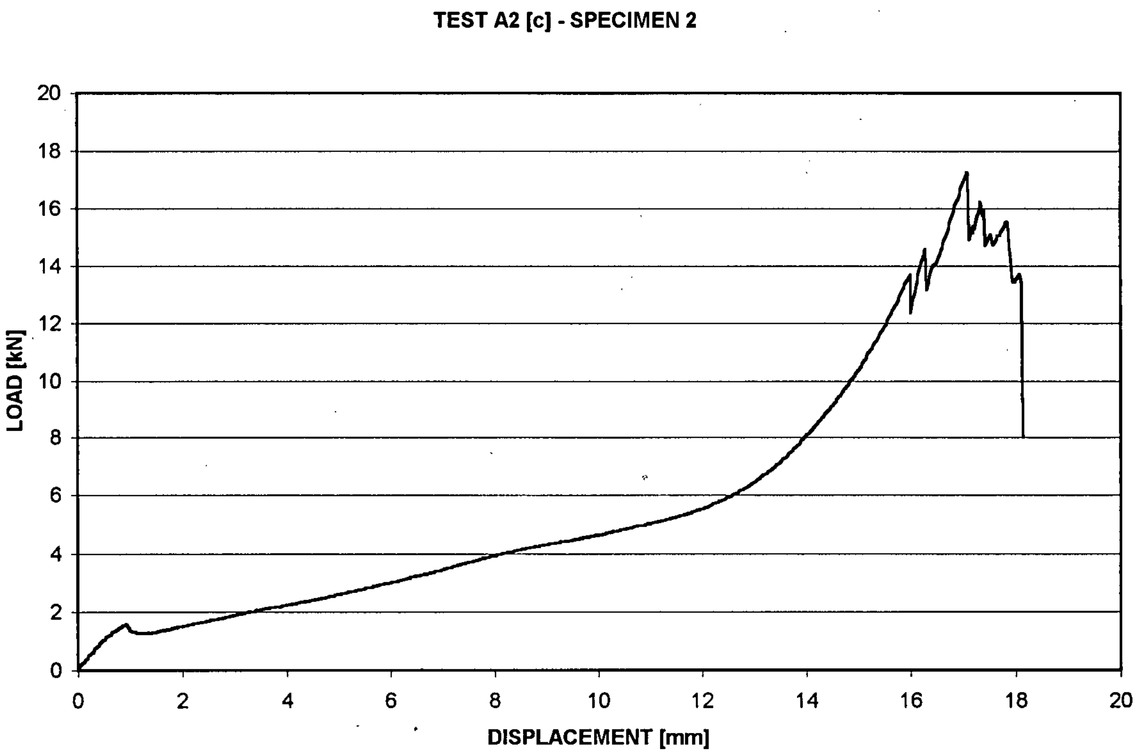


SPECIMEN NO. 2

- Wood Specimen : 38 x 150 x 400 mm (Fig. 2.1.)
- Bushing Type : Large, unreinforced
- Bushing Location : 120 mm, measured from the centroid of bushing to member end

NOTES:

Testing went ahead without any difficulties.

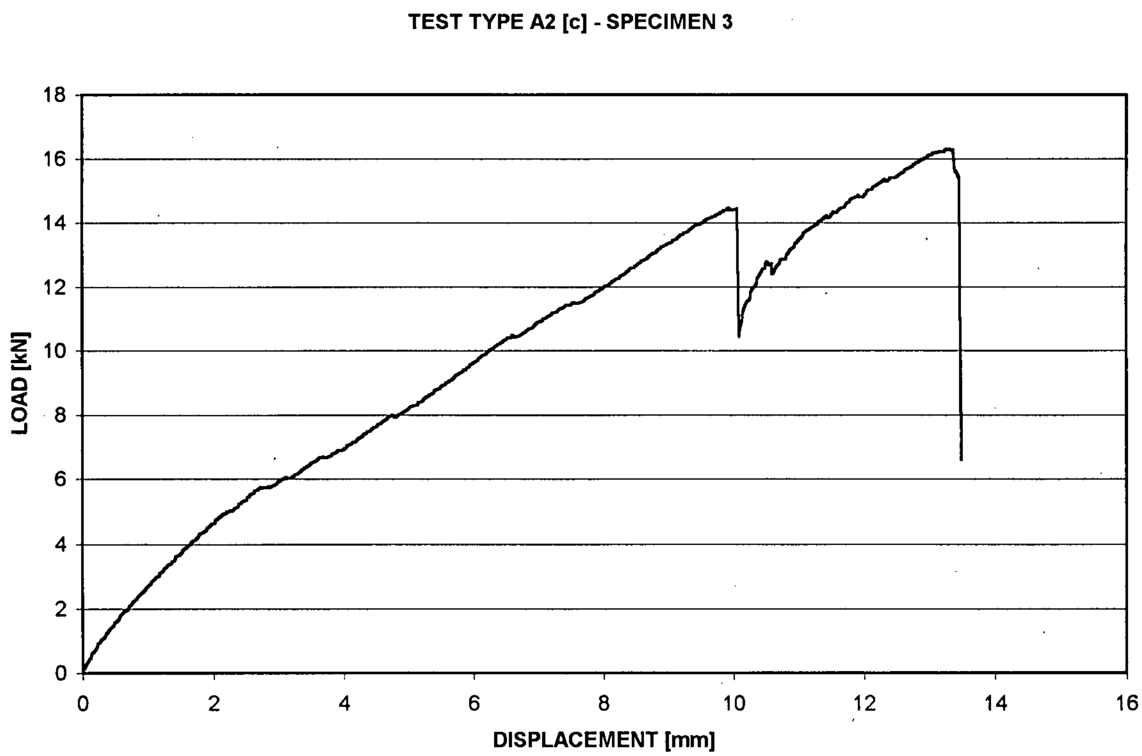


SPECIMEN NO. 3

- Wood Specimen : 38 x 150 x 400 mm (Fig. 2.1.)
- Bushing Type : Large, reinforced with wire mesh
- Bushing Location : 120 mm, measured from the centroid of bushing to member end

NOTES:

Testing went ahead without any difficulties.

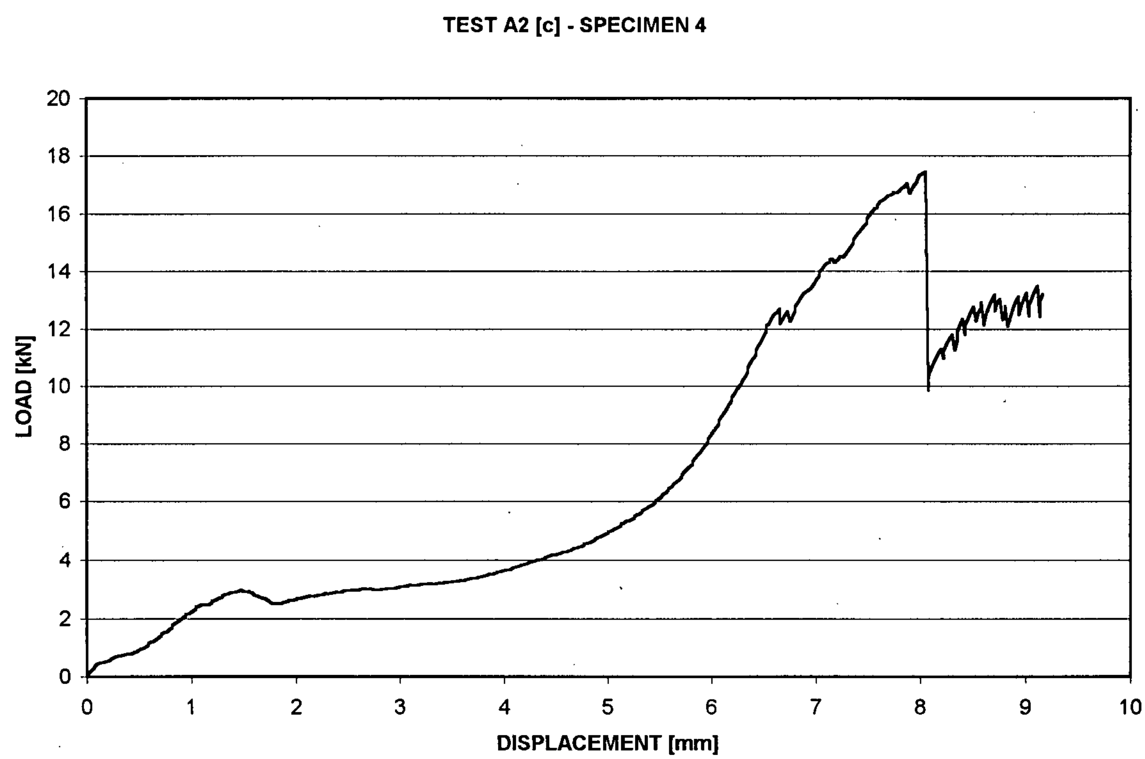


SPECIMEN NO. 4

- Wood Specimen : 38 x 150 x 400 mm (Fig. 2.1.)
- Bushing Type : Large, with thick internal pipe (Fig. 2.3.b)
- Bushing Location : 120 mm, measured from the centroid of bushing to member end

NOTES:

Testing went ahead without any difficulties.



TEST TYPE A3 [a]

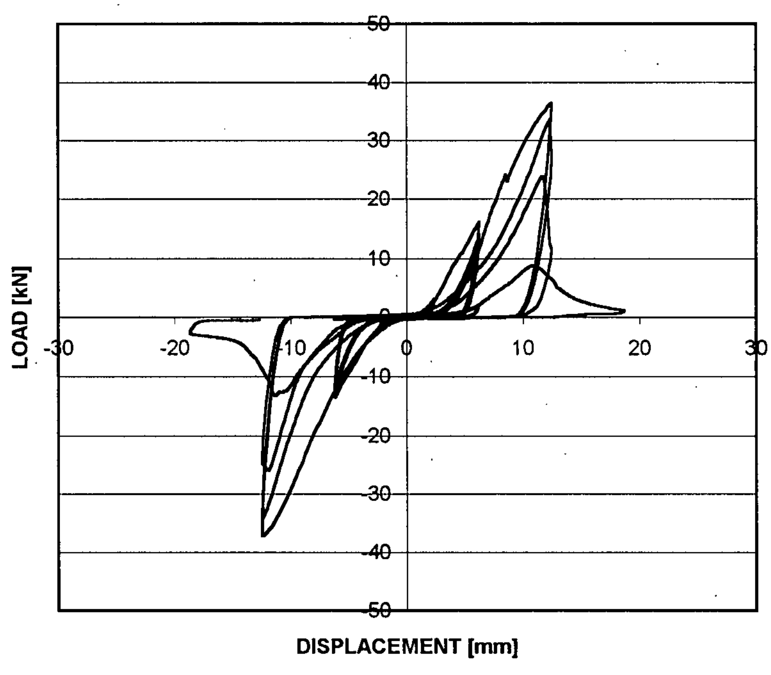
SPECIMEN NO. 1

- Wood Specimen : 38 x 150 x 400 mm (Fig. 2.1.)
- Bushing Type : Small (Fig.2.2.)
- Bushing Location : 120 mm, measured from the centroid of bushing to member end
- Protocol used : Forintek revised cyclic protocol (30.06.97), for $\delta_u = 25$ mm

NOTES:

Testing went ahead without any difficulties. Testing was terminated due to the wood element splitting, before the end of the protocol.

TEST A3 [a] - SPECIMEN 1

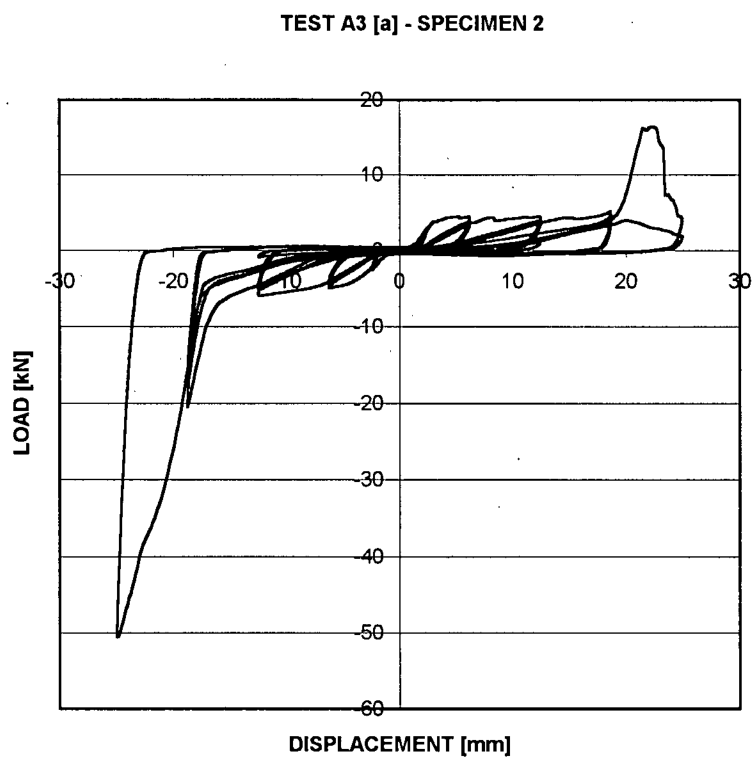


SPECIMEN NO. 2

- Wood Specimen : 38 x 150 x 400 mm (Fig. 2.1.)
- Bushing Type : Large, unreinforced
- Bushing Location : 120 mm, measured from the centroid of bushing to member end
- Protocol used : Forintek revised cyclic protocol (30.06.97), for δ_u = 25 mm

NOTES:

Testing went ahead without any difficulties. Testing was terminated due to specimen splitting before the end of the protocol.



TEST TYPE A3 [b]

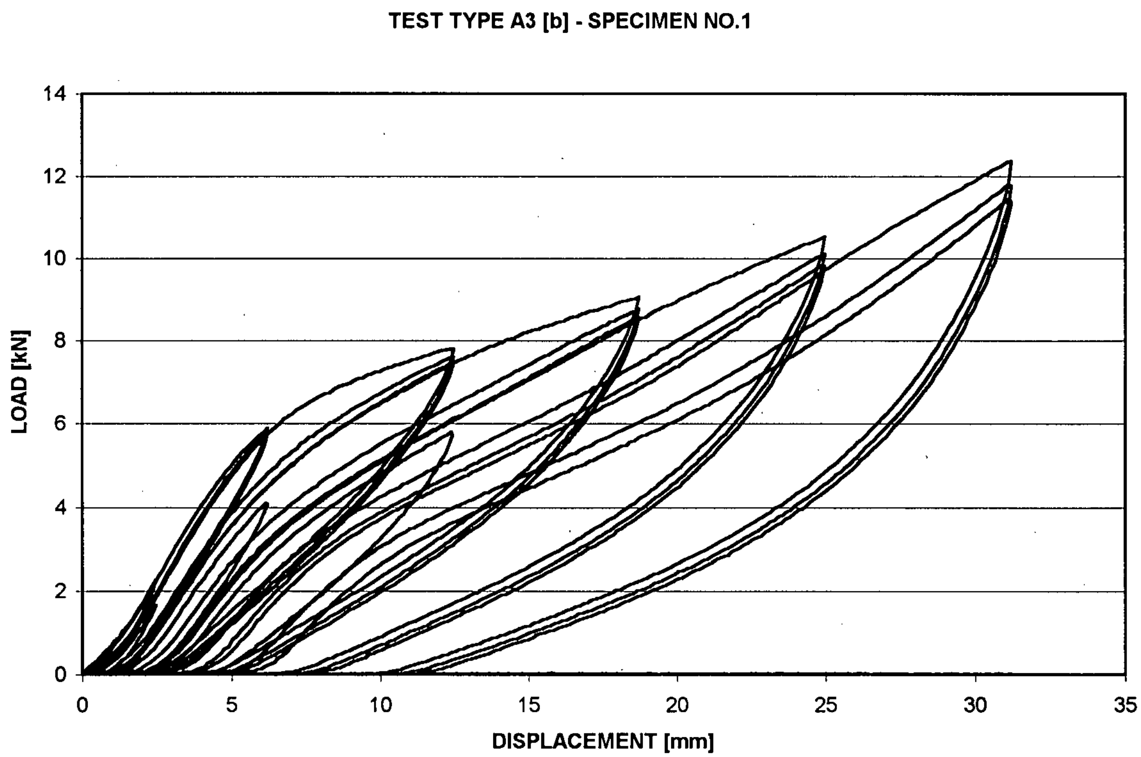
SPECIMEN NO. 1

Type of Specimen : Polyurethane Cylinder ϕ 45 x 85 mm

Load Protocol : Forintek revised cyclic protocol (30.06.97) - $\delta_u = 25$ mm

NOTES:

Testing went ahead without difficulties and was terminated when the programmed protocol ended.



SPECIMEN NO. 2

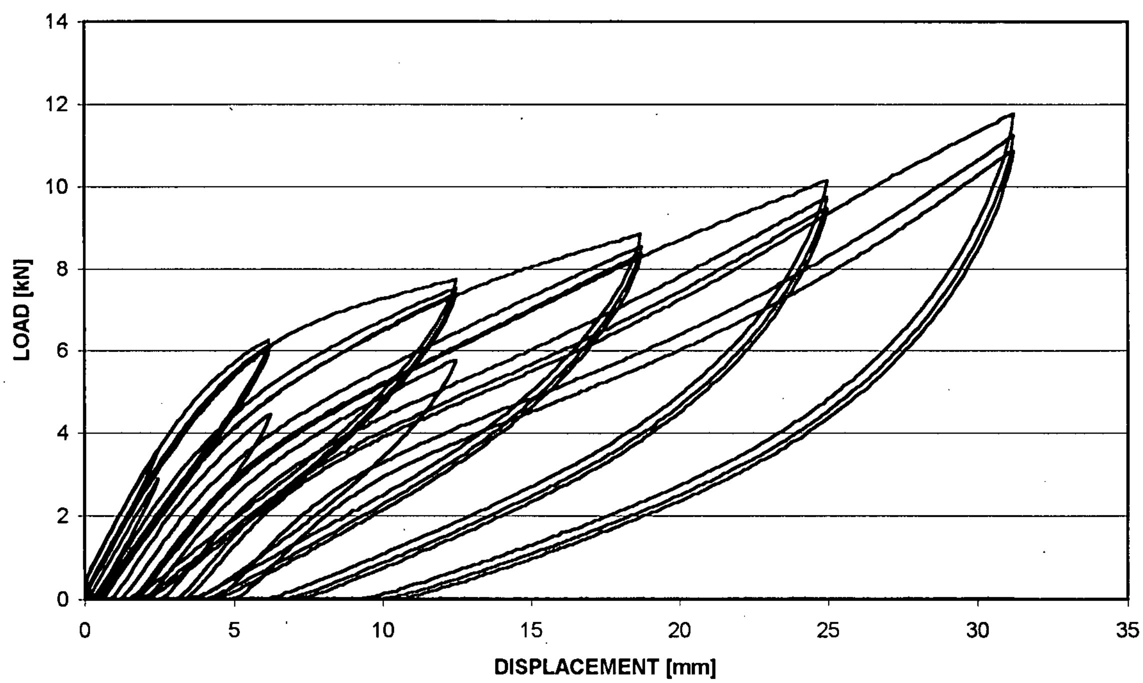
Type of Specimen : Polyurethane Cylinder ϕ 45 x 85 mm

Load Protocol : Forintek revised cyclic protocol (30.06.97) - δ_u = 25 mm

NOTES:

Testing went ahead without difficulties and was terminated when the programmed protocol ended.

TEST TYPE A3 [b] - SPECIMEN NO. 2



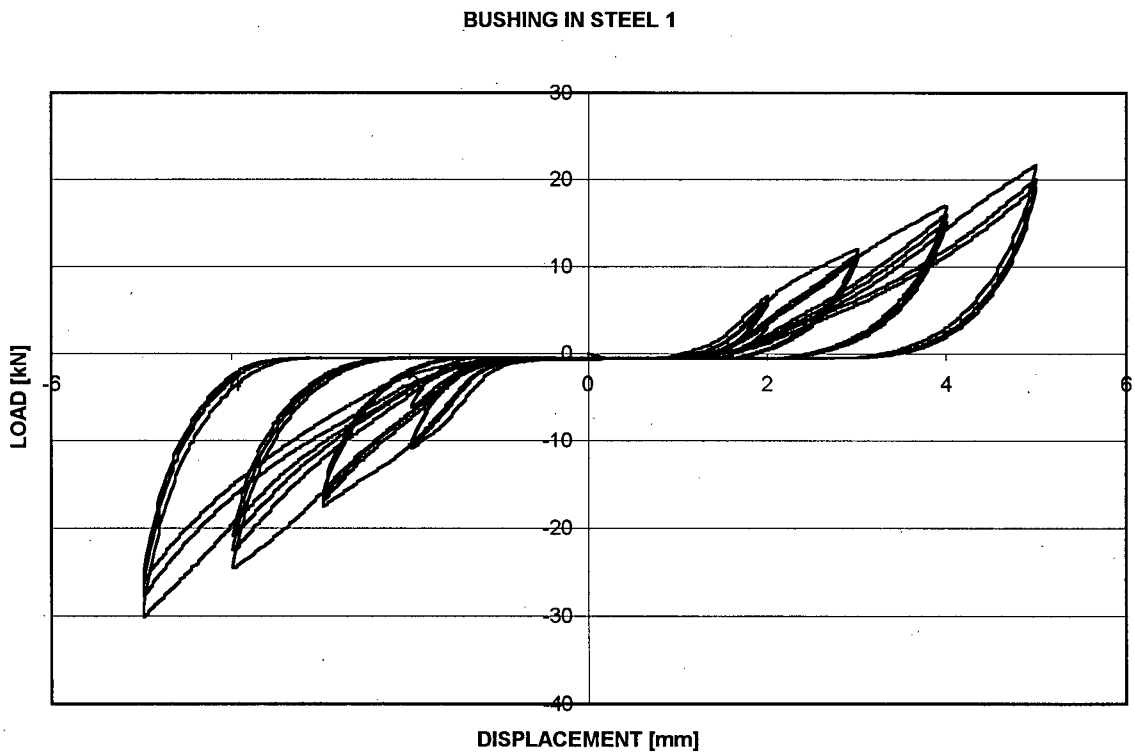
TEST TYPE A3 [c]

SPECIMEN NO. 1

Type of Specimen	:	Small bushing embedded in thick steel plate
Load Protocol	:	Forintek revised cyclic protocol (30.06.97) - $\delta_u = 4$ mm

NOTES:

Testing went ahead without difficulties and was terminated when the programmed protocol ended.

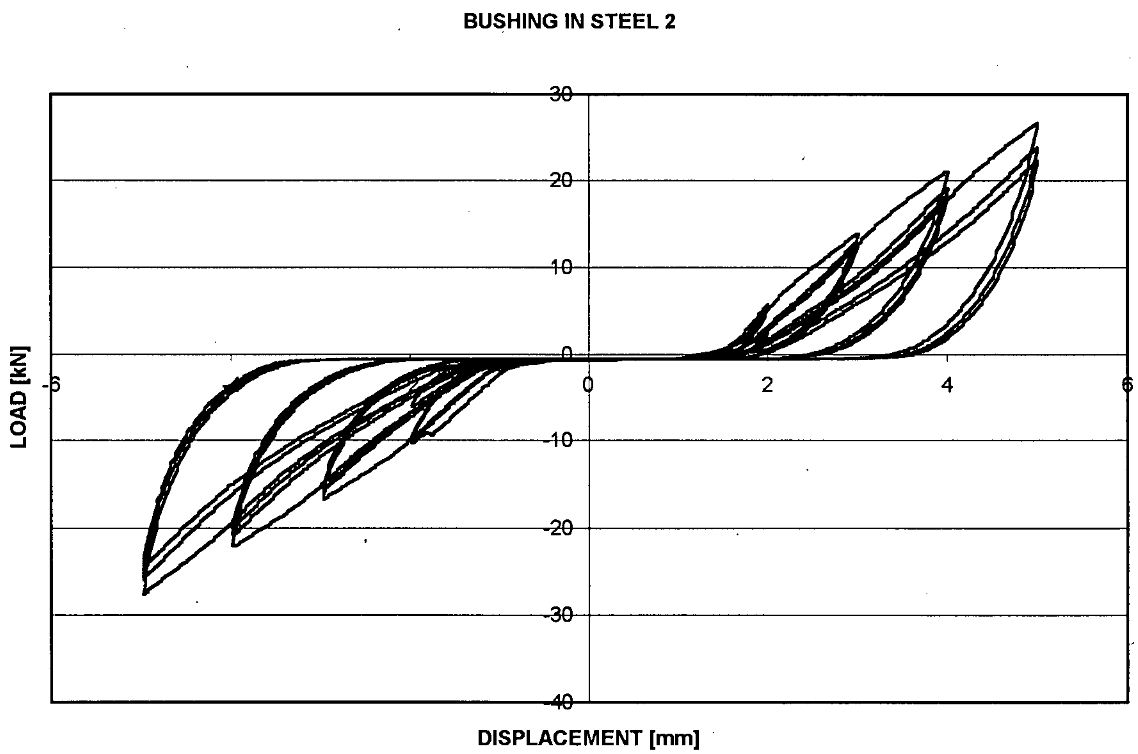


SPECIMEN NO. 2

Type of Specimen	:	Small bushing embedded in thick steel plate
Load Protocol	:	Forintek revised cyclic protocol (30.06.97) - $\delta_u = 4$ mm

NOTES:

Testing went ahead without difficulties and was terminated when the programmed protocol ended.



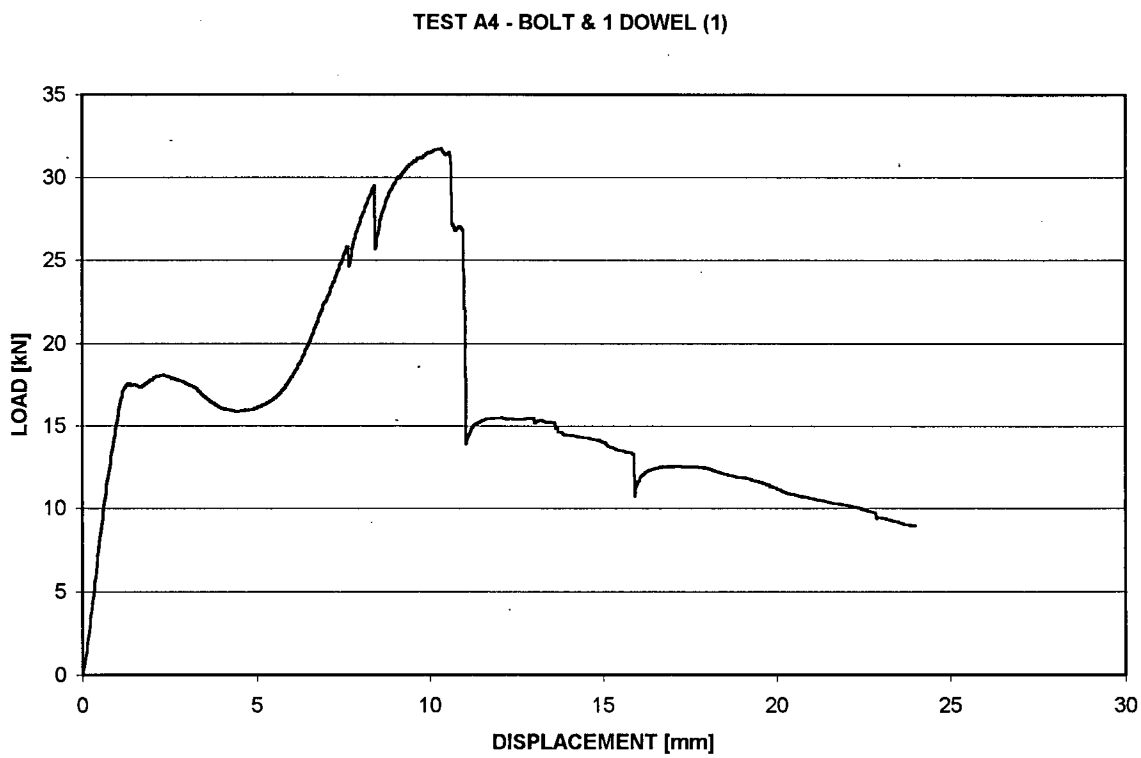
TEST TYPE A4

SPECIMEN NO. 1

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Connection Type : Reinforced with 1 dowel, without bushing
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Dowel Location : 15 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties.

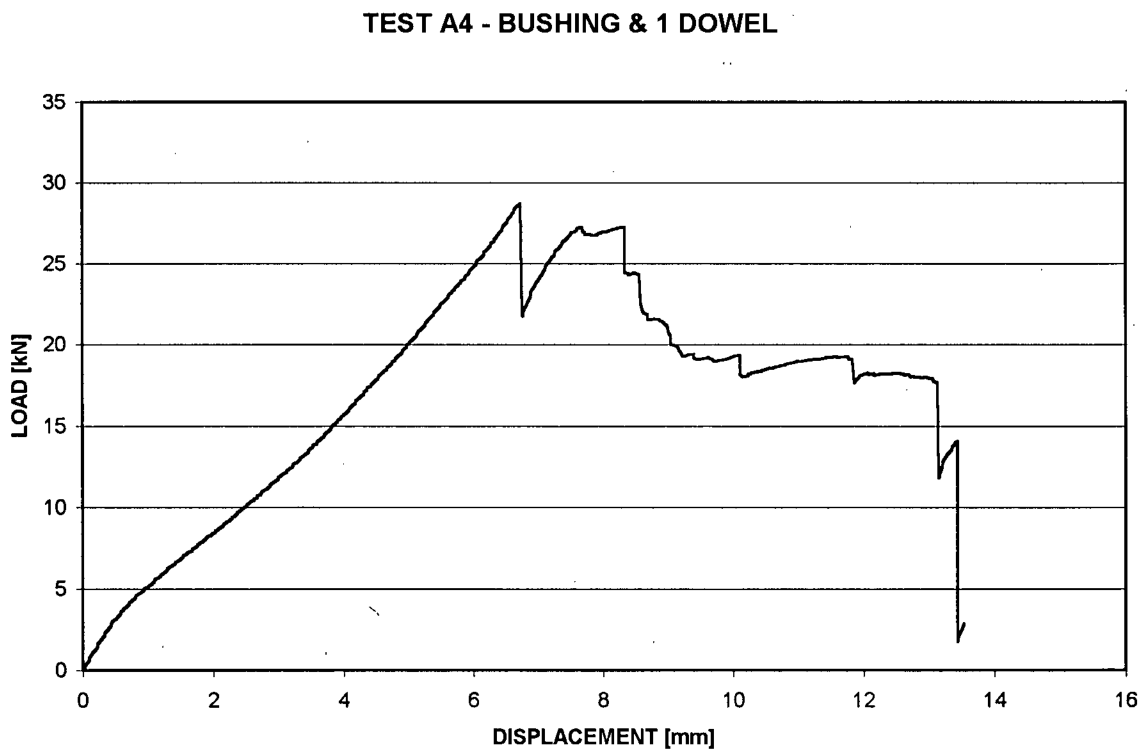


SPECIMEN NO. 2

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Connection Type : Reinforced with 1 dowel, with bushing
- Bushing Location : 120 mm, measured from centroid of bushing to member end
- Dowel Location : 25 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties.



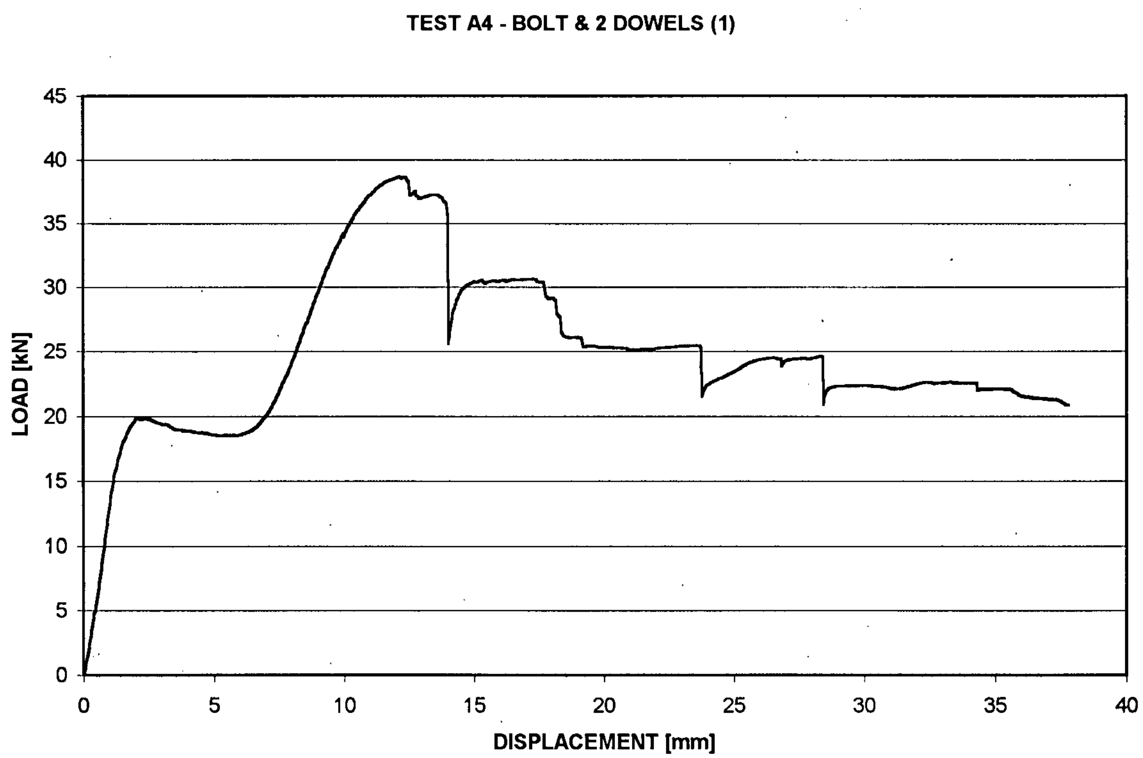
SPECIMEN NO. 3

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Connection Type : Reinforced with 2 dowels, without bushing
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Dowel Locations : 15 mm from the bolt axis, perpendicular to the bolt axis

  65 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties.



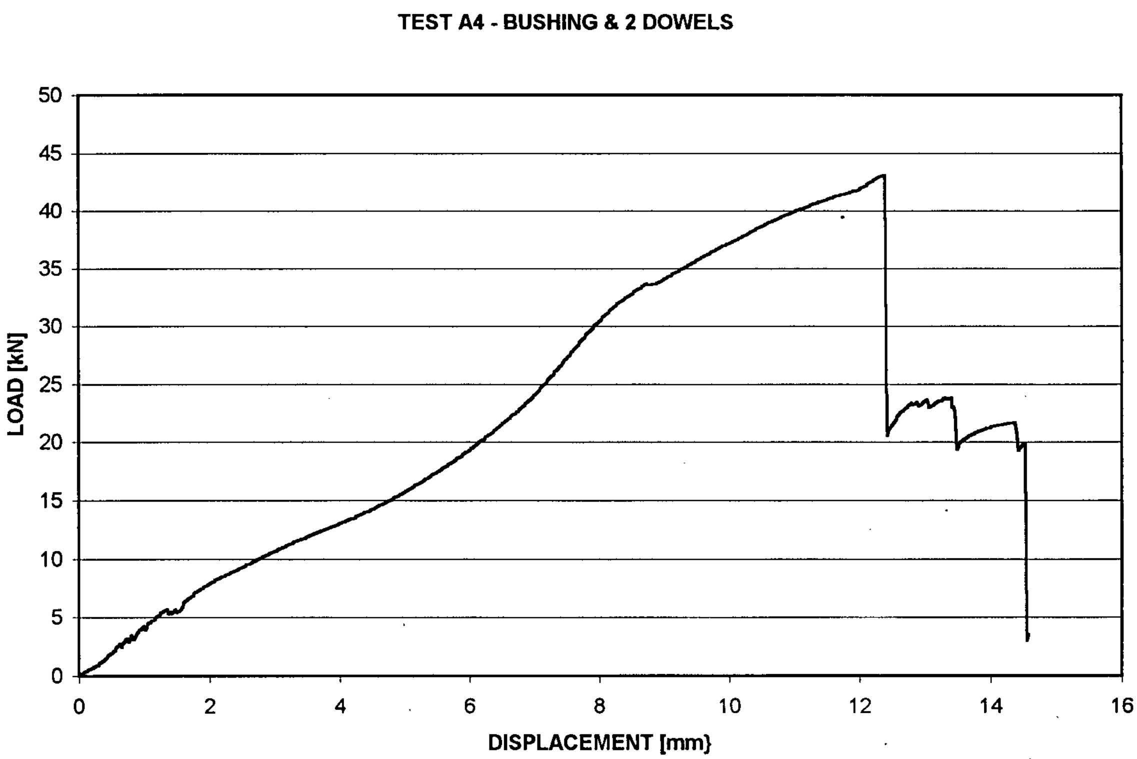
SPECIMEN NO. 4

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Connection Type : Reinforced with 2 dowels, with bushing
- Bushing Location : 120 mm, measured from centroid of bushing to member end
- Dowel Locations : 25 mm from the bolt axis, perpendicular to the bolt axis

  75 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties.

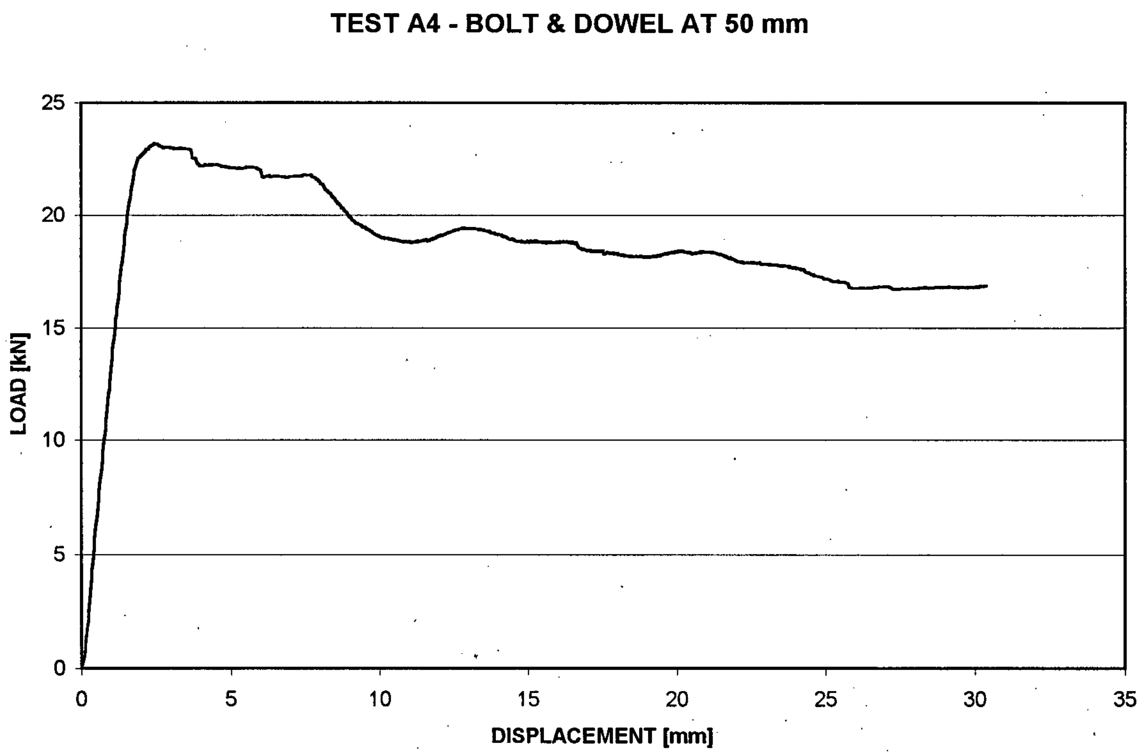


SPECIMEN NO. 5

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Connection Type : Reinforced with 1 dowel at 50 mm , without bushing
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Dowel Locations : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties.



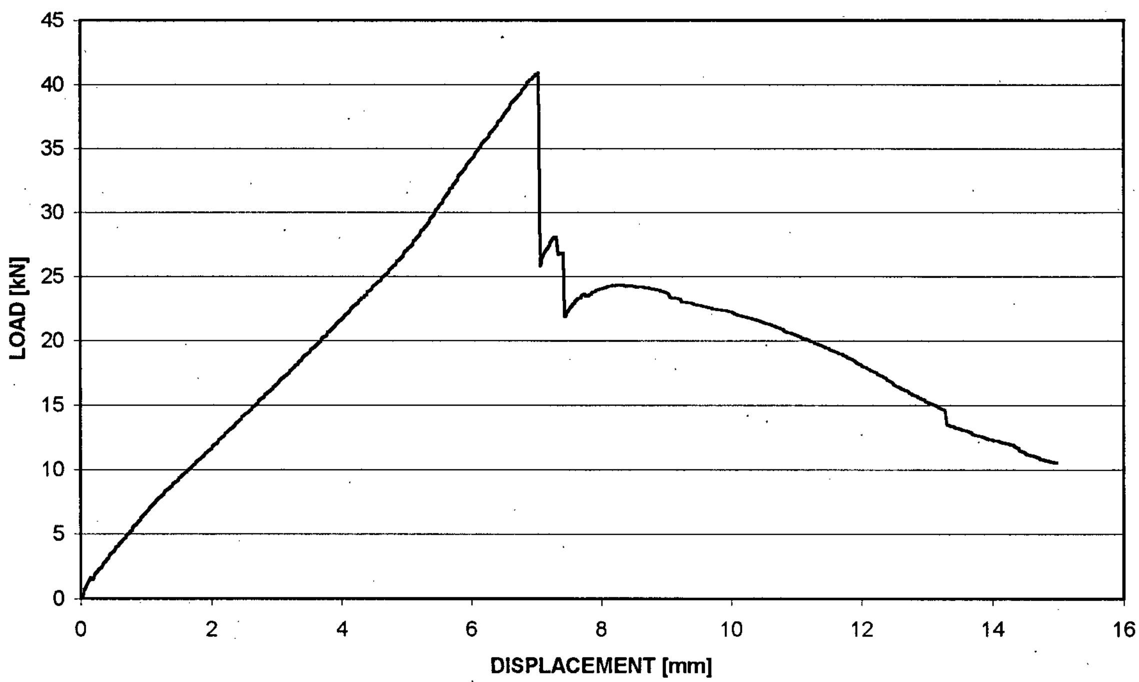
SPECIMEN NO. 6

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Connection Type : Reinforced with 1 dowel at 50 mm , with bushing
- Bushing Location : 120 mm, measured from centroid of bushing to member end
- Dowel Locations : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties.

TEST A4 - BUSHING & 1 DOWEL AT 50 mm



B.2. TENSION TESTS

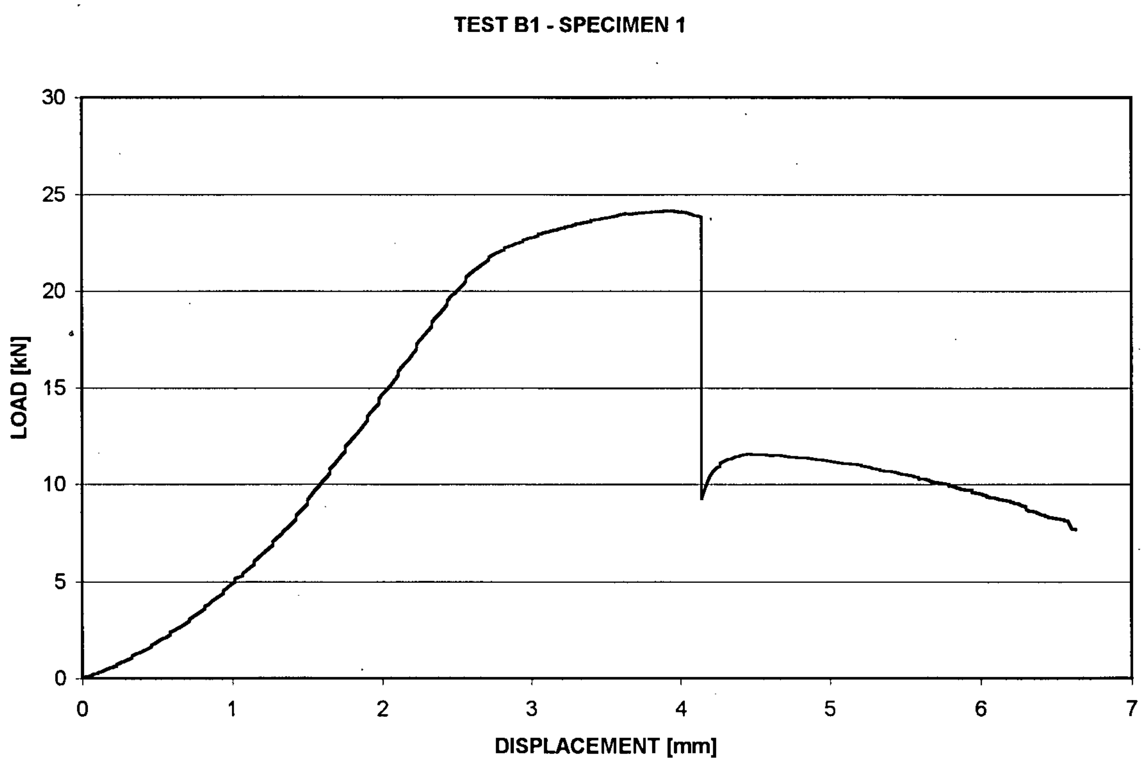
TEST TYPE B1

SPECIMEN NO. 1

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the failure of the element, due to splitting.

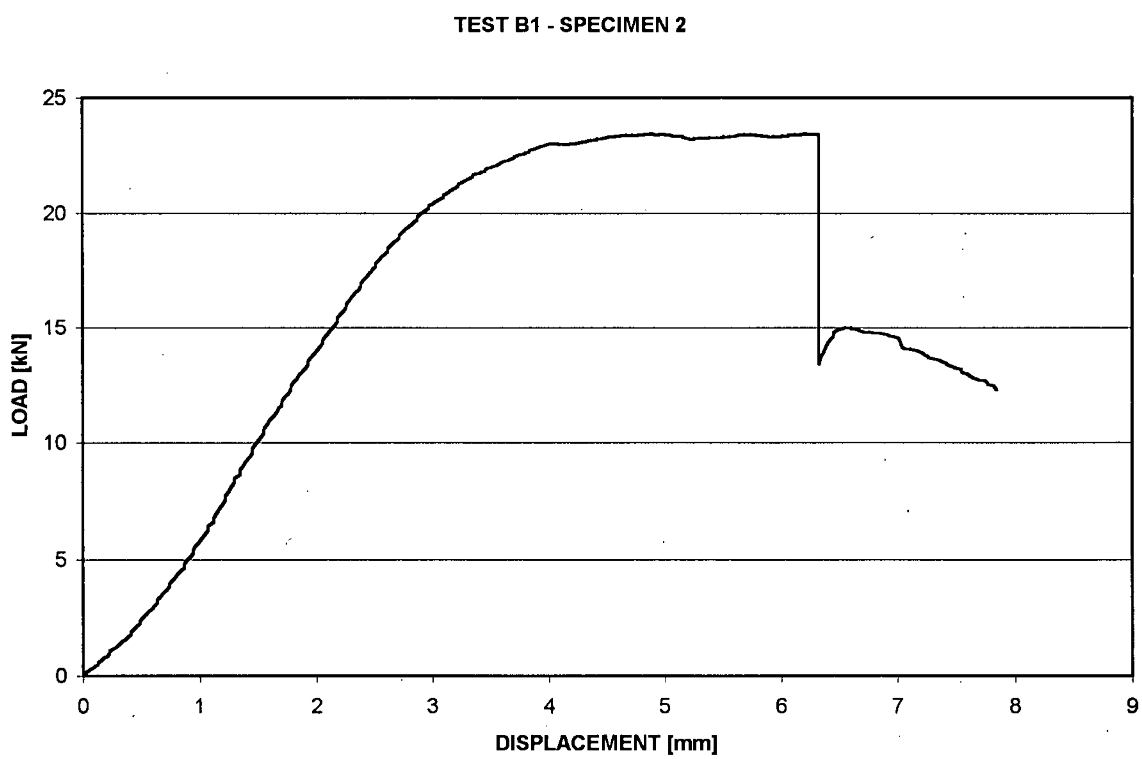


SPECIMEN NO. 2

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the failure of the element, due to splitting.

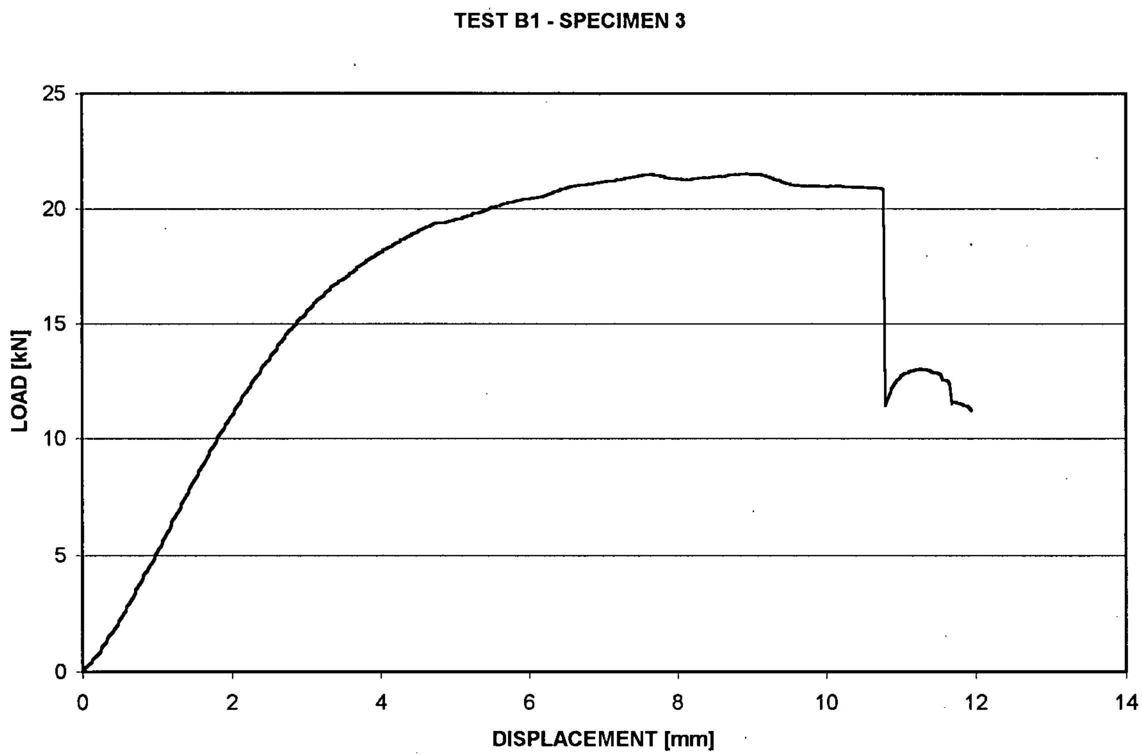


SPECIMEN NO. 3

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the failure of the element, due to splitting.

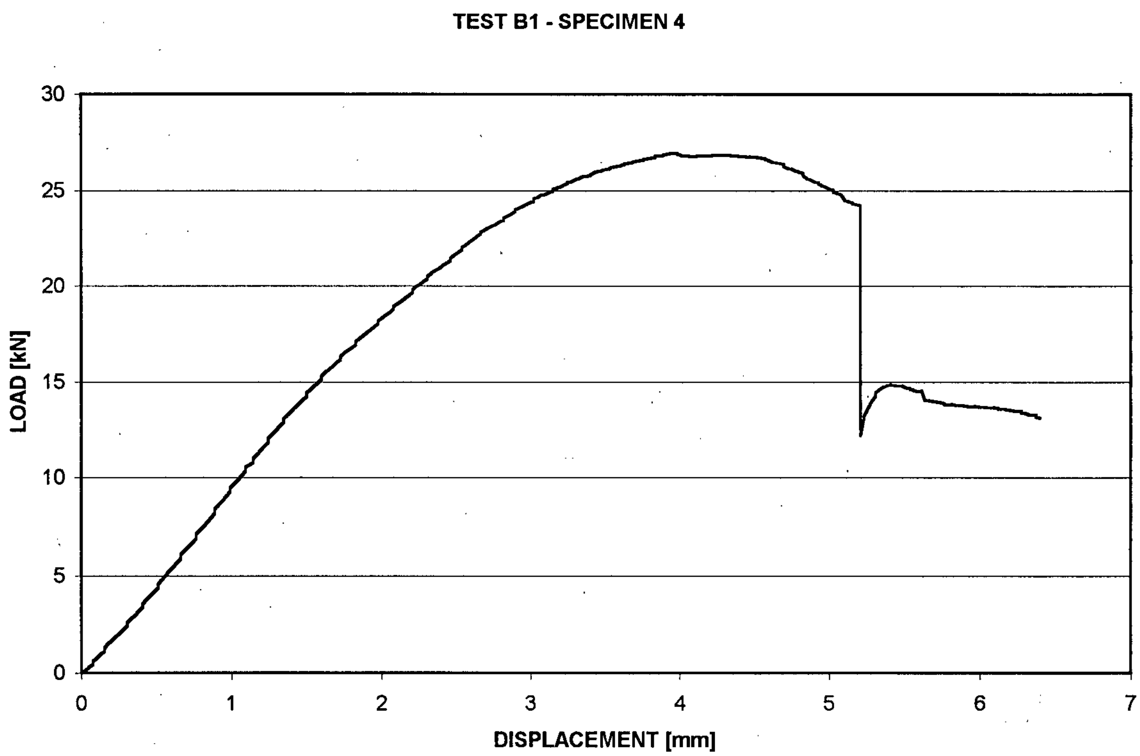


SPECIMEN NO. 4

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the failure of the element, due to splitting.

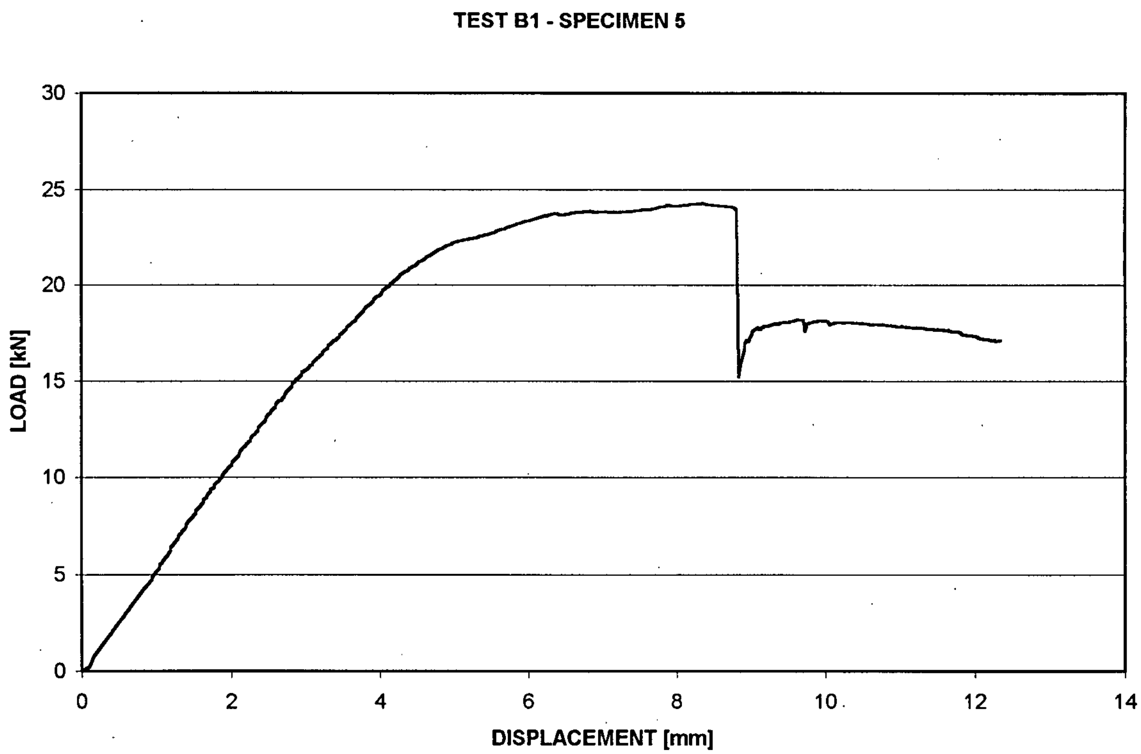


SPECIMEN NO. 5

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the failure of the element, due to splitting.

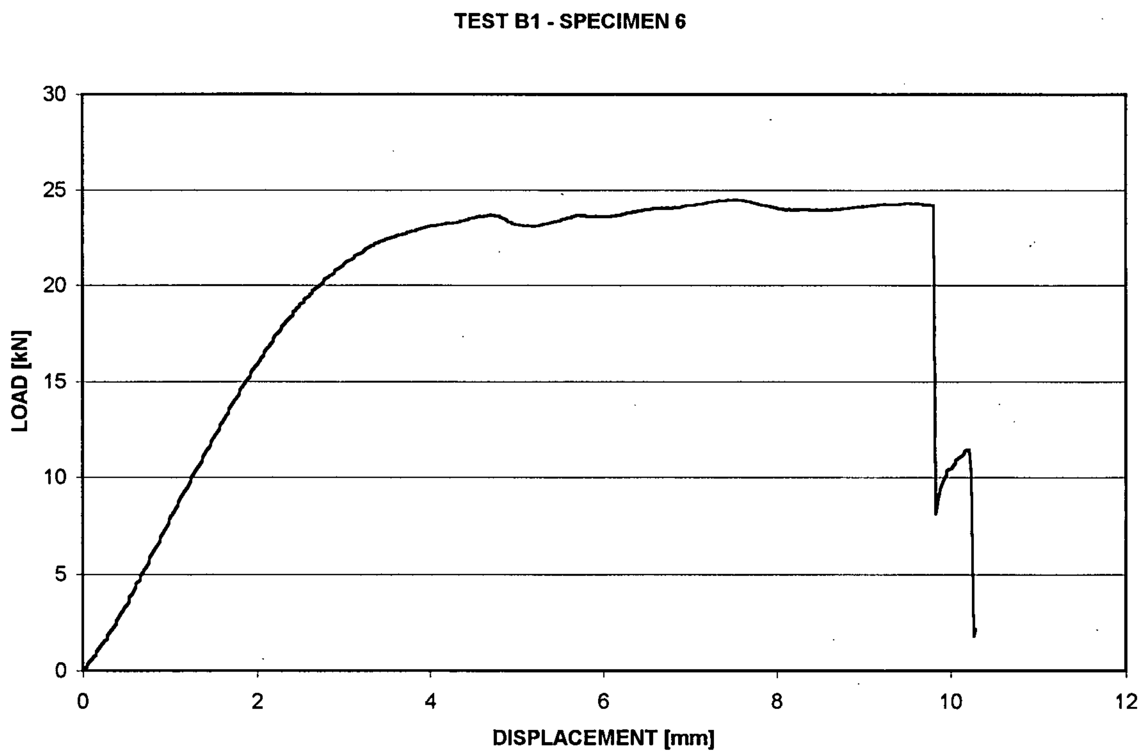


SPECIMEN NO. 6

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the failure of the element, due to splitting.

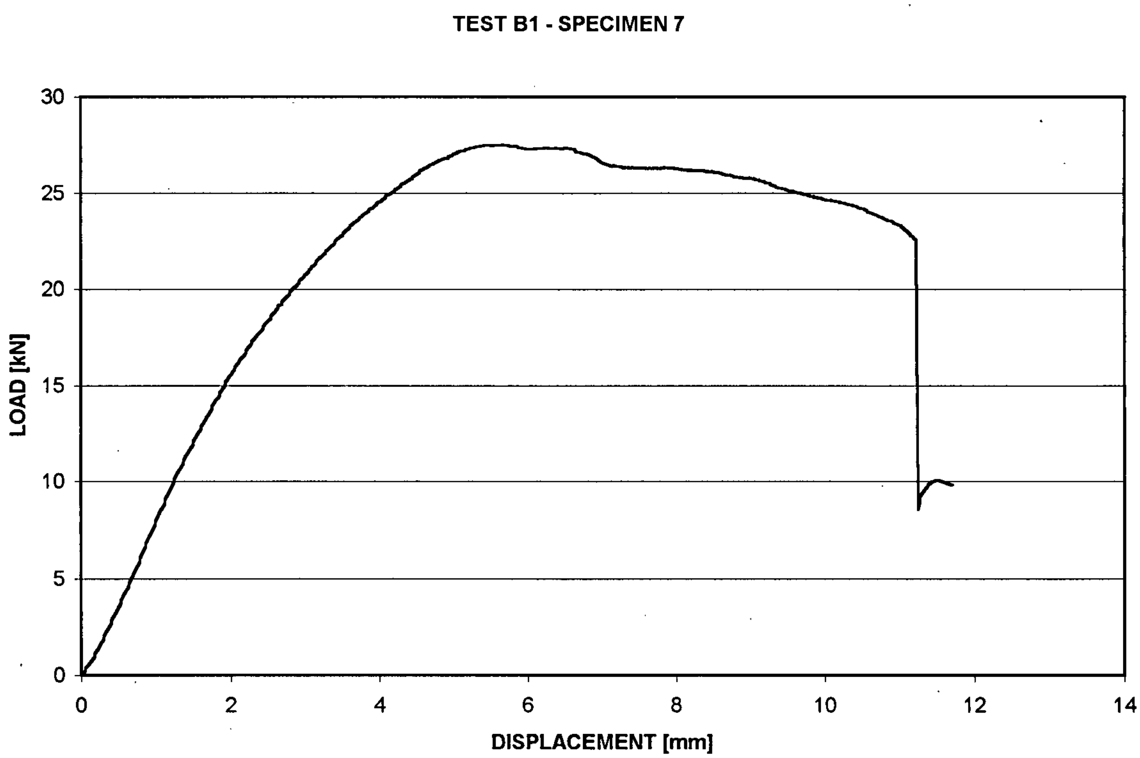


SPECIMEN NO. 7

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the failure of the element, due to splitting.

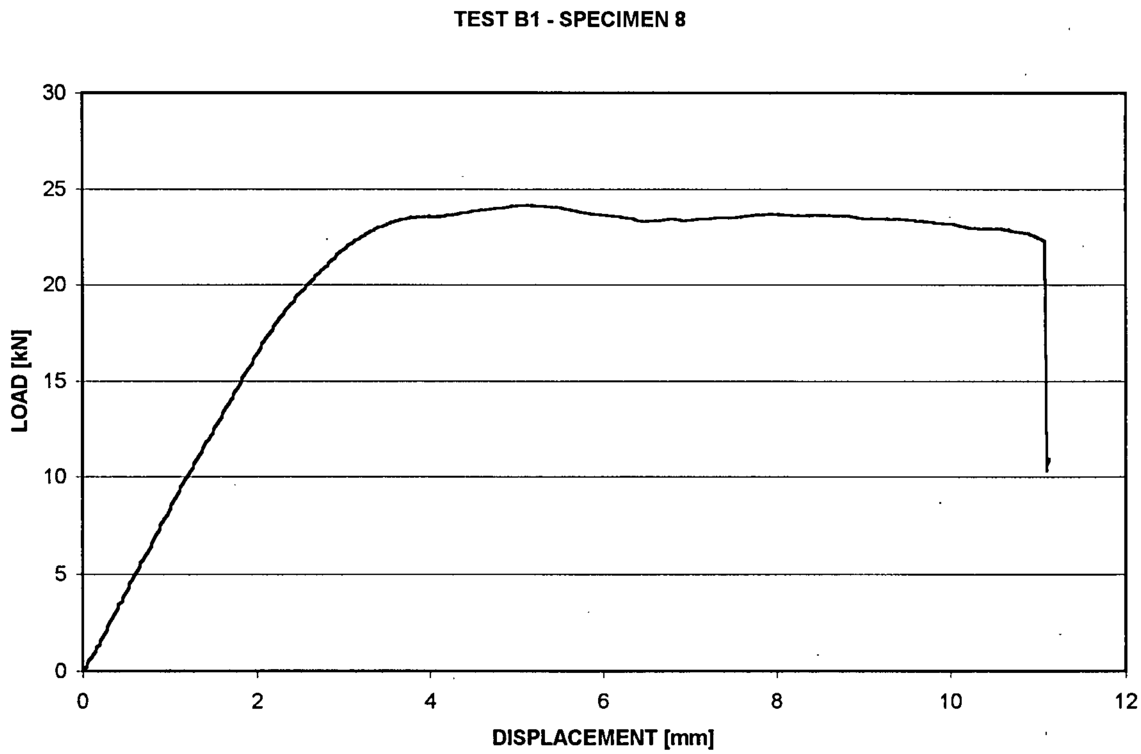


SPECIMEN NO. 8

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the failure of the element, due to splitting.

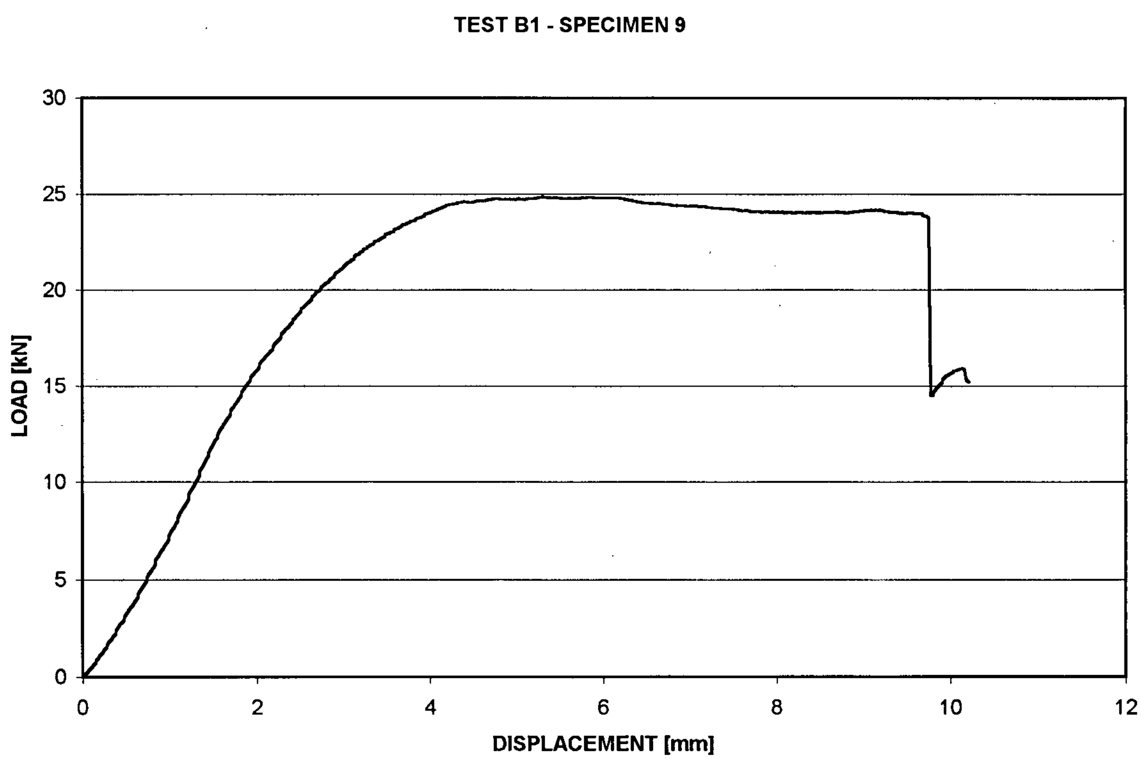


SPECIMEN NO. 9

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the failure of the element, due to splitting.

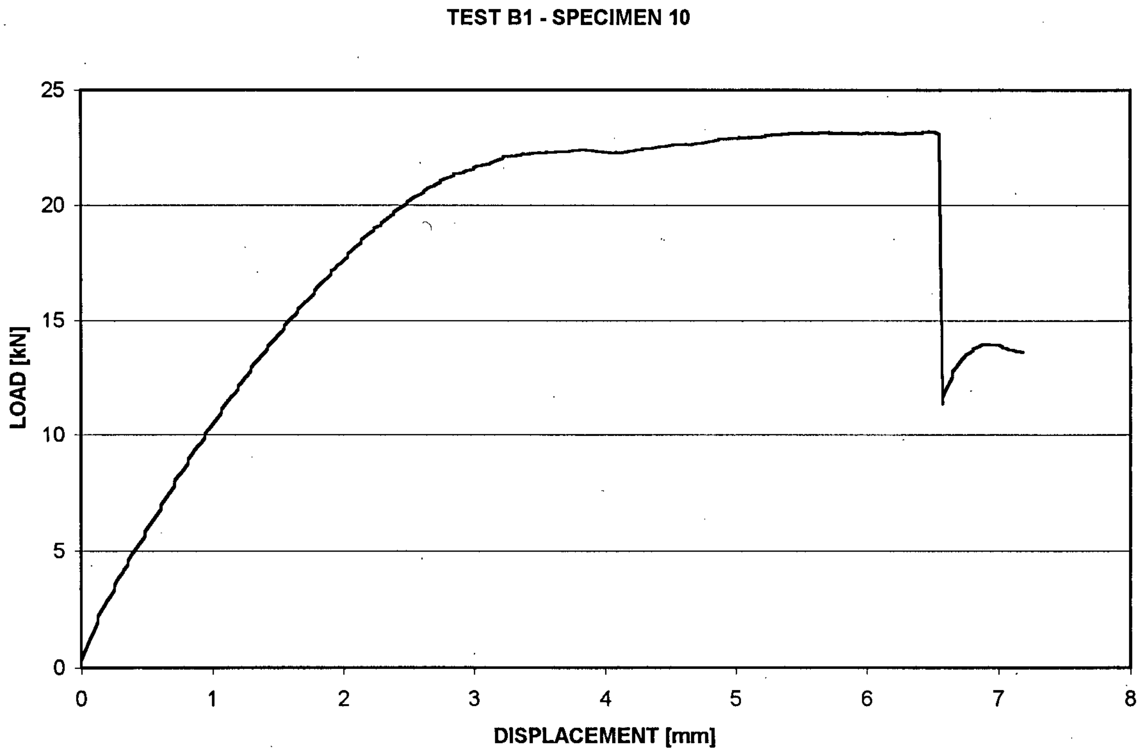


SPECIMEN NO. 10

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the failure of the element, due to splitting.



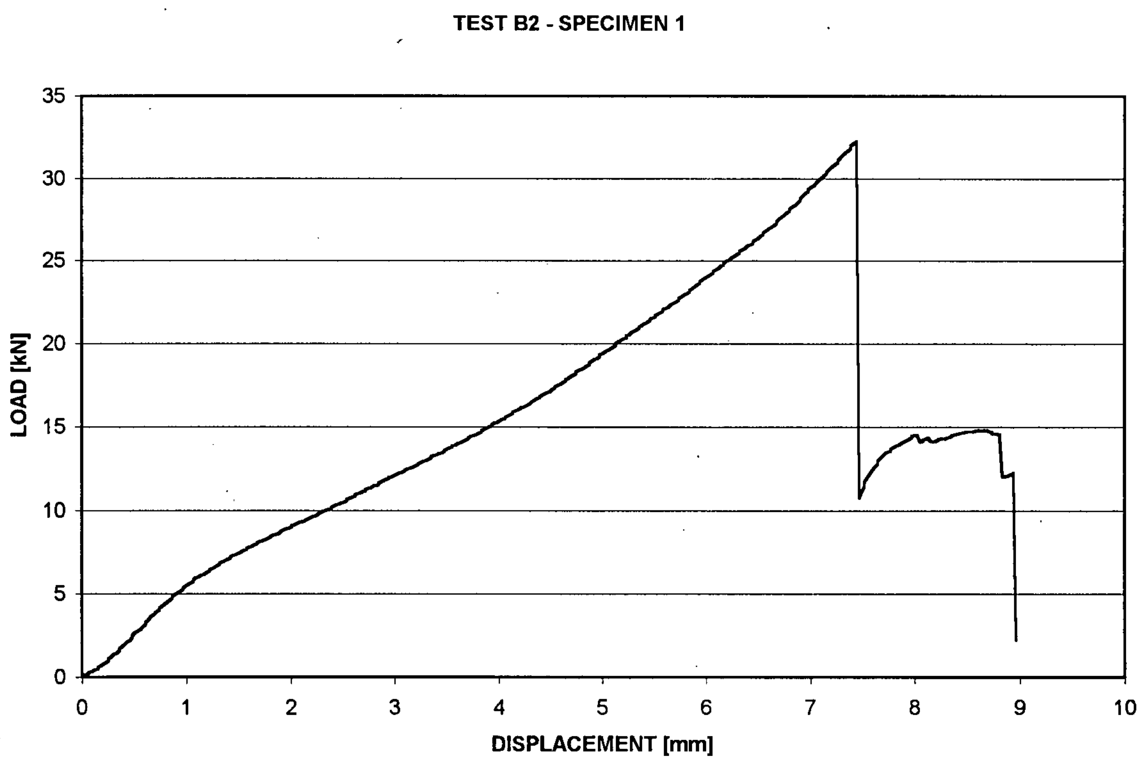
TEST TYPE B2

SPECIMEN NO. 1

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, unreinforced

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after failure of wood due to splitting.

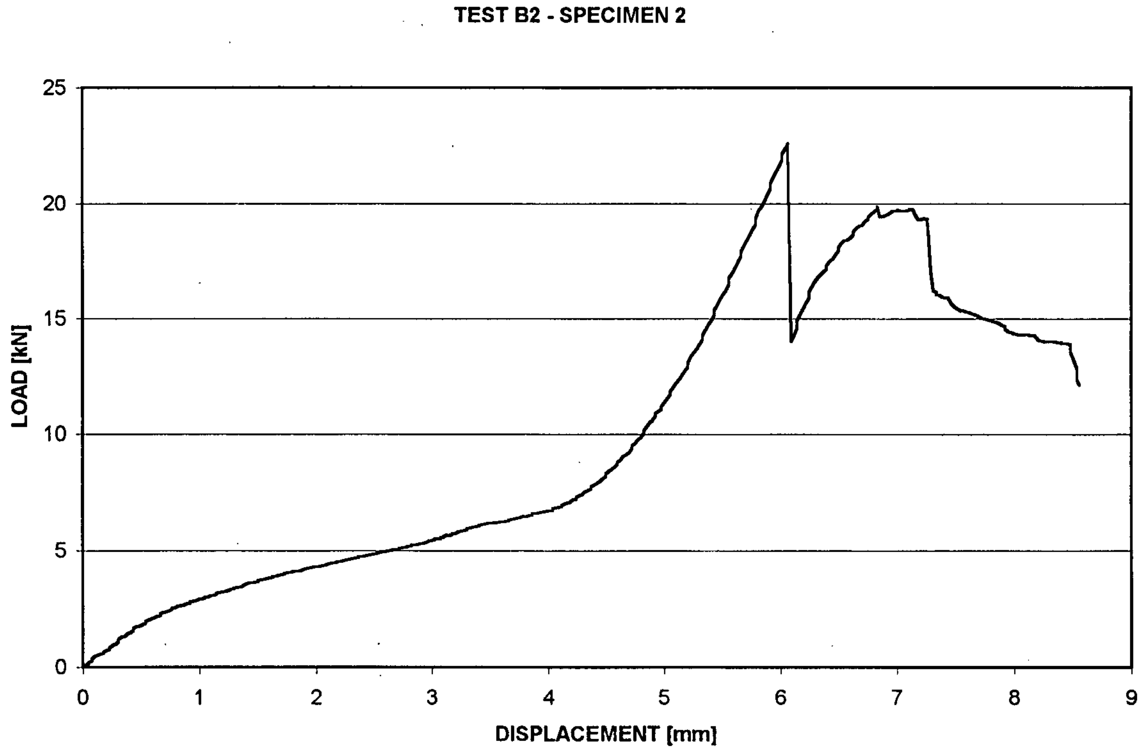


SPECIMEN NO. 2

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, unreinforced

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after failure of wood due to splitting.

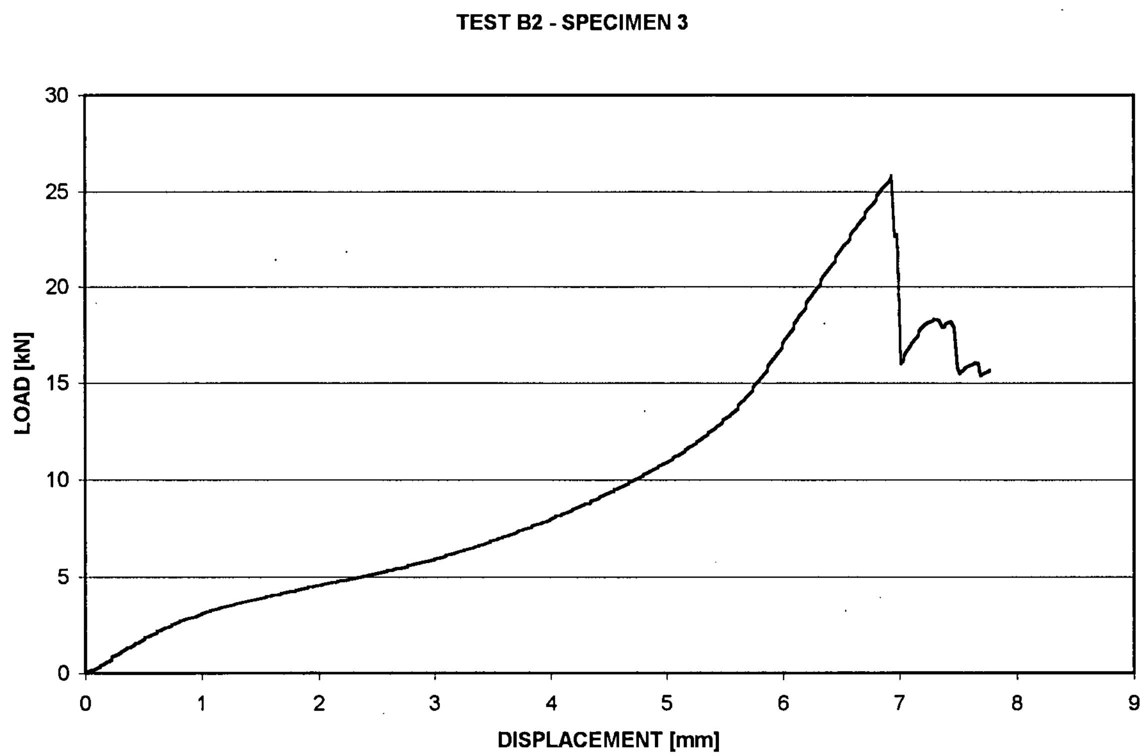


SPECIMEN NO. 3

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, unreinforced

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after failure of wood due to splitting.

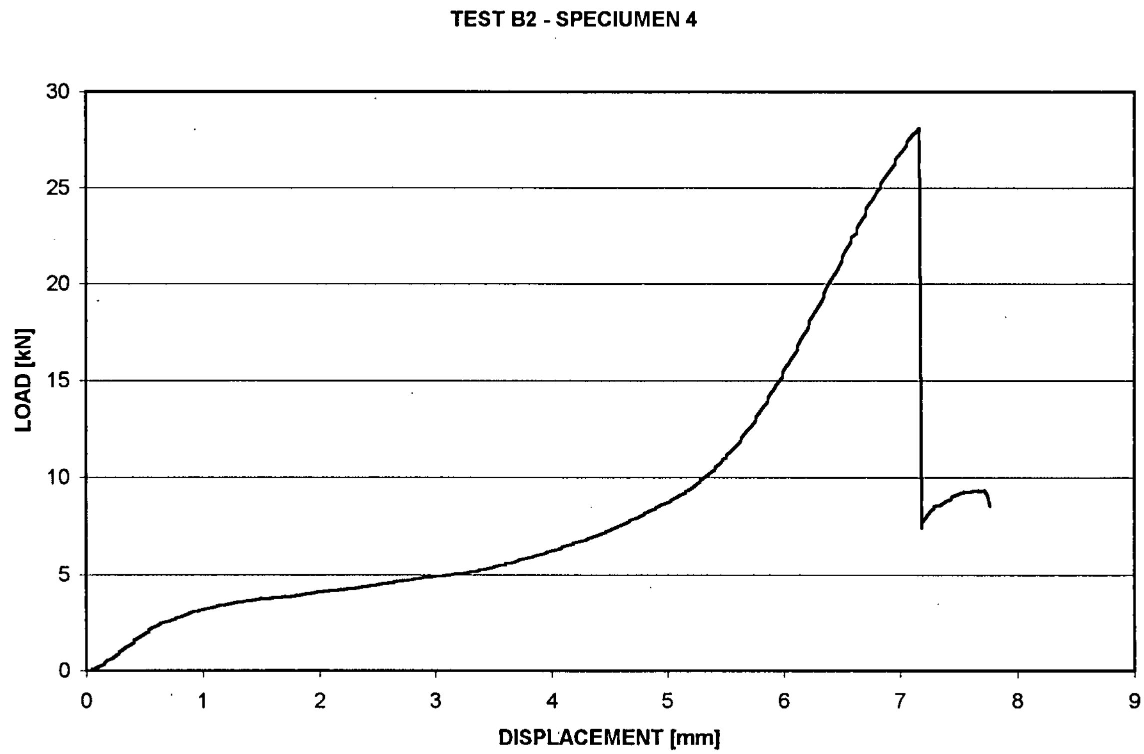


SPECIMEN NO. 4

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, unreinforced

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after failure of wood due to splitting.

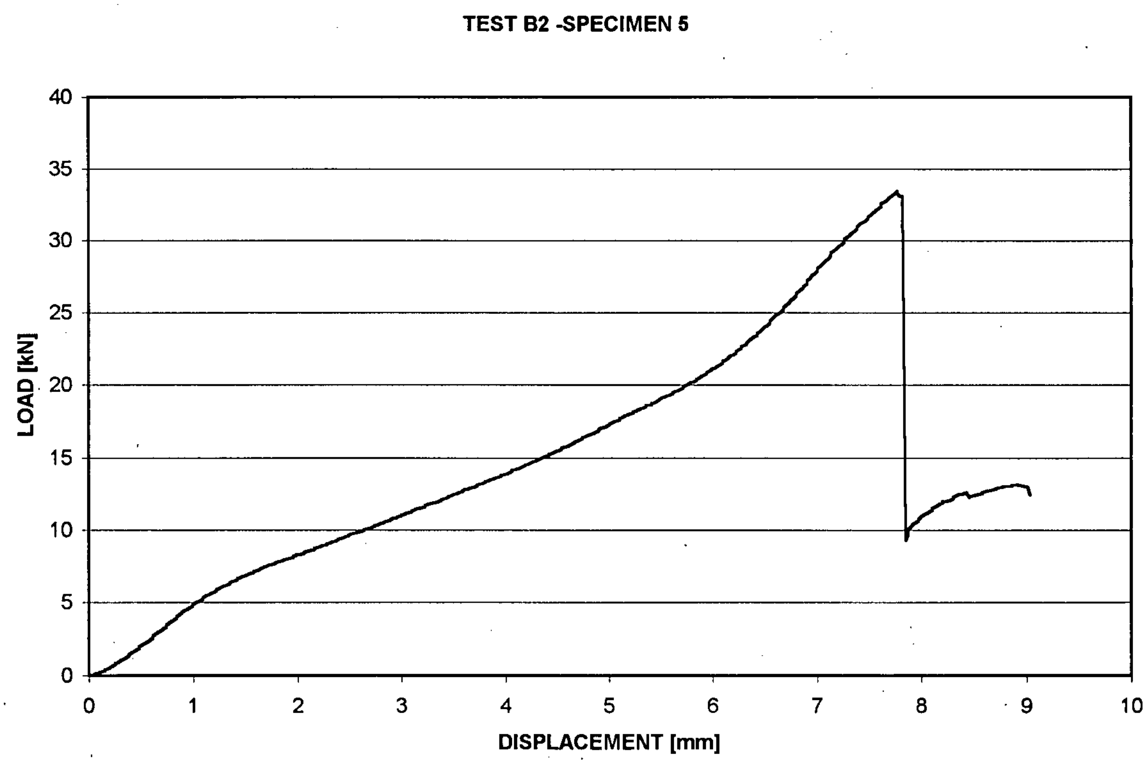


SPECIMEN NO. 5

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, unreinforced

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after failure of wood due to splitting.

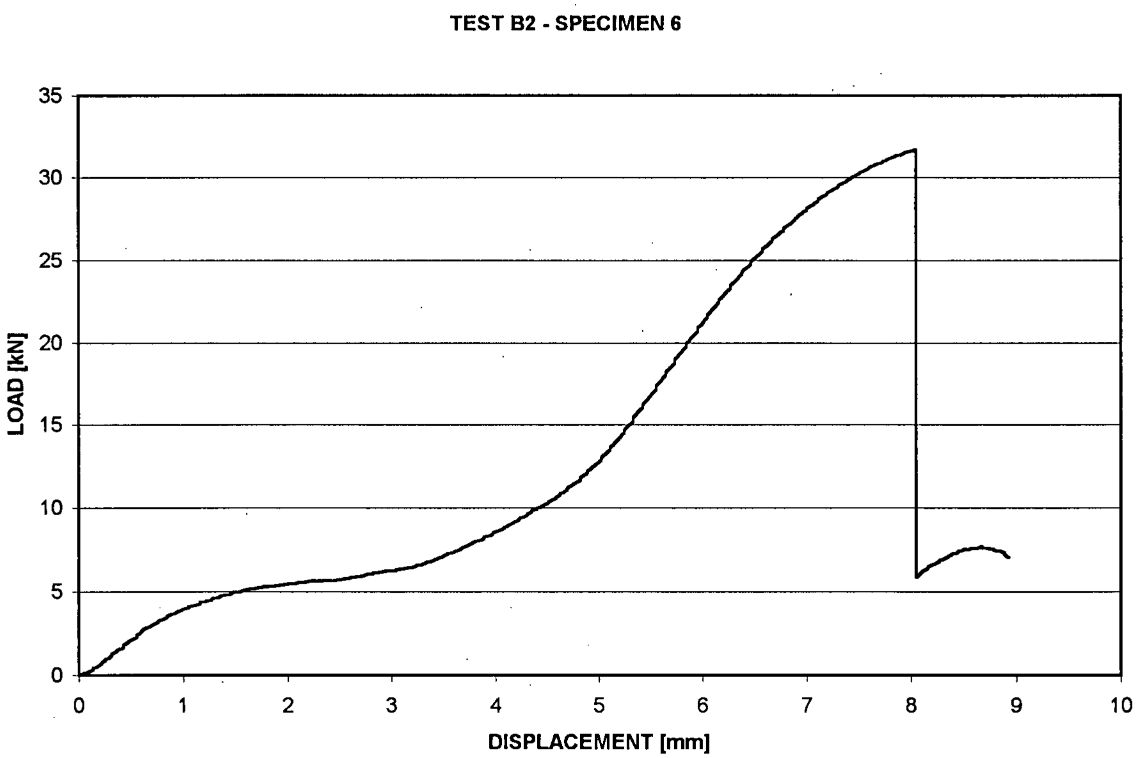


SPECIMEN NO. 6

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, unreinforced

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after failure of wood due to splitting.



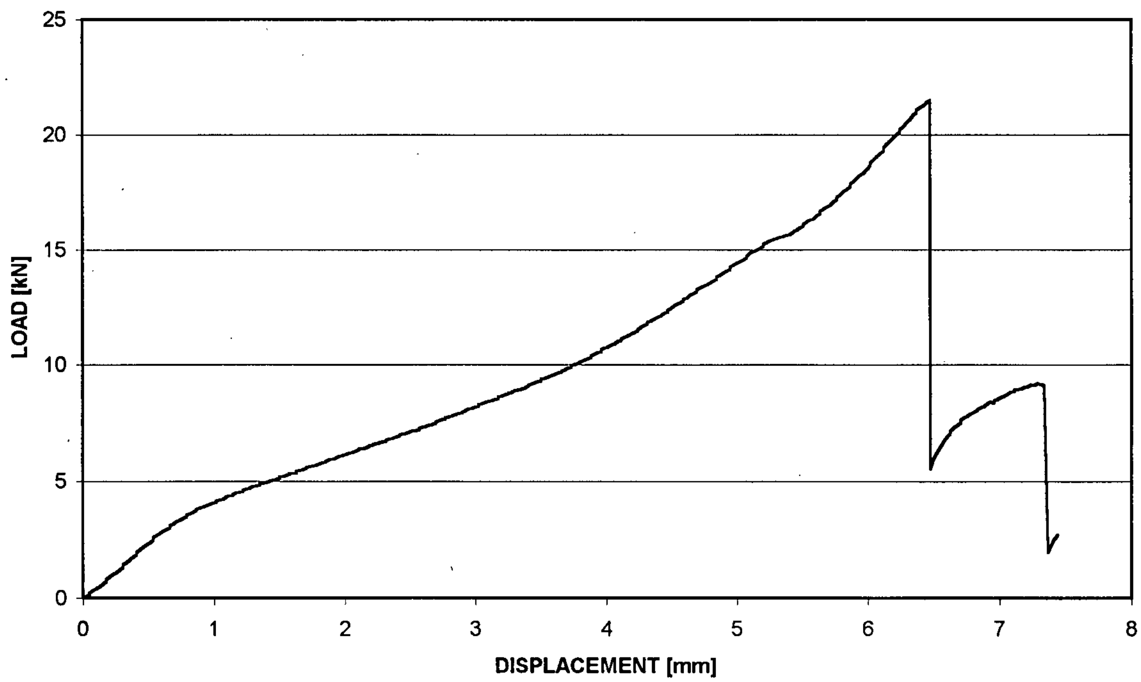
SPECIMEN NO. 7

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, unreinforced

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after failure of wood due to splitting.

TEST B2 - SPECIMEN 7

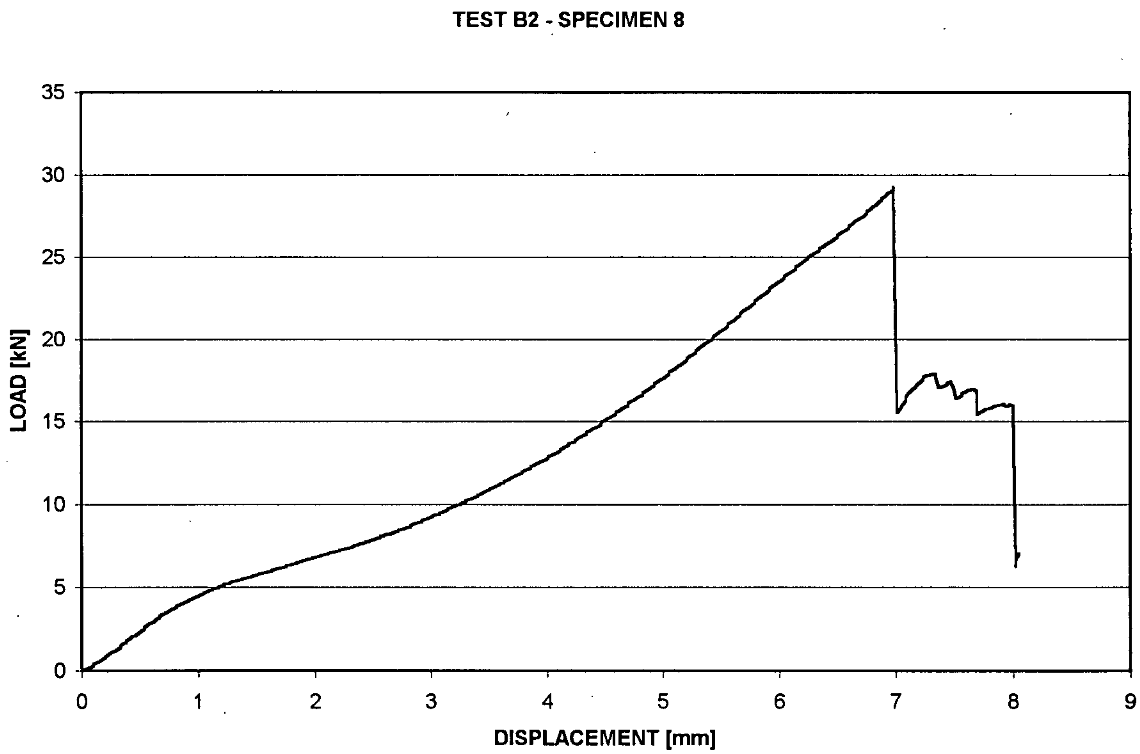


SPECIMEN NO. 8

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from axis to the member end
- Bushing Type : Small, unreinforced

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after failure of wood due to splitting.

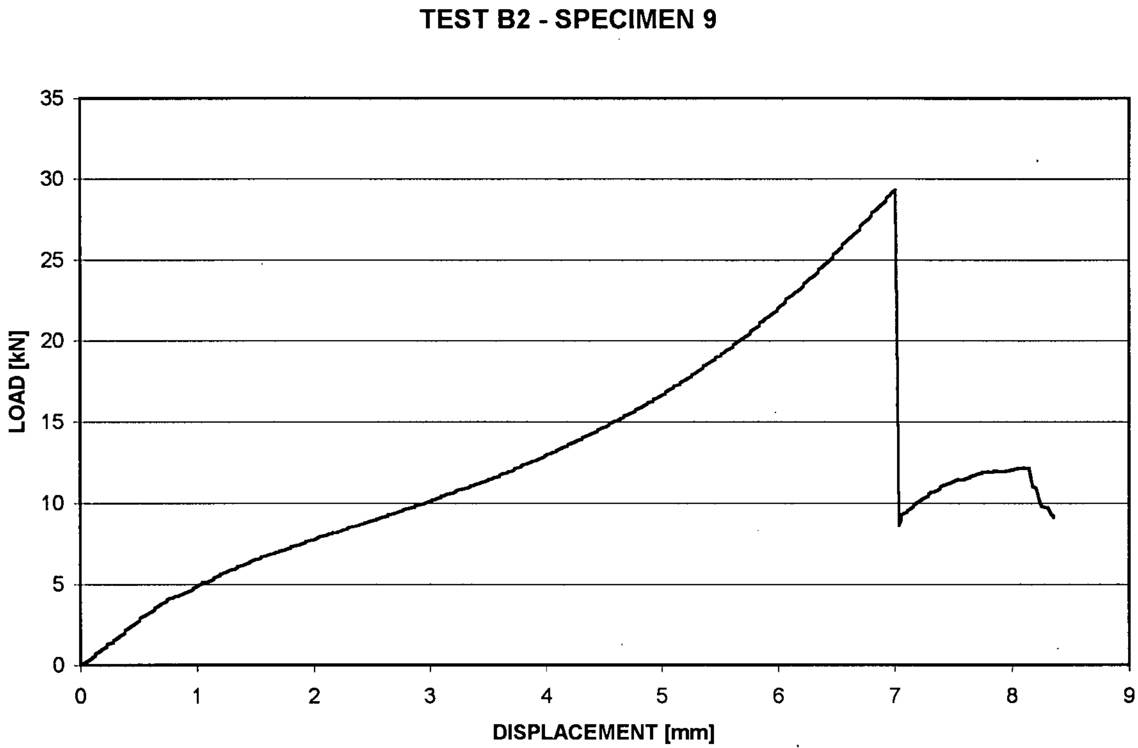


SPECIMEN NO. 9

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from axis to the member end
- Bushing Type : Small, unreinforced

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after failure of wood due to splitting.

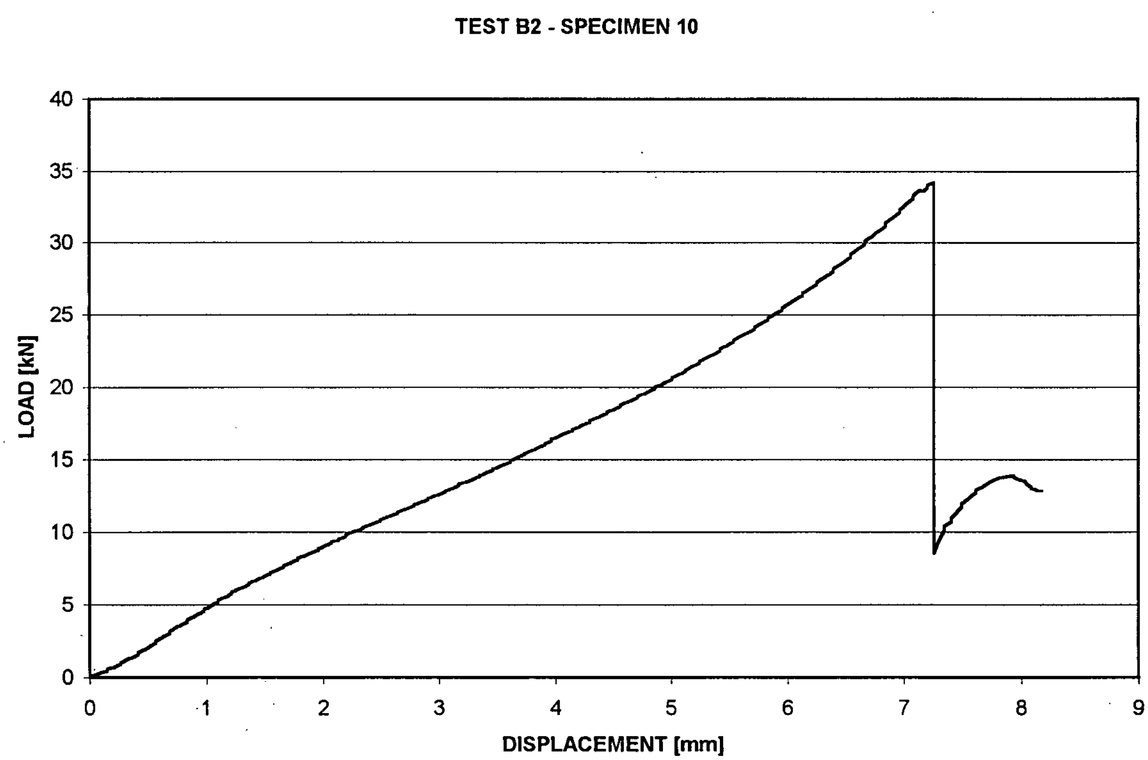


SPECIMEN NO. 10

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from axis to the member end
- Bushing Type : Small, unreinforced

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after failure of wood due to splitting.



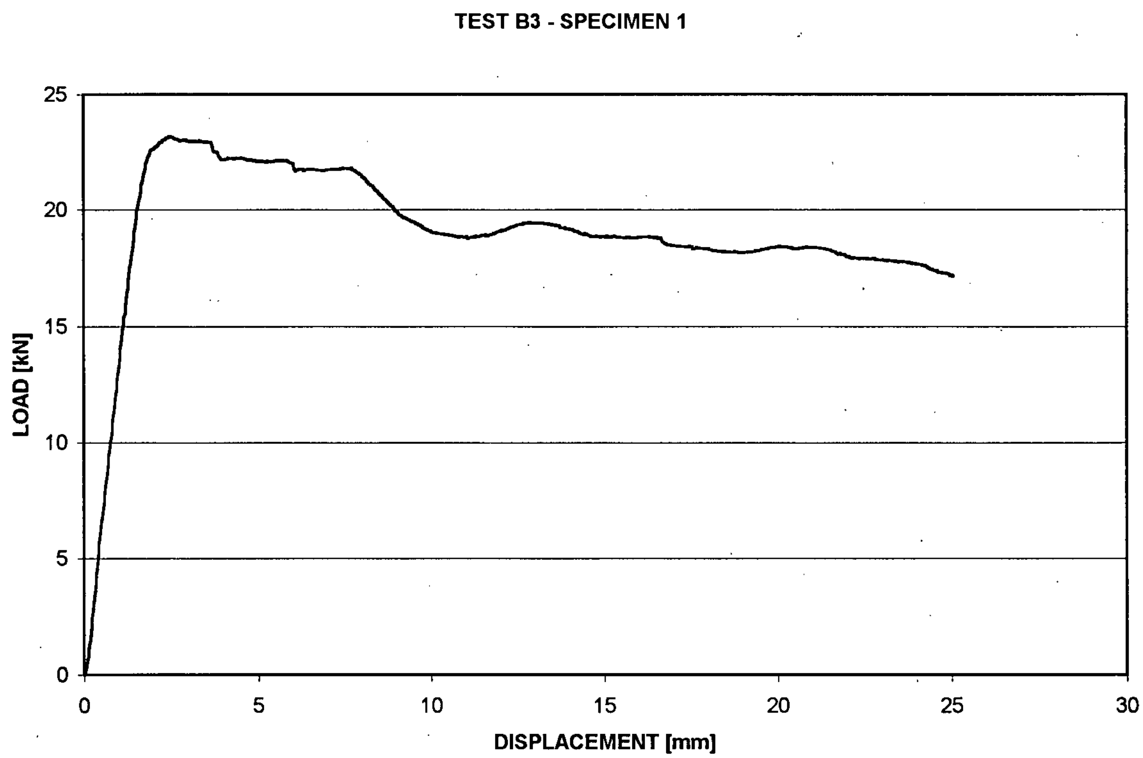
TEST TYPE B3

SPECIMEN NO. 1

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after reaching the predetermined displacement of 25 mm.

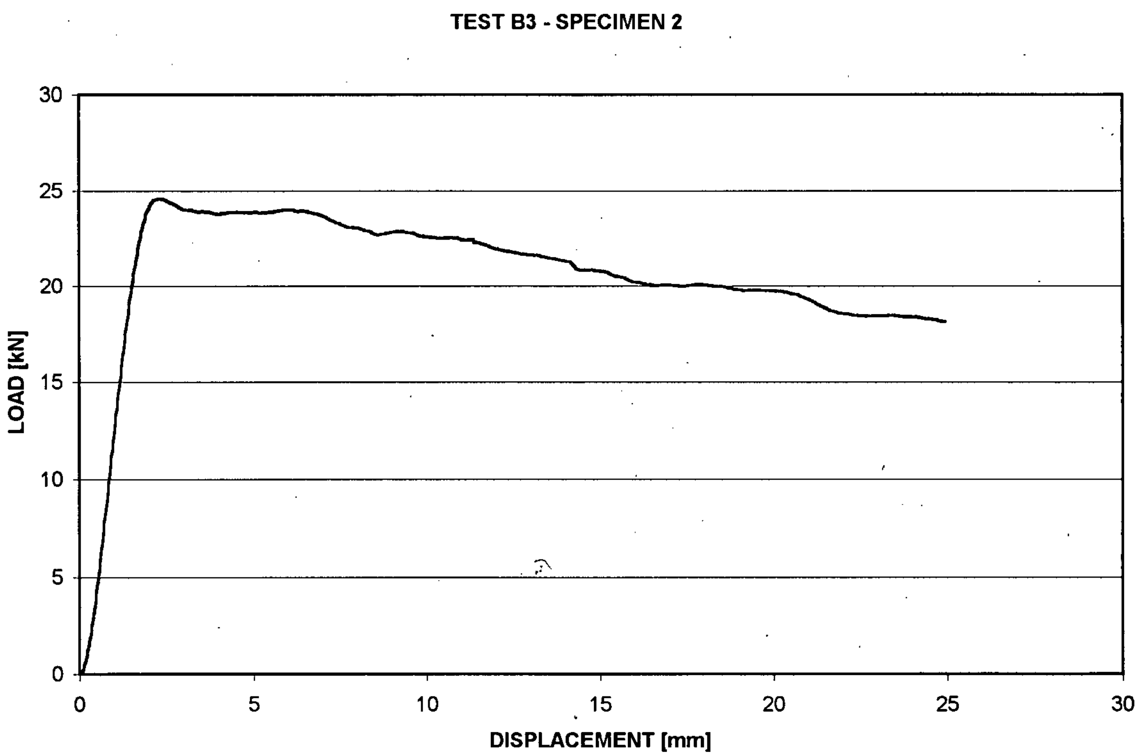


SPECIMEN NO. 2

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after reaching the predetermined displacement of 25 mm.

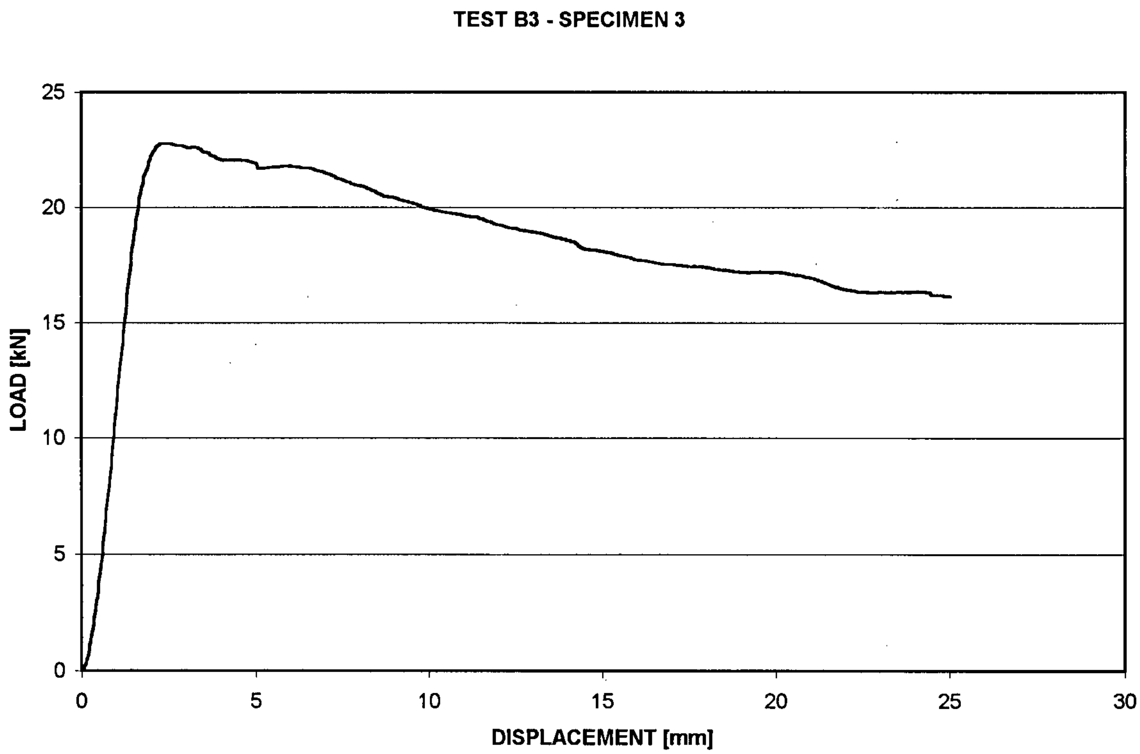


SPECIMEN NO. 3

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after reaching the predetermined displacement of 25 mm.

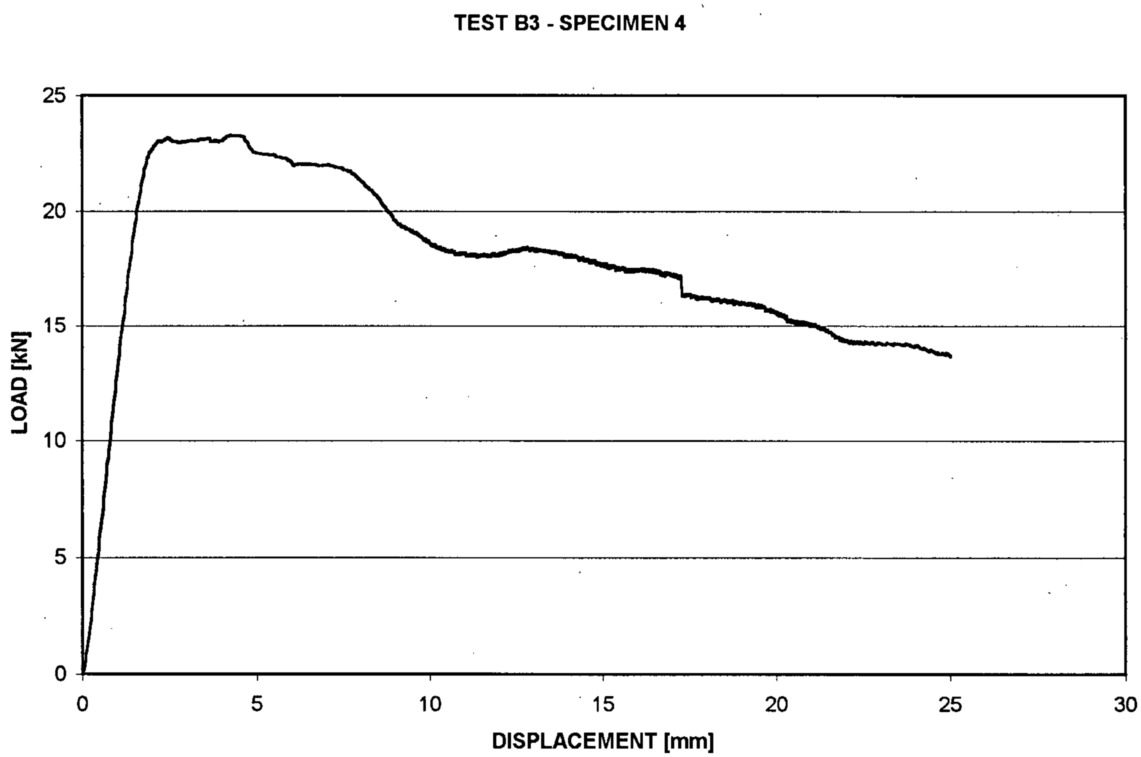


SPECIMEN NO. 4

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after reaching the predetermined displacement of 25 mm.

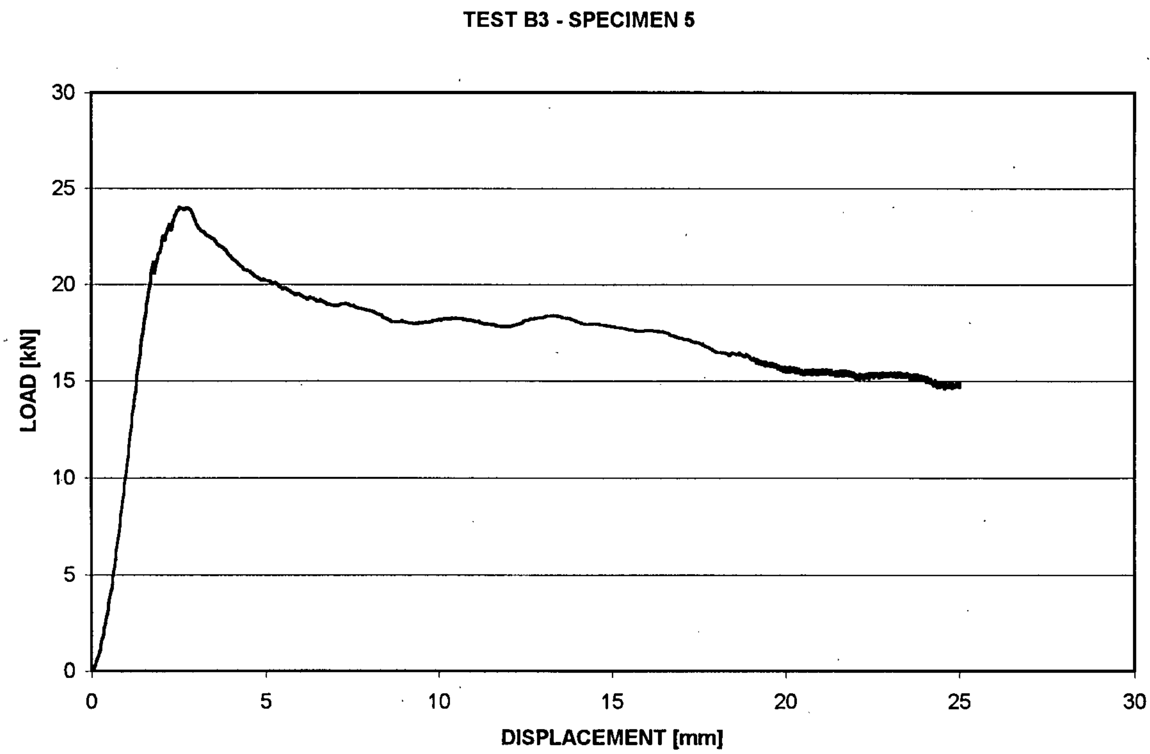


SPECIMEN NO. 5

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after reaching the predetermined displacement of 25 mm.

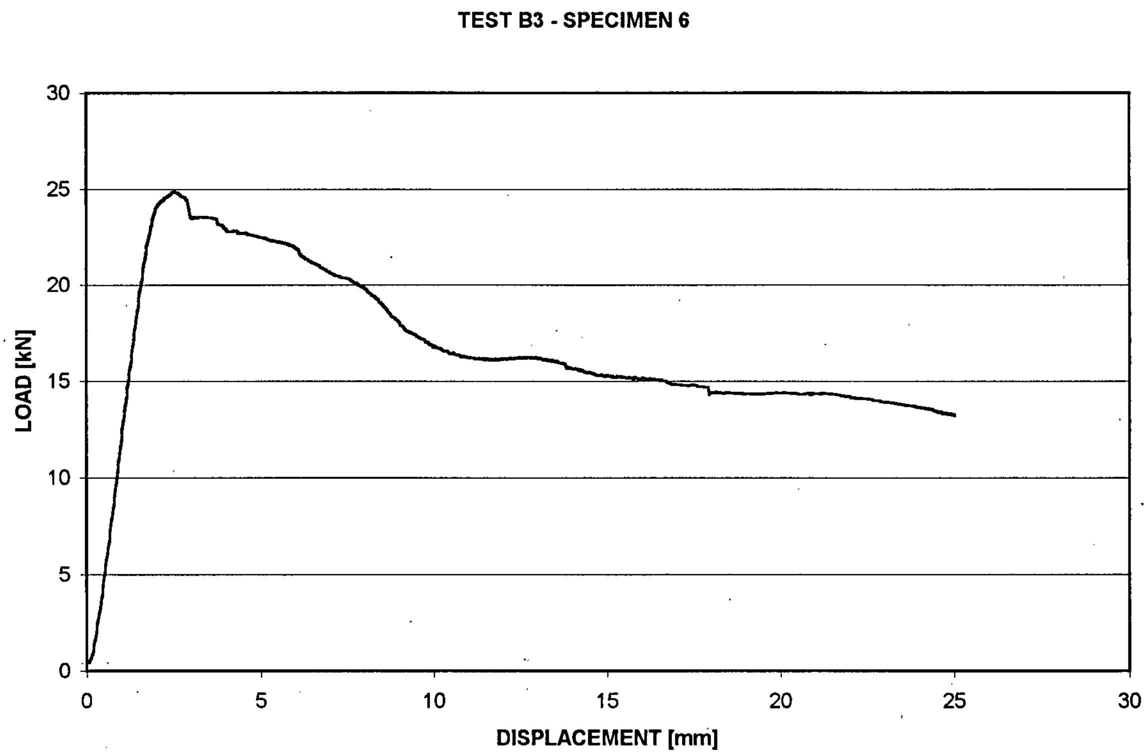


SPECIMEN NO. 6

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after reaching the predetermined displacement of 25 mm.

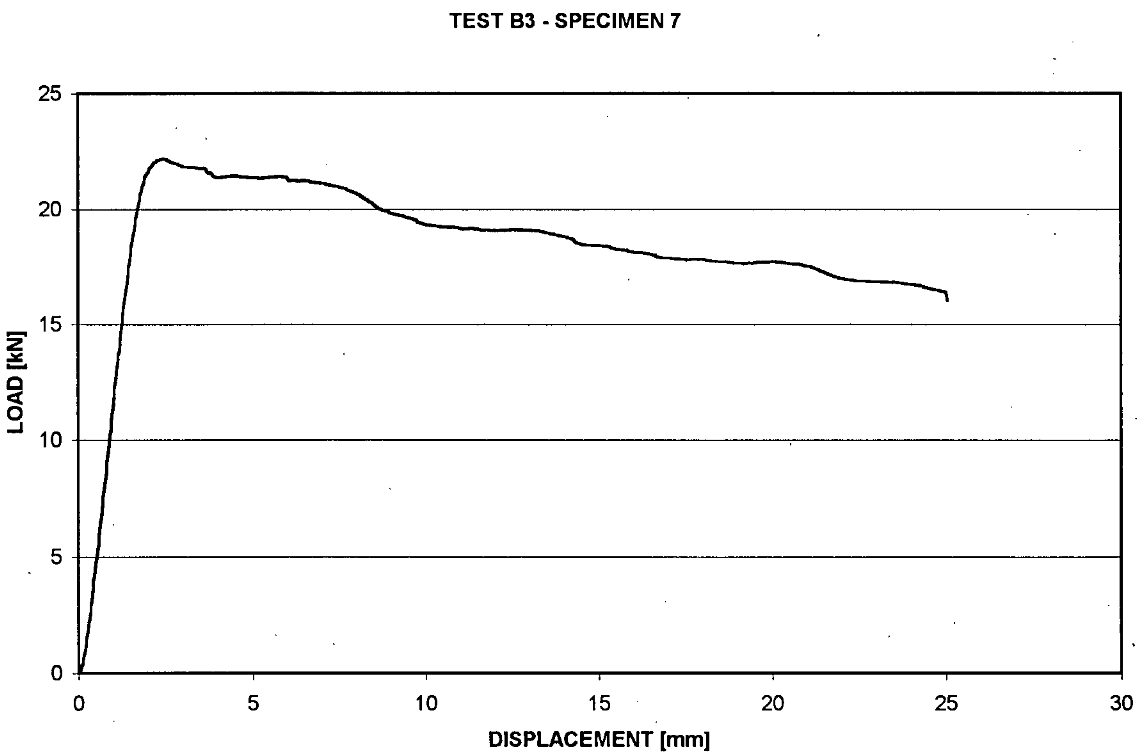


SPECIMEN NO. 7

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after reaching the predetermined displacement of 25 mm.

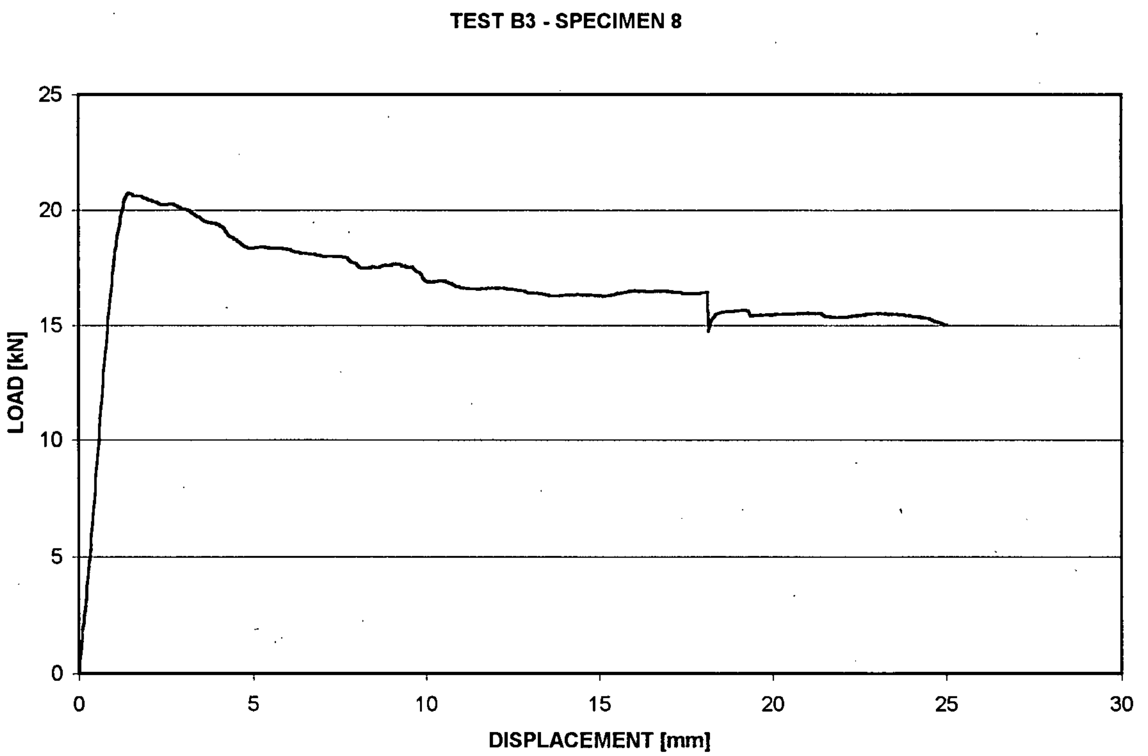


SPECIMEN NO. 8

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after reaching the predetermined displacement of 25 mm.

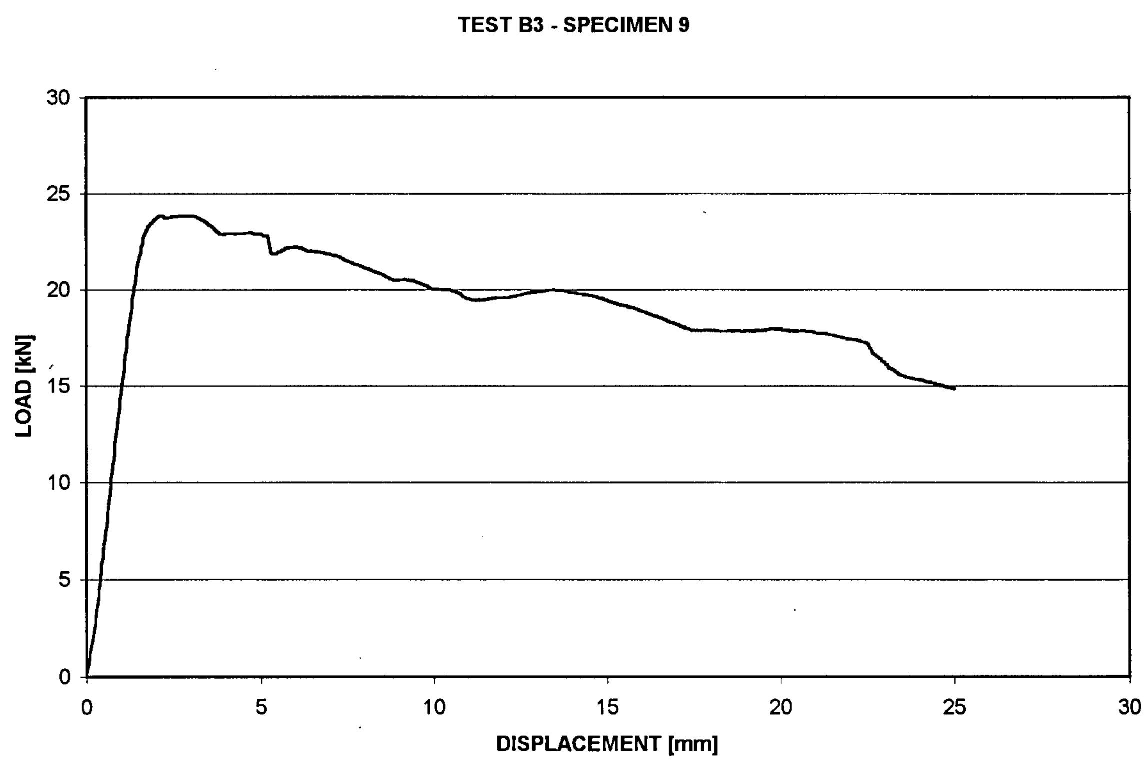


SPECIMEN NO. 9

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after reaching the predetermined displacement of 25 mm.

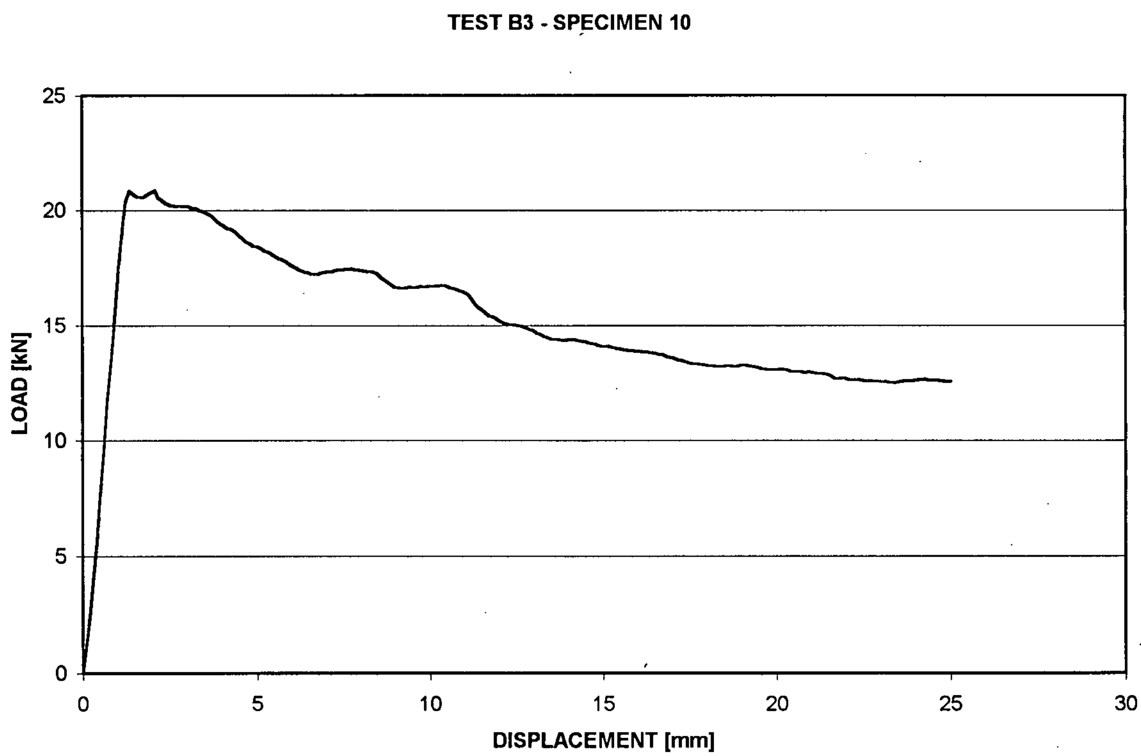


SPECIMEN NO. 10

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after reaching the predetermined displacement of 25 mm.



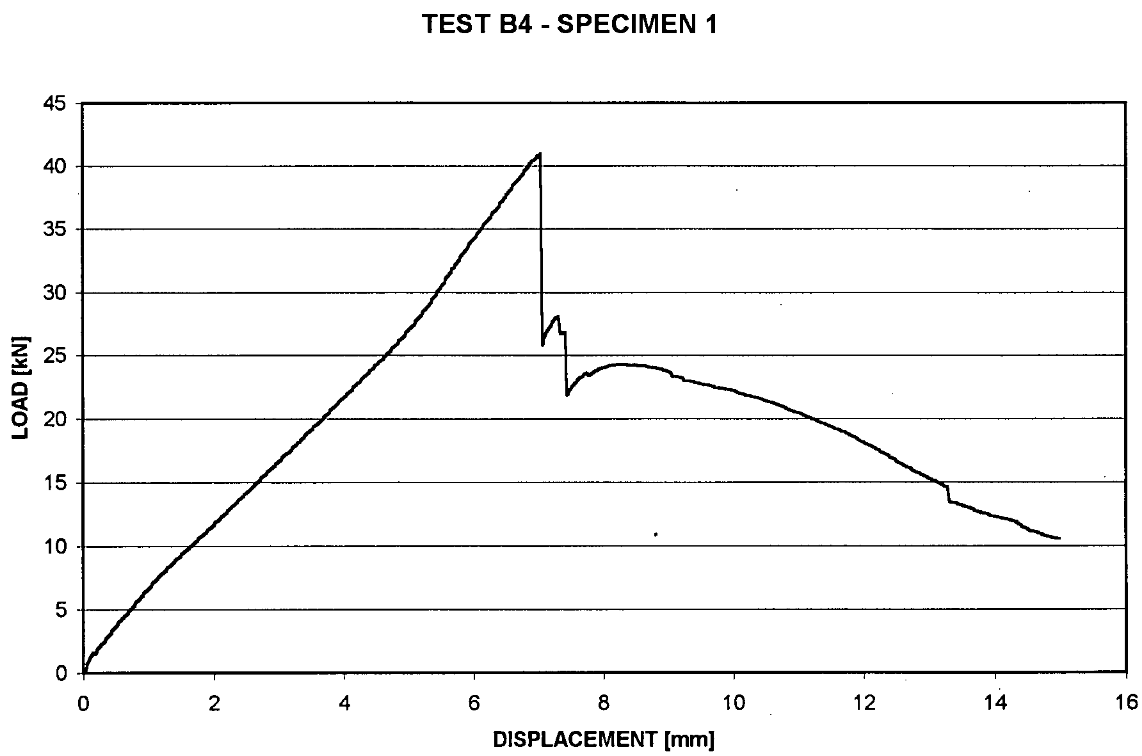
TEST TYPE B4

SPECIMEN NO. 1

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, not reinforced
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after failure of wood due to splitting.

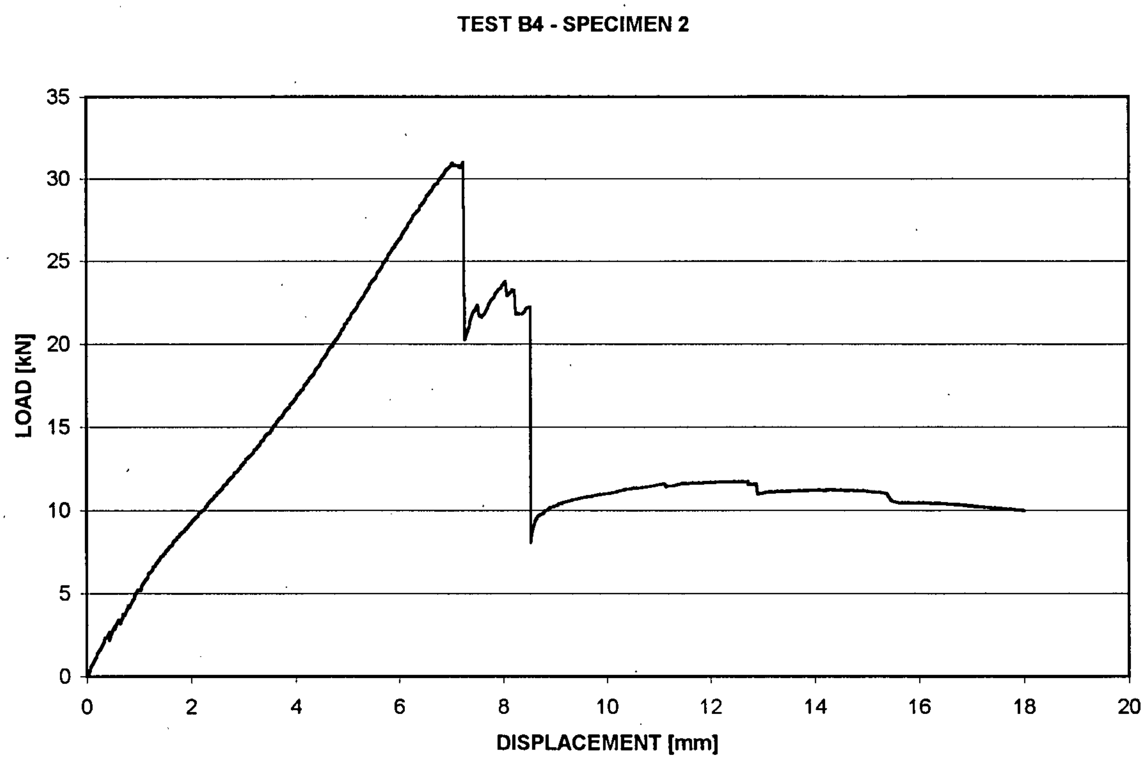


SPECIMEN NO. 2

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, not reinforced
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after wood failure due to splitting.

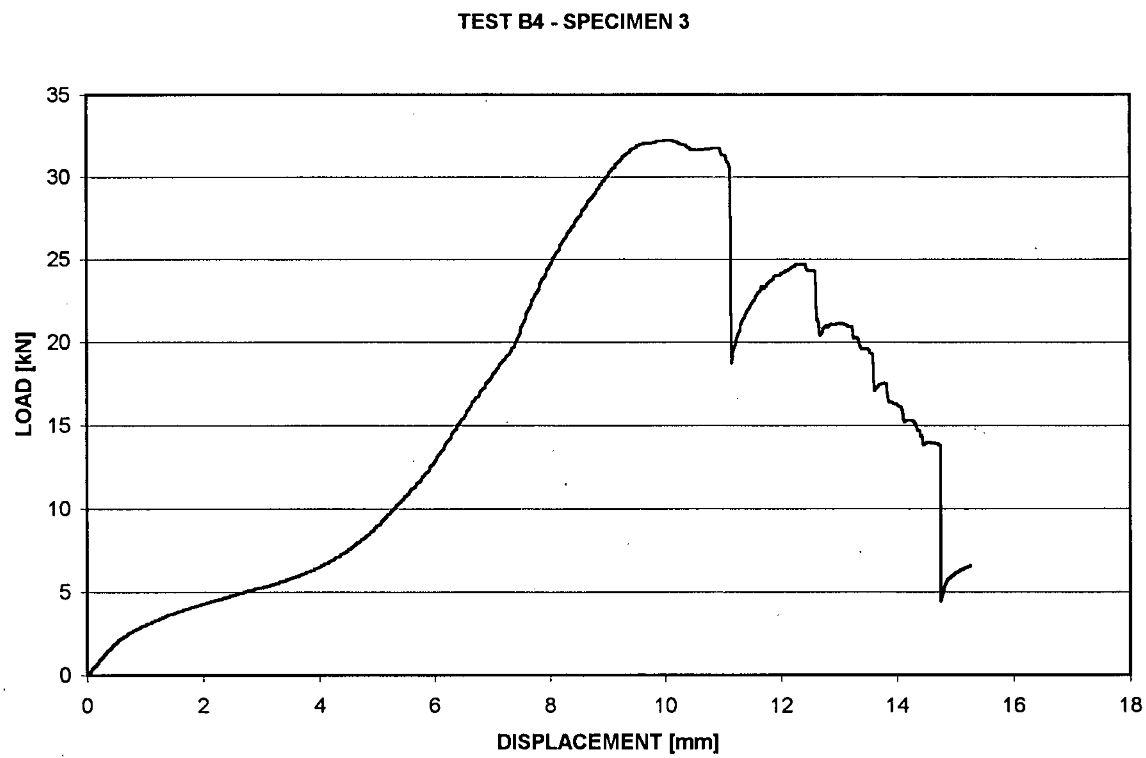


SPECIMEN NO. 3

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, not reinforced
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after wood failure due to splitting.

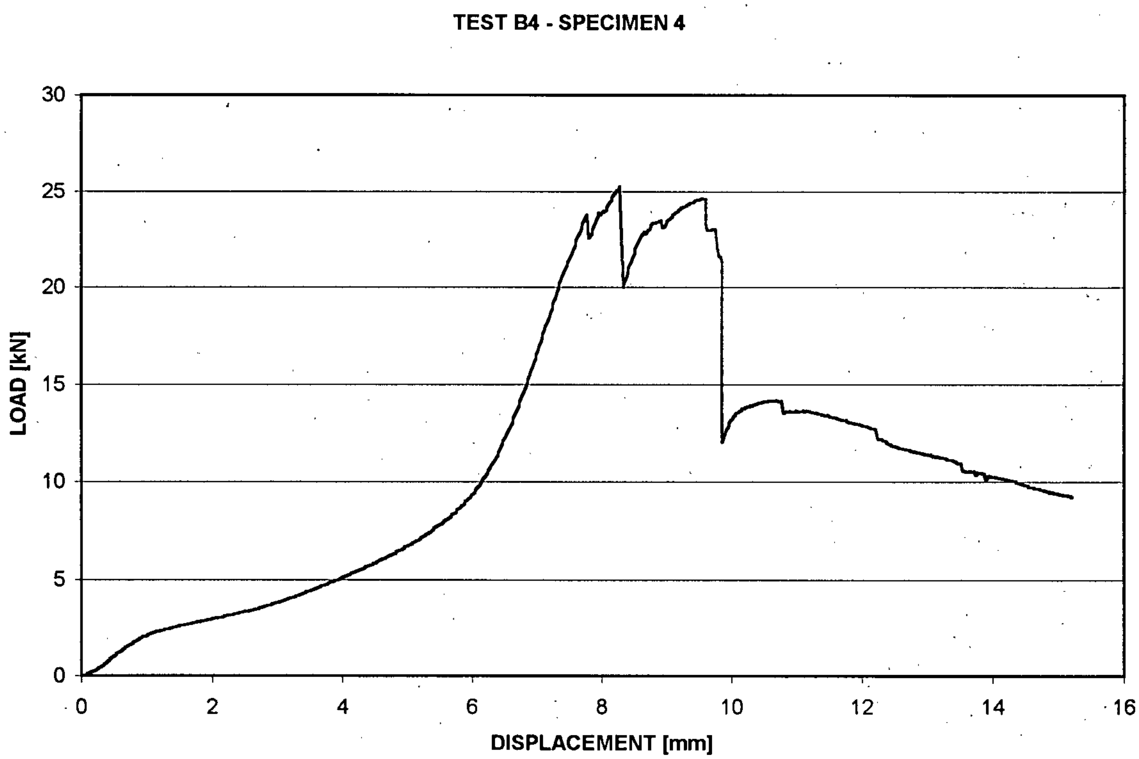


SPECIMEN NO. 4

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, not reinforced
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after wood failure due to splitting.

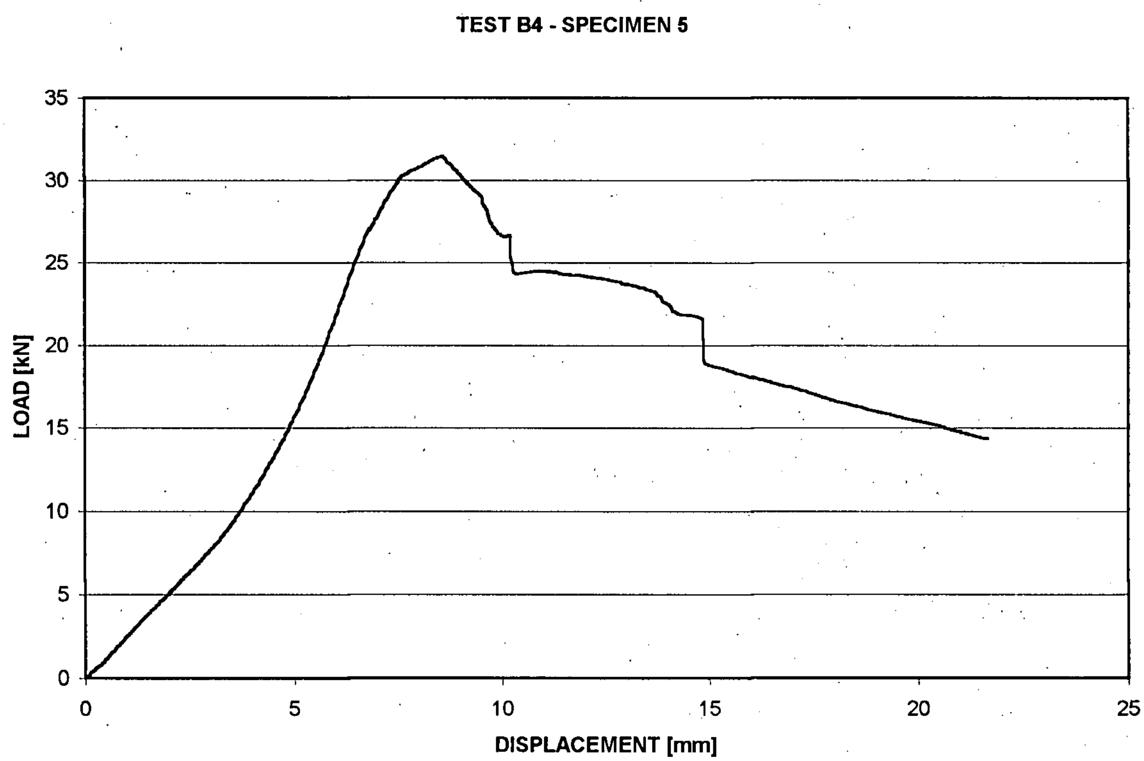


SPECIMEN NO. 5

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, not reinforced
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after wood failure due to splitting.

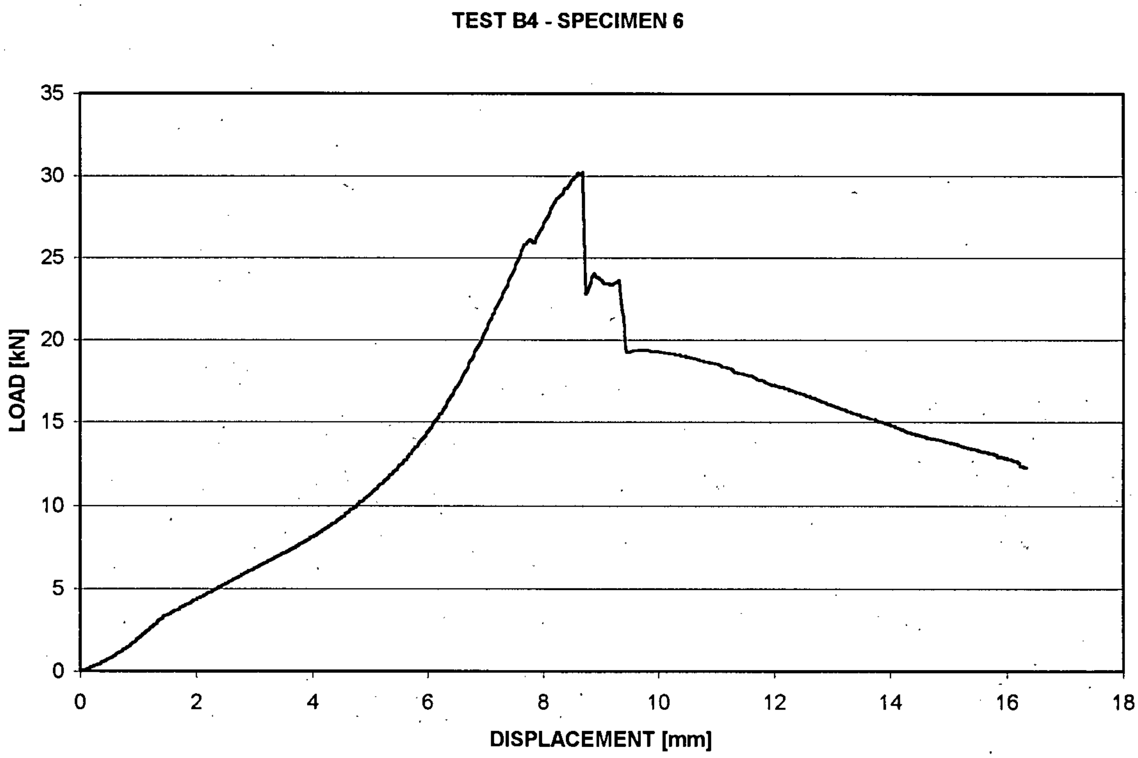


SPECIMEN NO. 6

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, not reinforced
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after wood failure due to splitting.

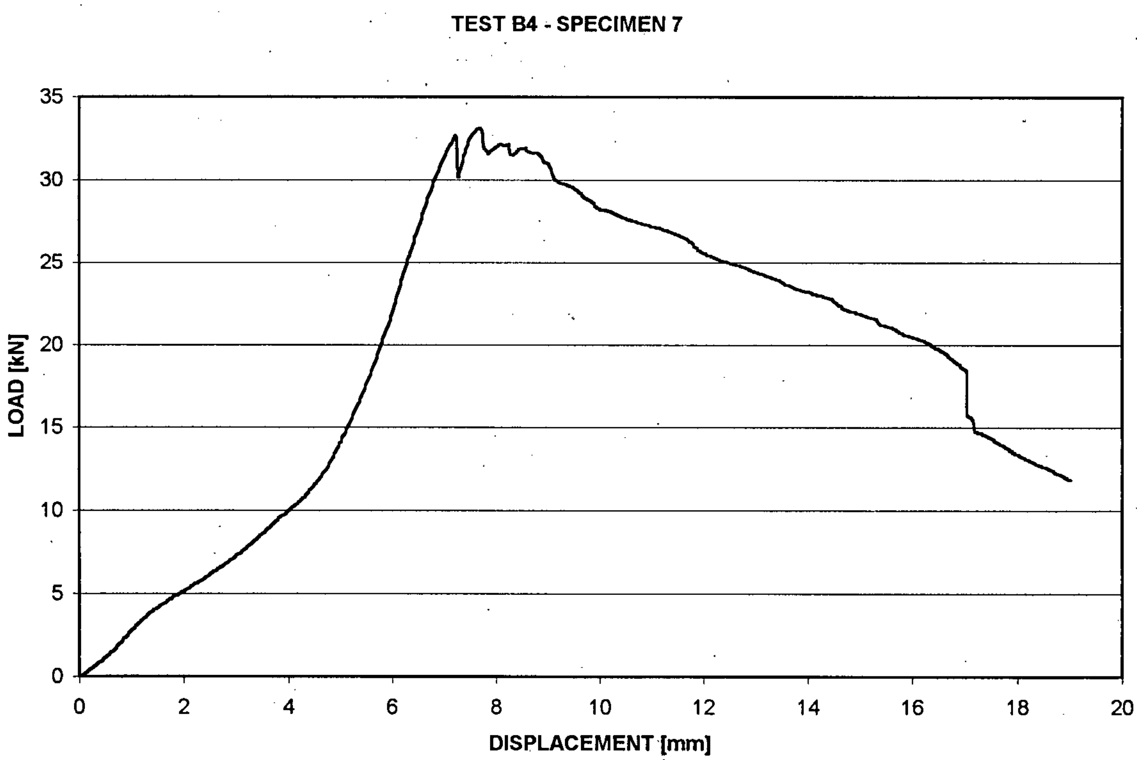


SPECIMEN NO. 7

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, not reinforced
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after wood failure due to splitting.

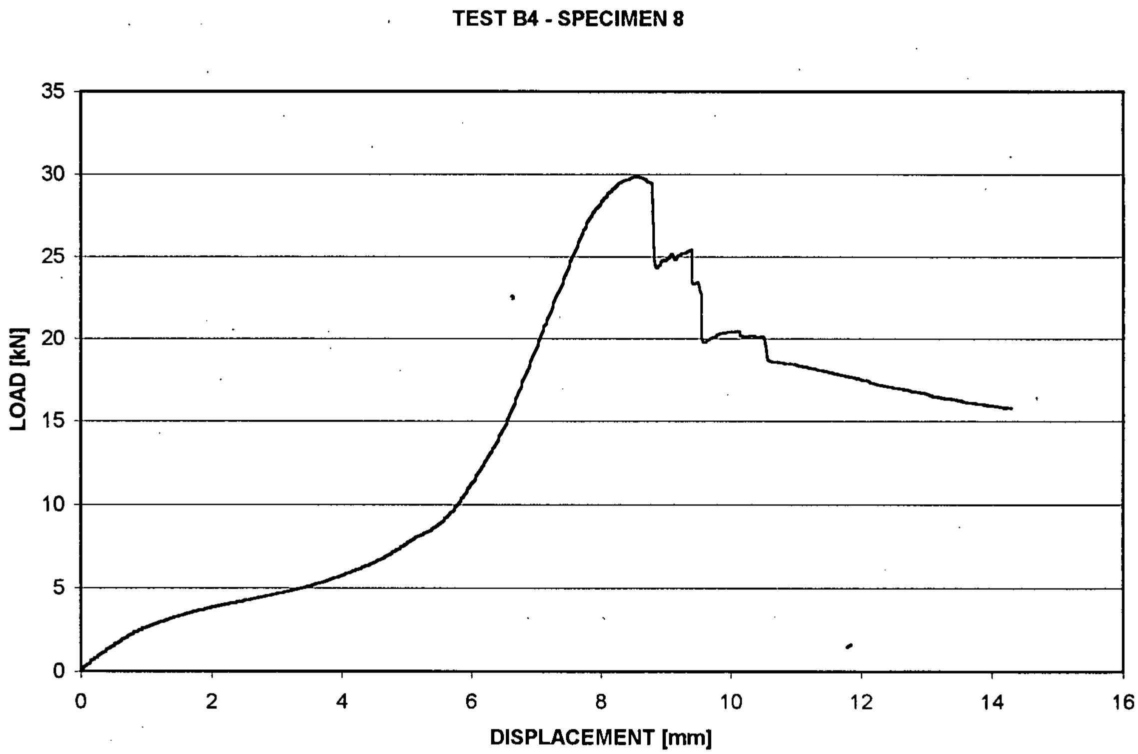


SPECIMEN NO. 8

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, not reinforced
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after wood failure due to splitting.

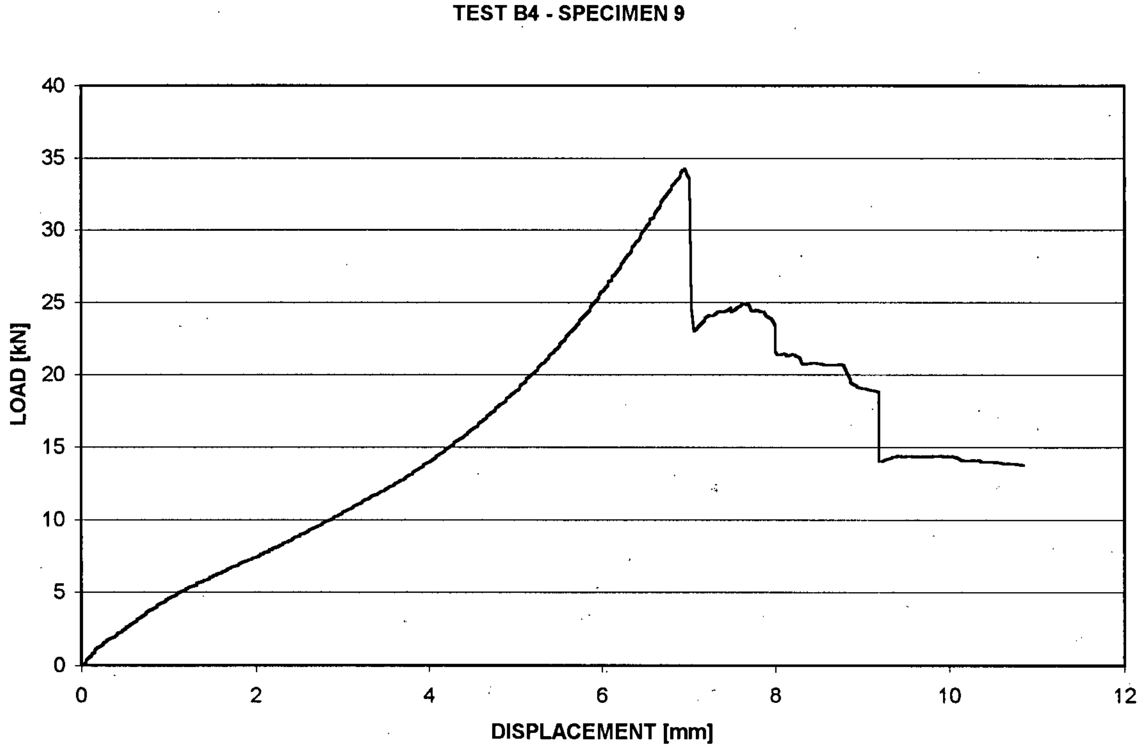


SPECIMEN NO. 9

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, not reinforced
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after wood failure due to splitting.

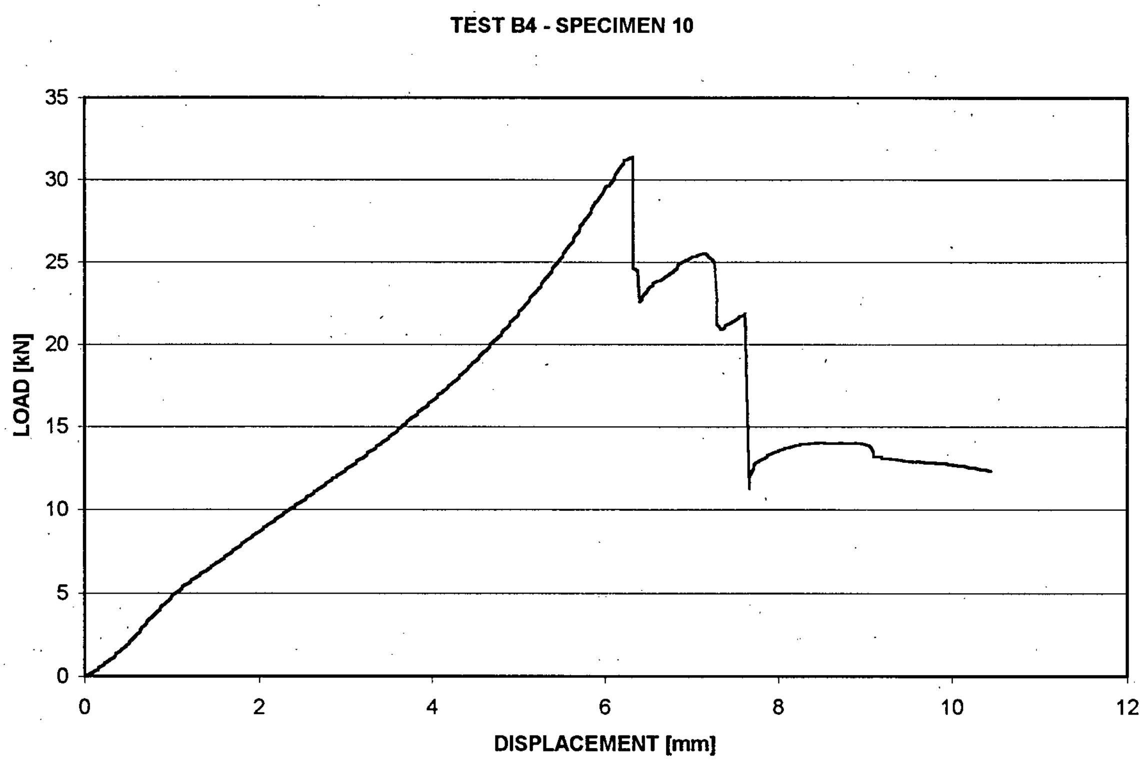


SPECIMEN NO. 10

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, not reinforced
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after wood failure due to splitting.



B.3. CYCLIC TESTS

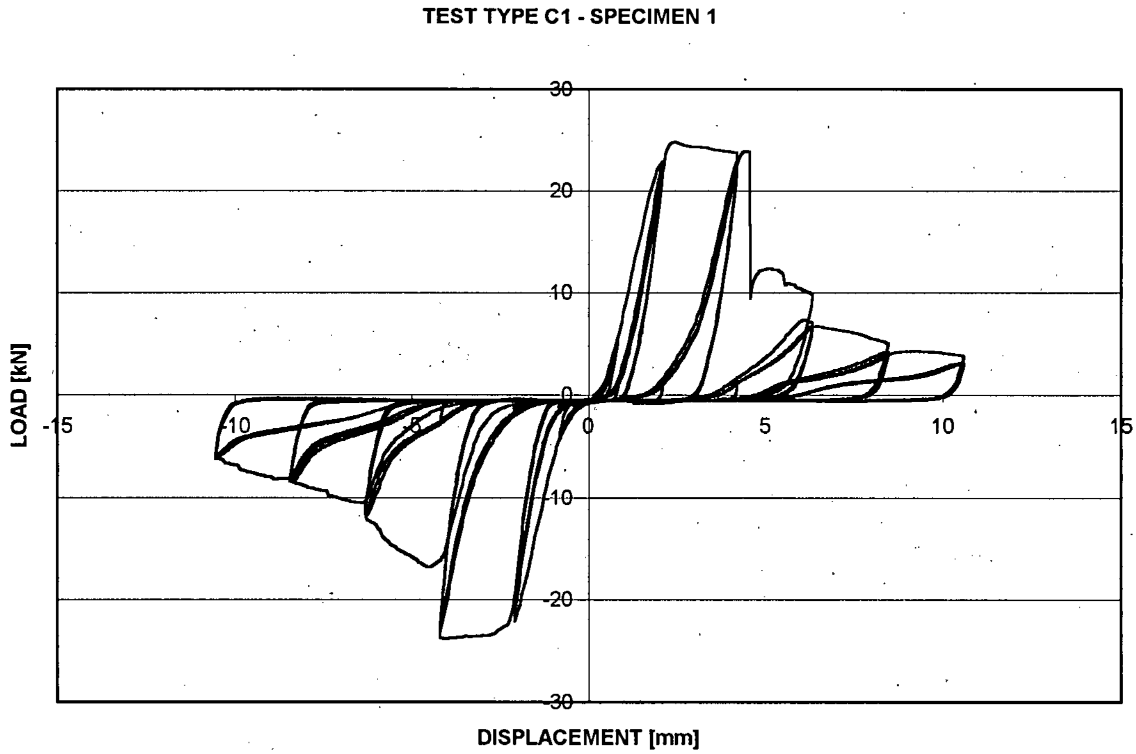
TEST TYPE C1

SPECIMEN NO. 1

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the end of the cyclic protocol.

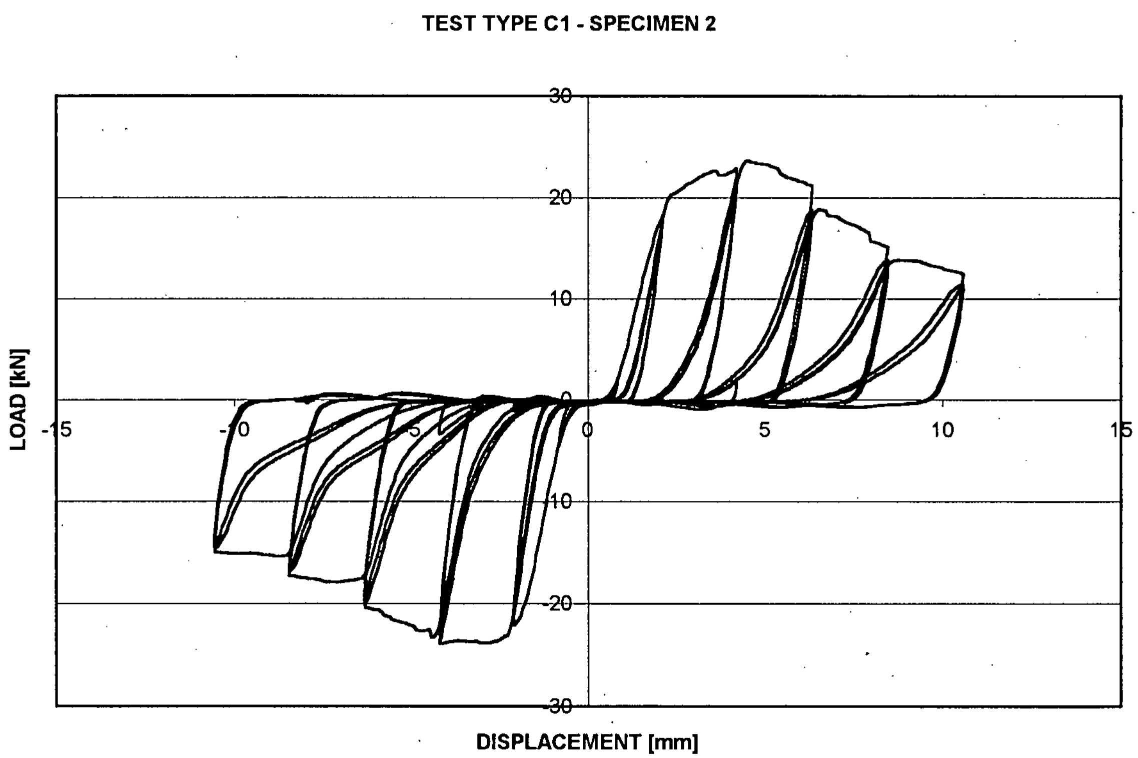


SPECIMEN NO. 2

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after wood failure due to splitting.



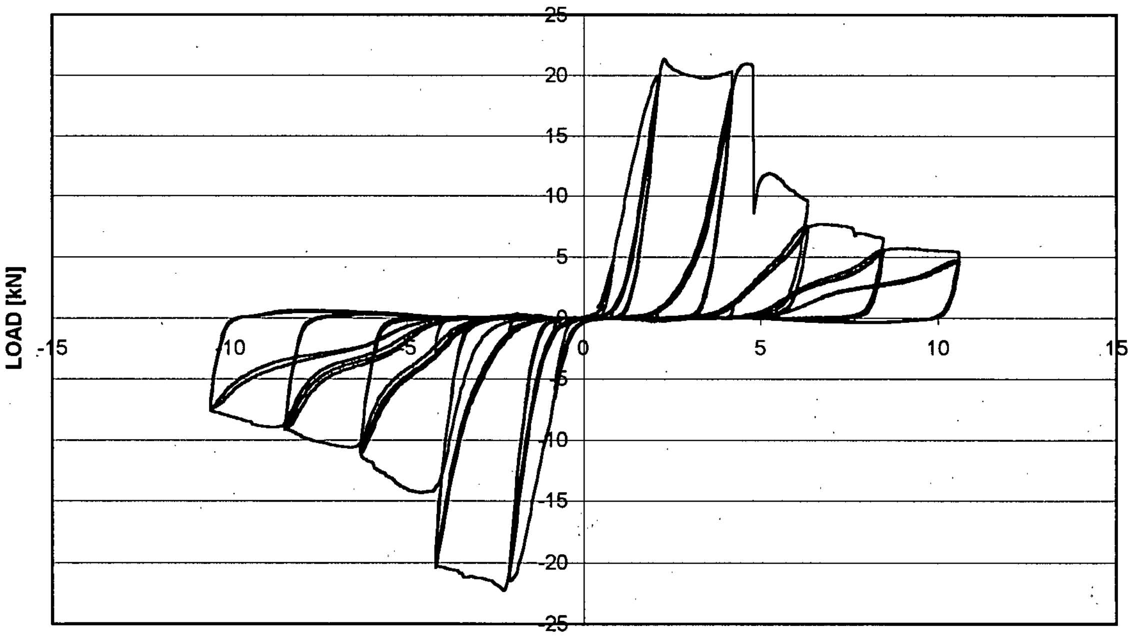
SPECIMEN NO. 3

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after wood failure due to splitting.

TEST TYPE C1 - SPECIMEN 3

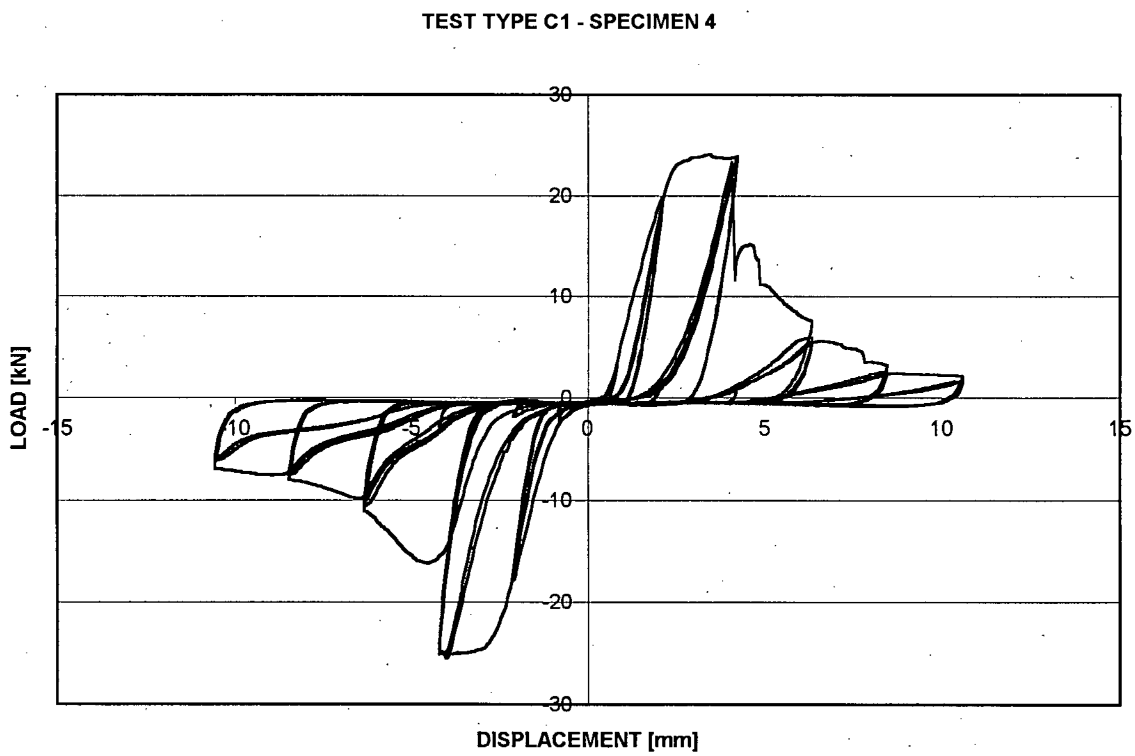


SPECIMEN NO. 4

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after wood failure due to splitting.

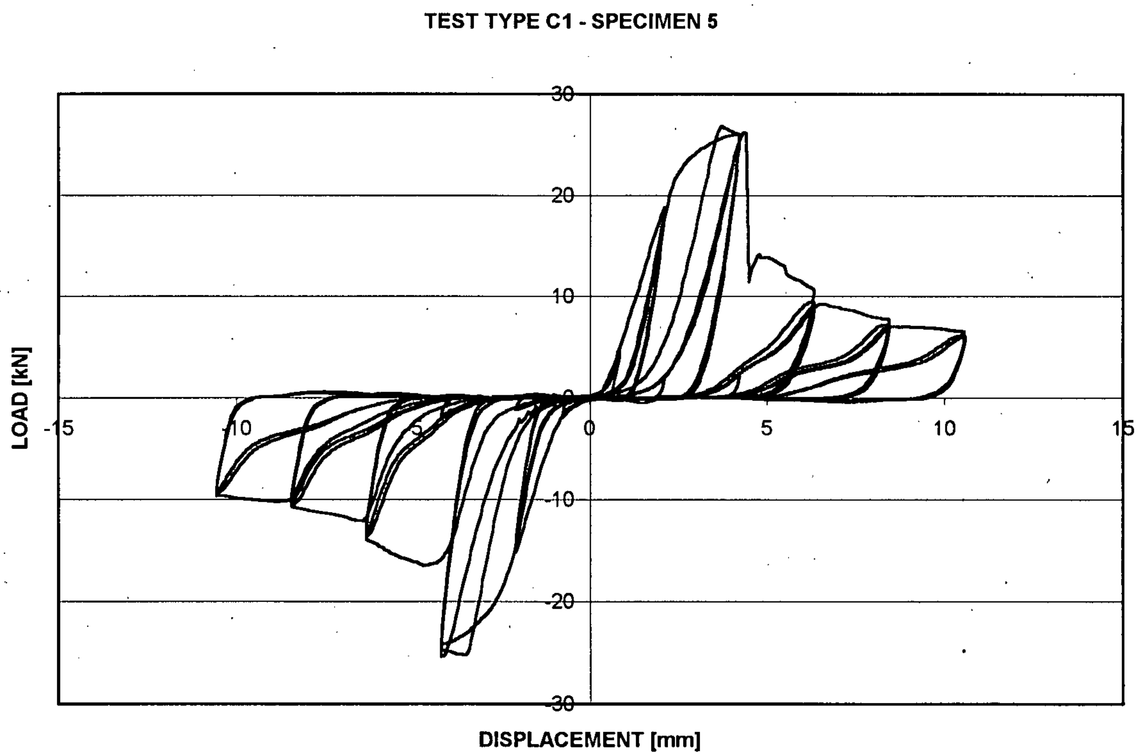


SPECIMEN NO. 5

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end.

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after wood failure due to splitting.



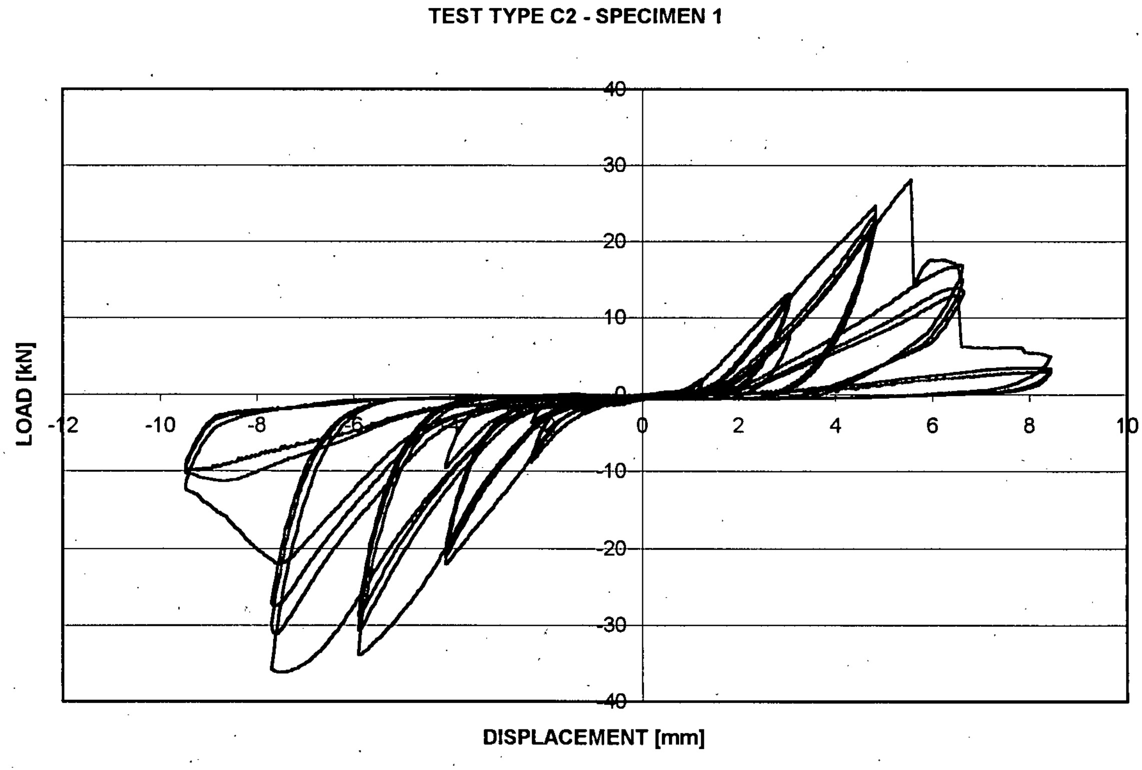
TEST TYPE C2

SPECIMEN NO. 1

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, not reinforced

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the cyclic protocol ended.

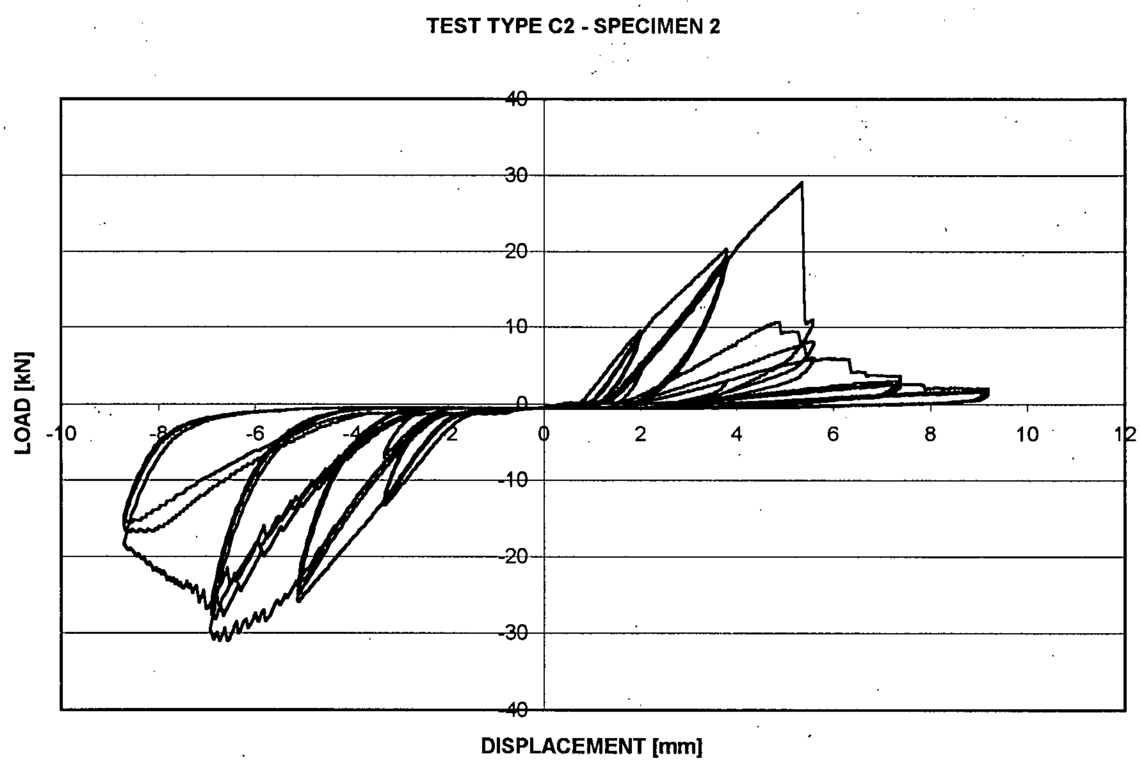


SPECIMEN NO. 2

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, not reinforced

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the cyclic protocol ended.

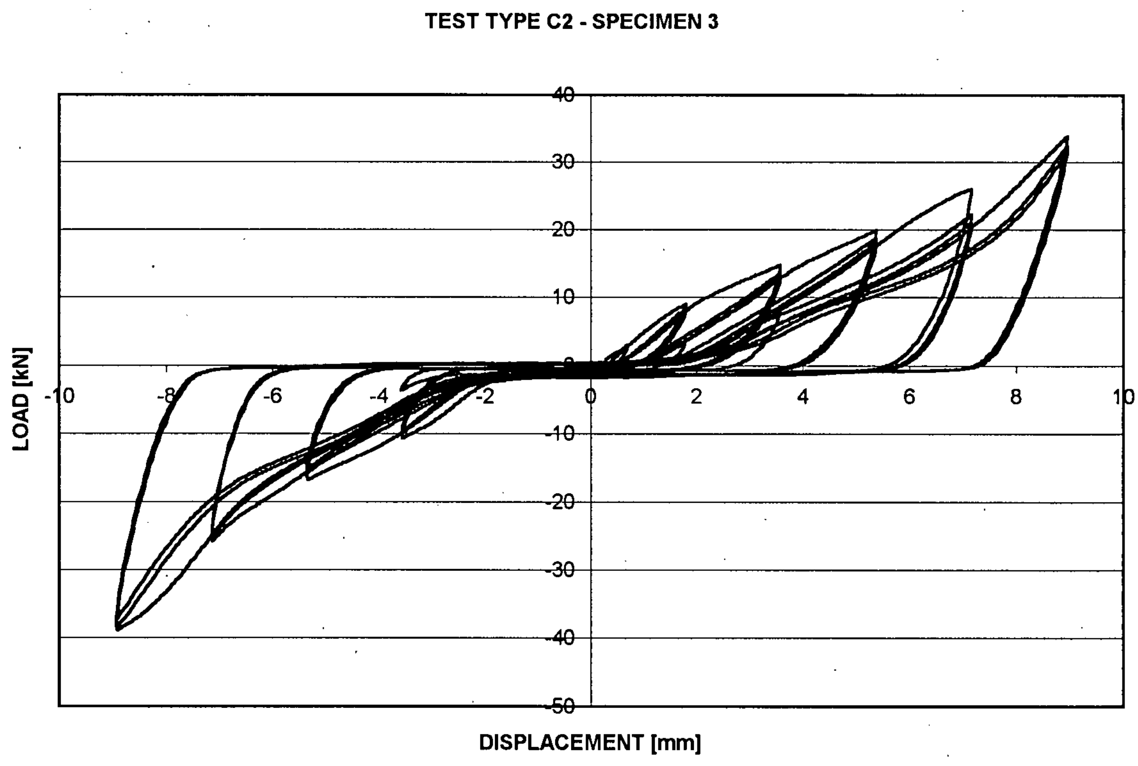


SPECIMEN NO. 3

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, not reinforced

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the cyclic protocol ended.

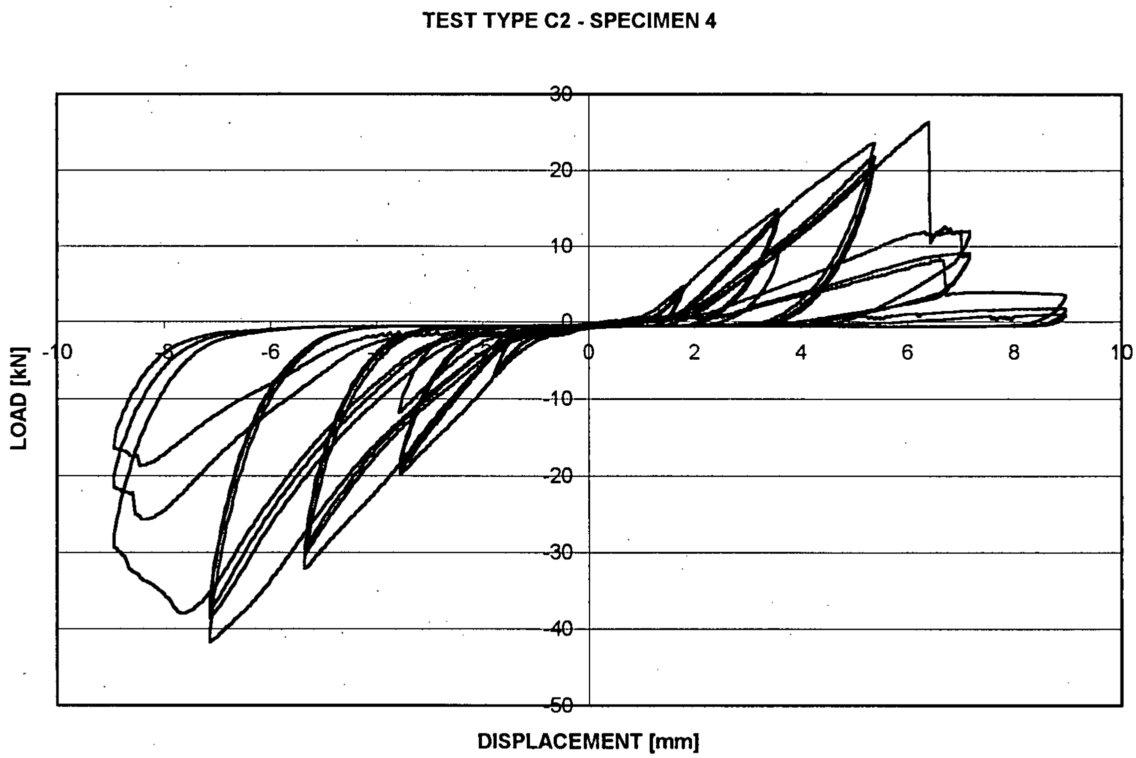


SPECIMEN NO. 4

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, not reinforced

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the cyclic protocol ended.

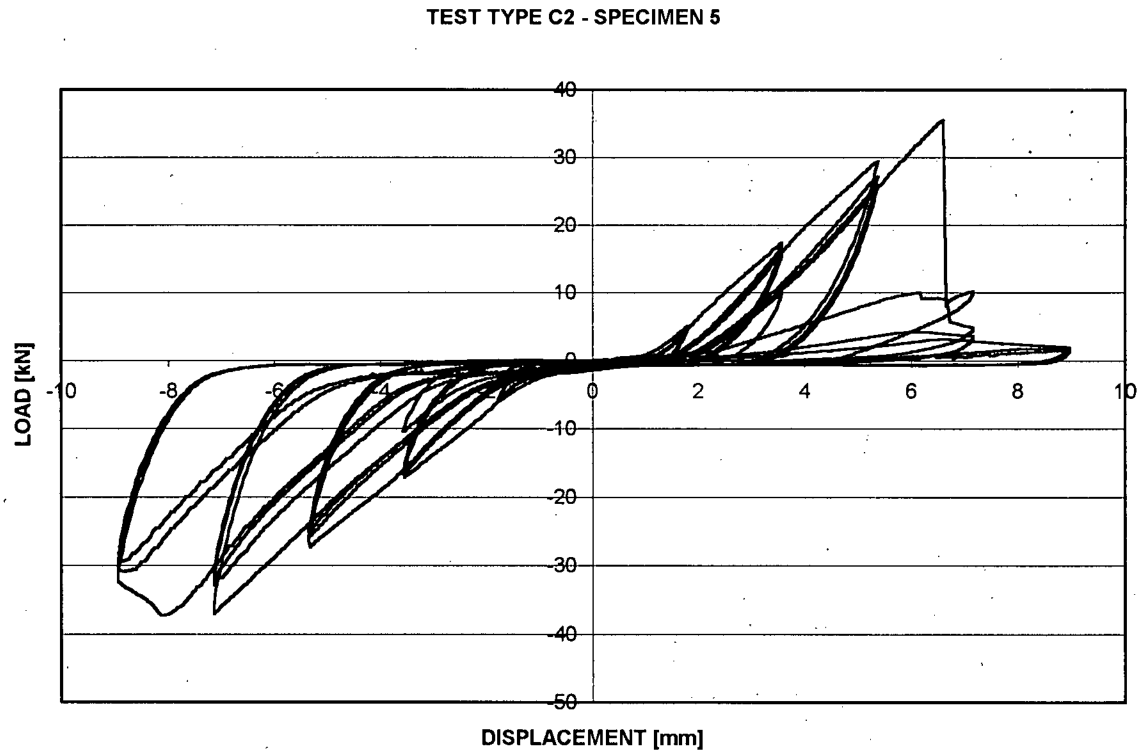


SPECIMEN NO. 5

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, not reinforced

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the cyclic protocol ended.



TEST TYPE C3

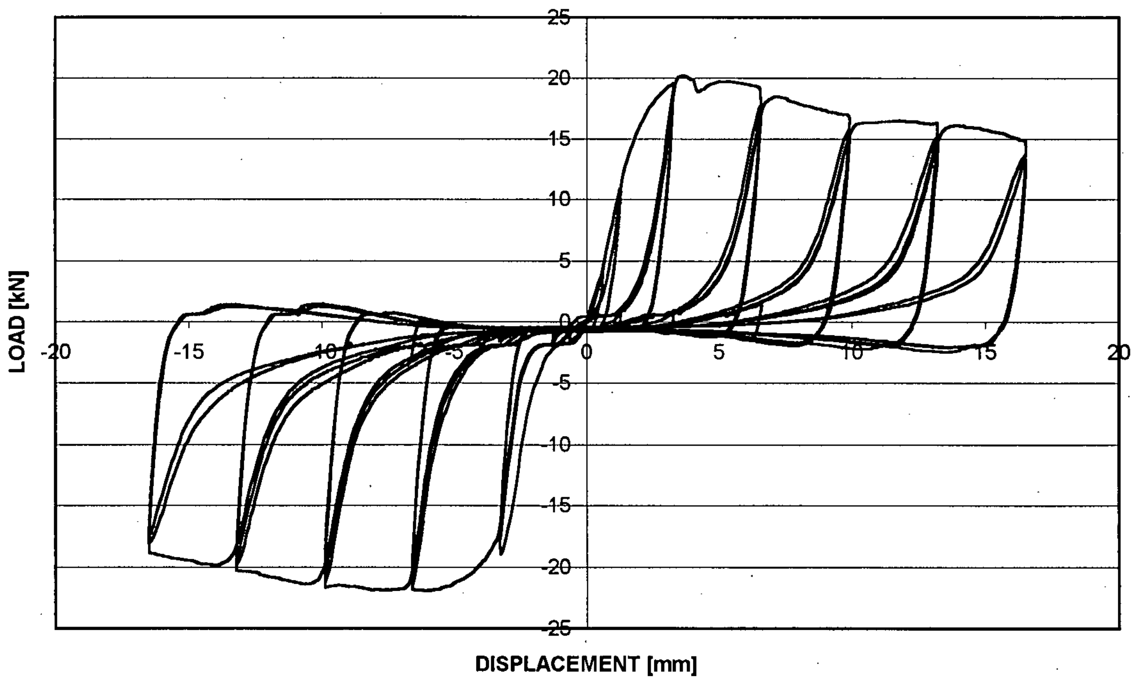
SPECIMEN NO. 1

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the end of the cyclic protocol.

TEST TYPE C3 - SPECIMEN 1

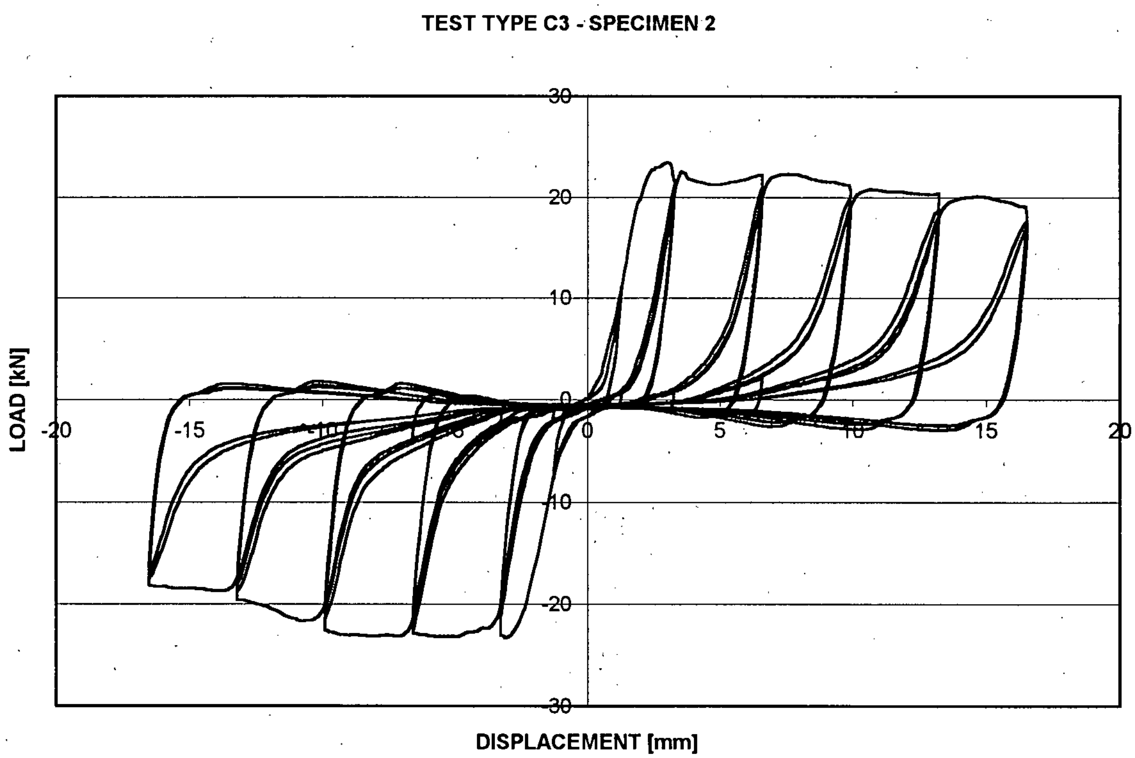


SPECIMEN NO. 2

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the end of the cyclic protocol.



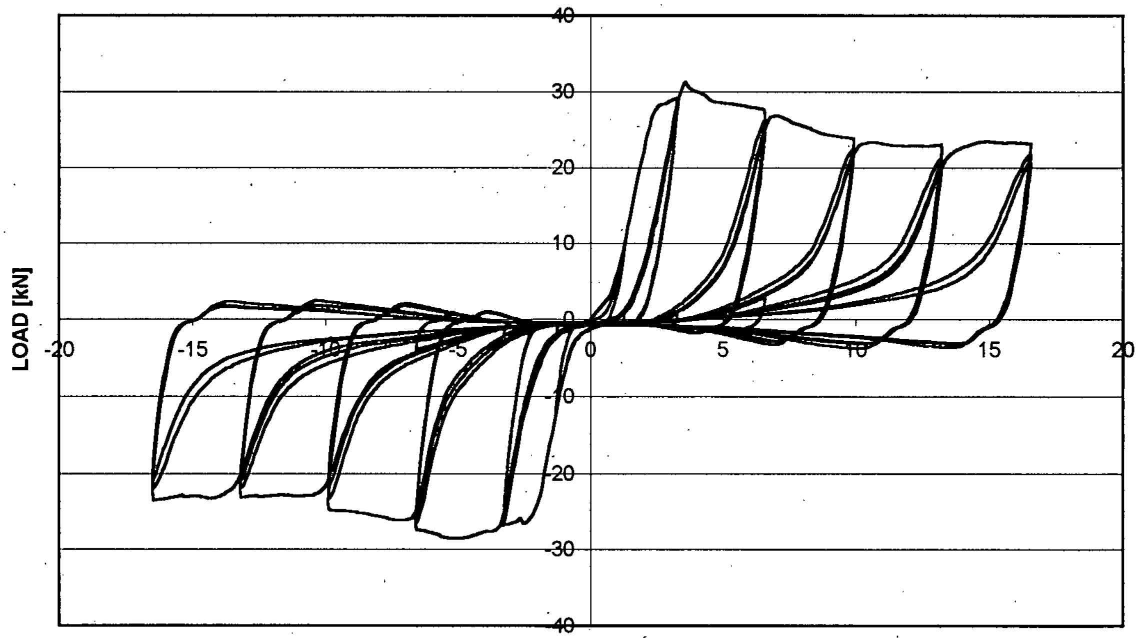
SPECIMEN NO. 3

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the end of the cyclic protocol.

TEST TYPE C3 - SPECIMEN 3



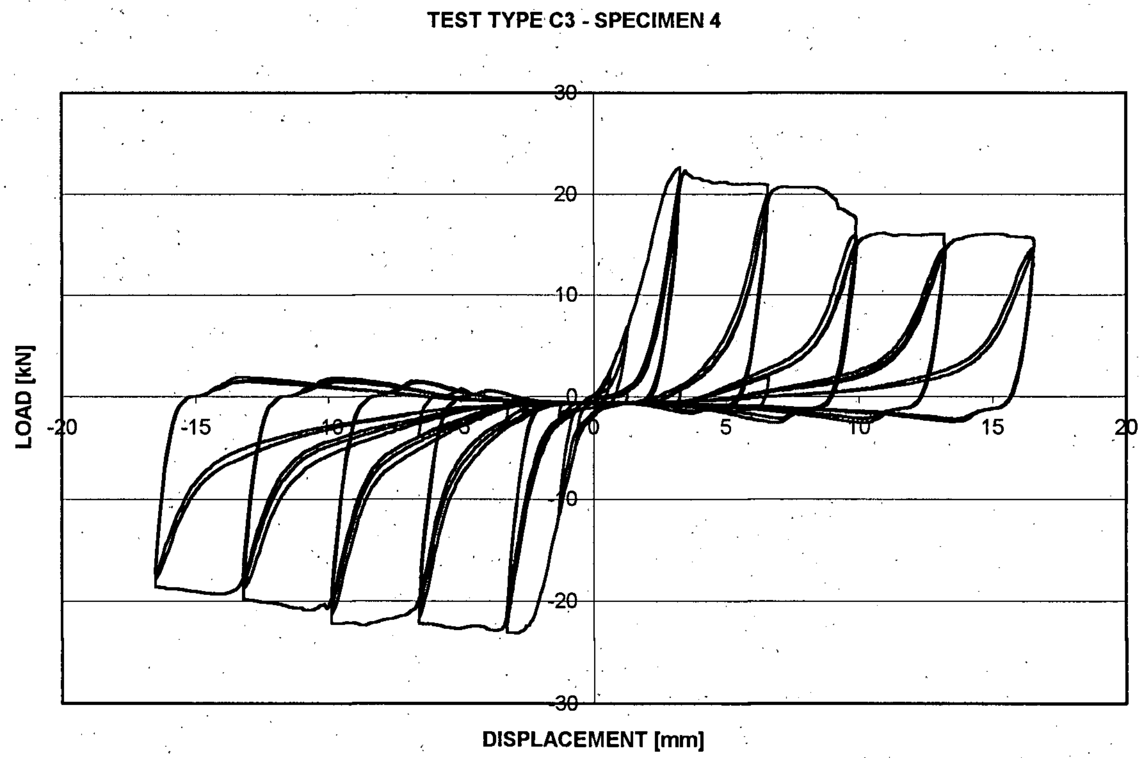
DISPLACEMENT [mm]

SPECIMEN NO. 4

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the end of the cyclic protocol.



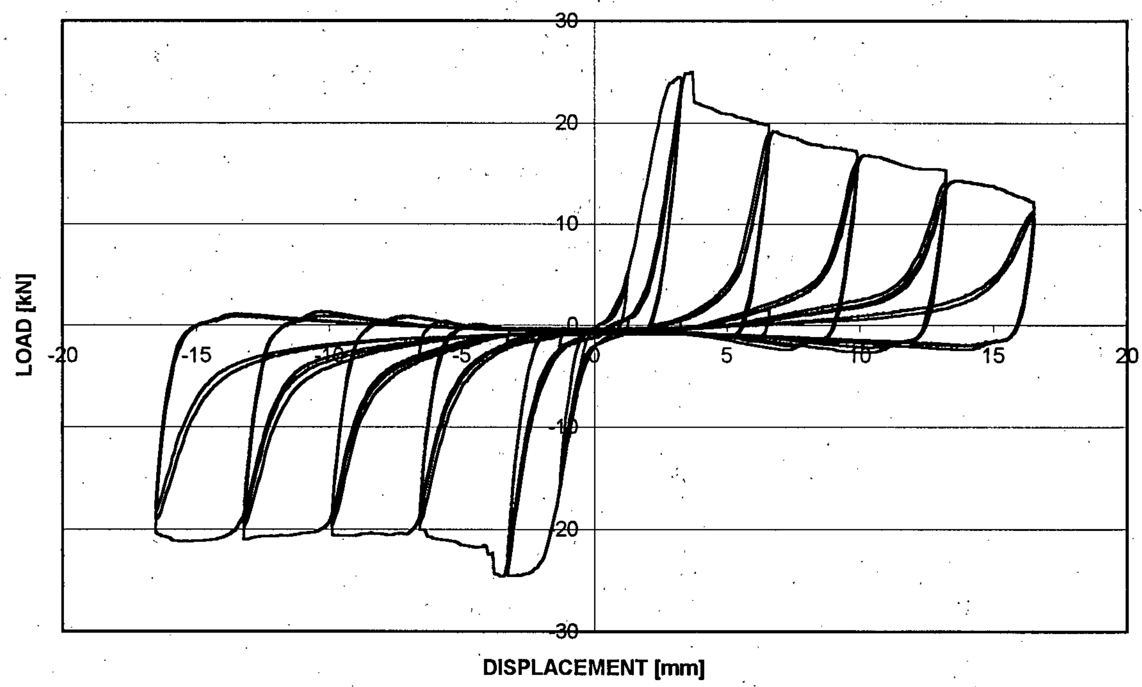
SPECIMEN NO. 5

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the end of the cyclic protocol.

TEST TYPE C3 - SPECIMEN 5



TEST TYPE C4

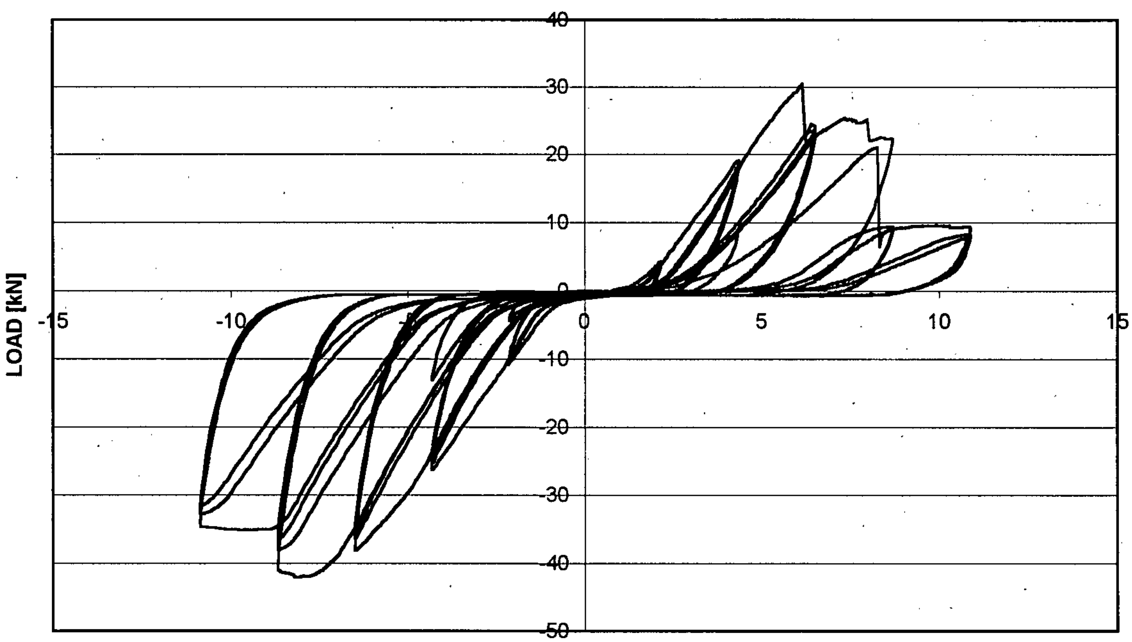
SPECIMEN NO. 1

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, not reinforced
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the end of the cyclic protocol.

TEST TYPE C4 - SPECIMEN 1



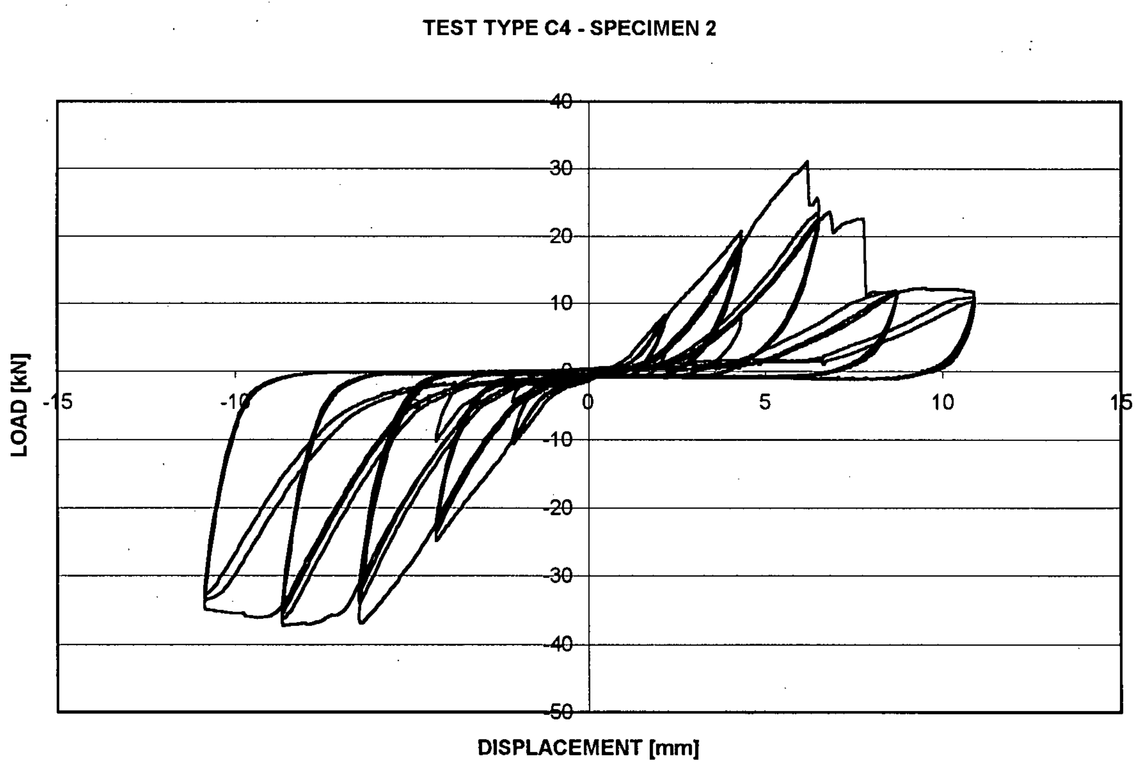
DISPLACEMENT [mm]

SPECIMEN NO. 2

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, not reinforced
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the end of the cyclic protocol.

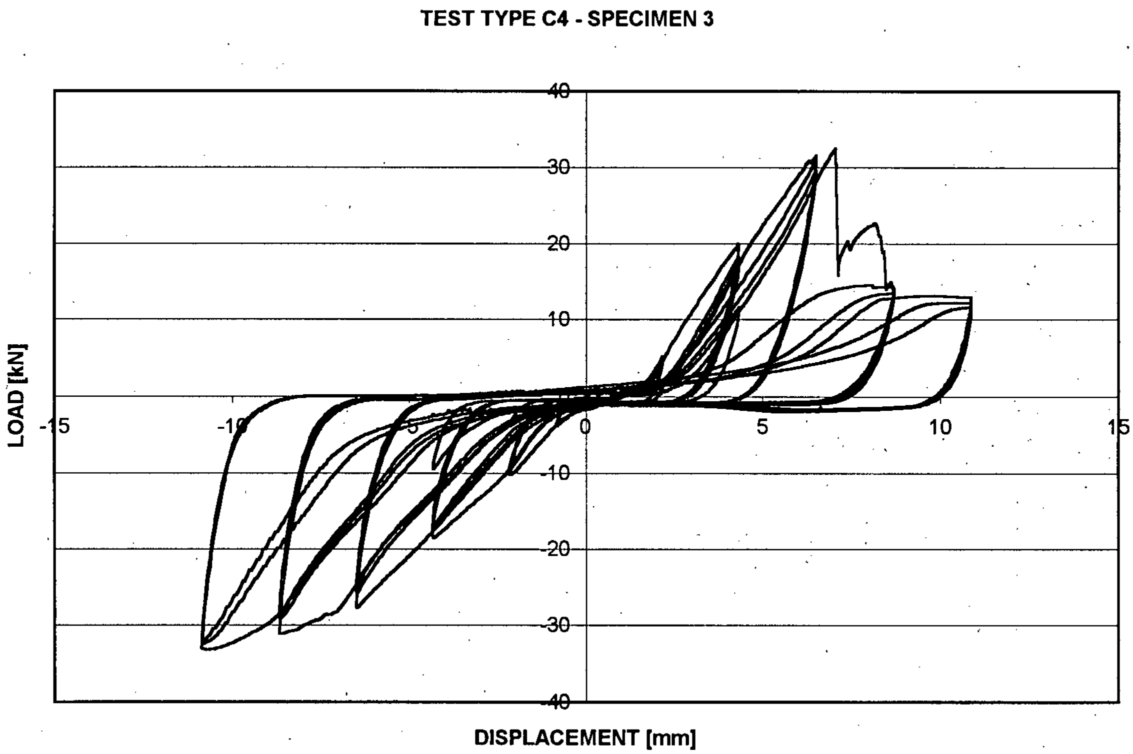


SPECIMEN NO. 3

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, not reinforced
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the end of the cyclic protocol.

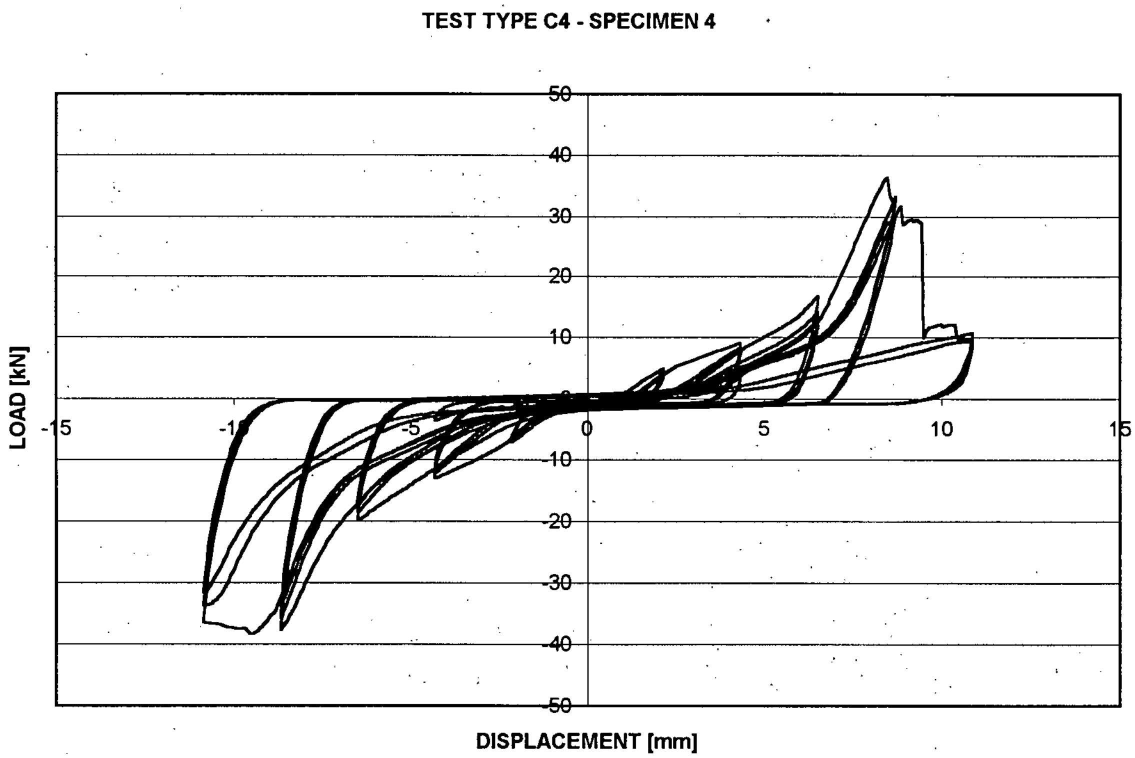


SPECIMEN NO. 4

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, not reinforced
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the end of the cyclic protocol.

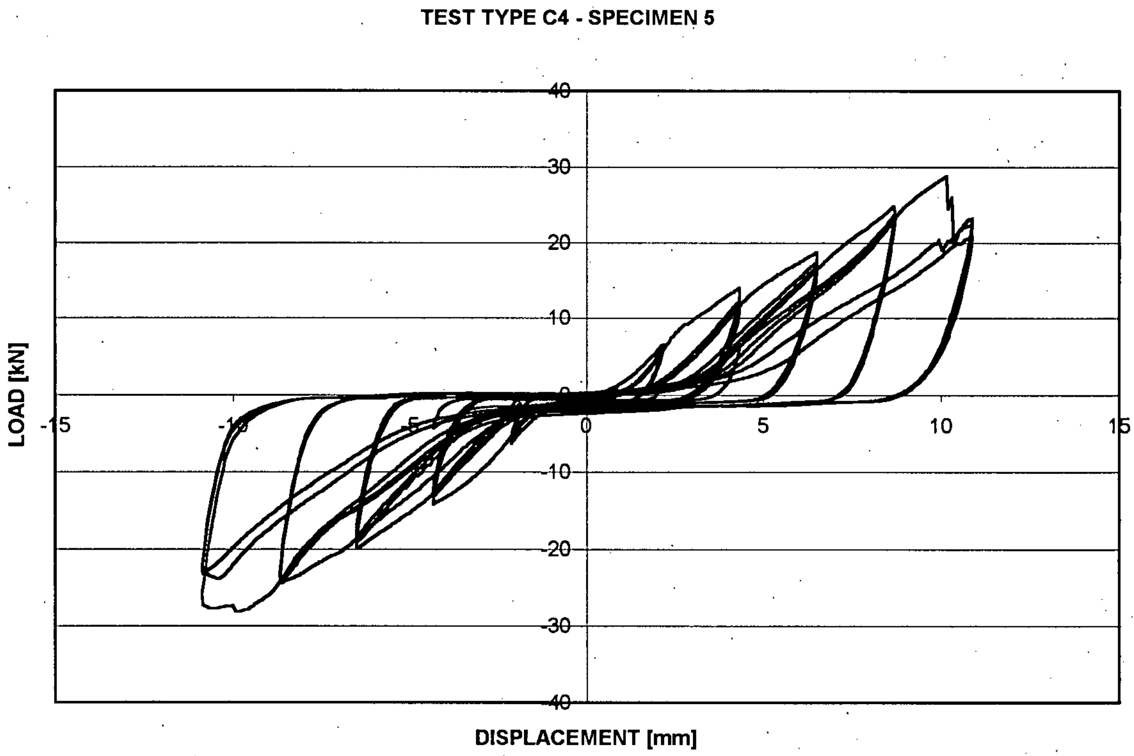


SPECIMEN NO. 5

- Wood Specimen : 38 x 90 x 500 mm (Fig. 2.4)
- Bolt Location : 120 mm, measured from bolt axis to the member end
- Bushing Type : Small, not reinforced
- Dowel Location : 50 mm from the bolt axis, perpendicular to the bolt axis

NOTES:

Testing went ahead without difficulties. Testing procedure was terminated after the end of the cyclic protocol.



PHOTOS

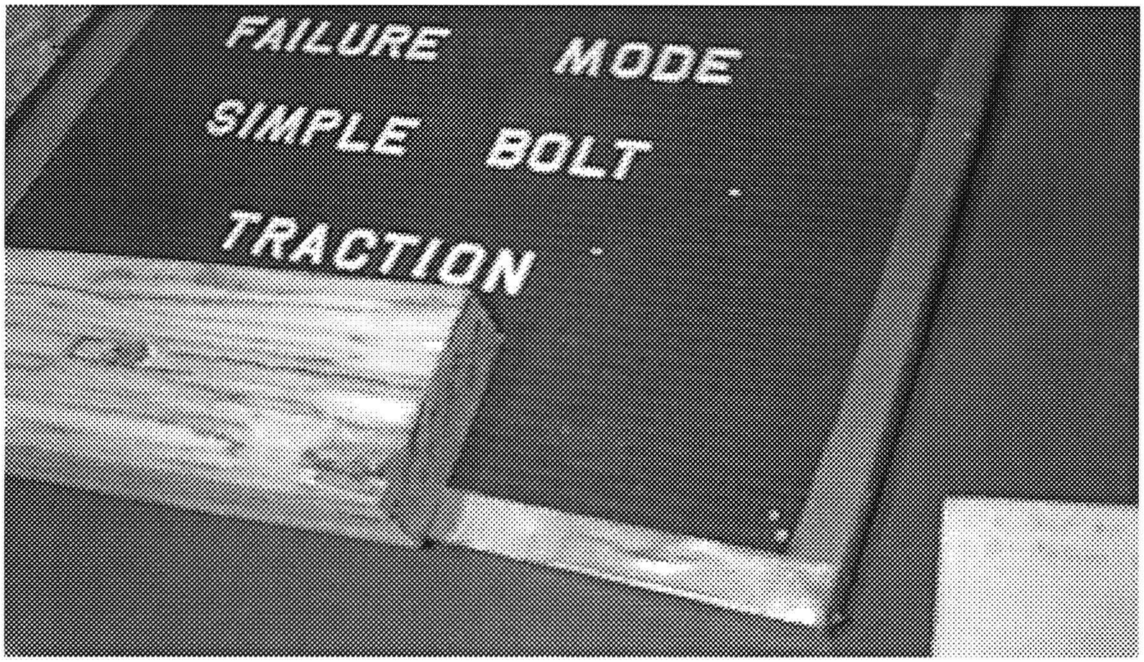


Fig. B.1.: Simple Bolt Connection – Failure Mode

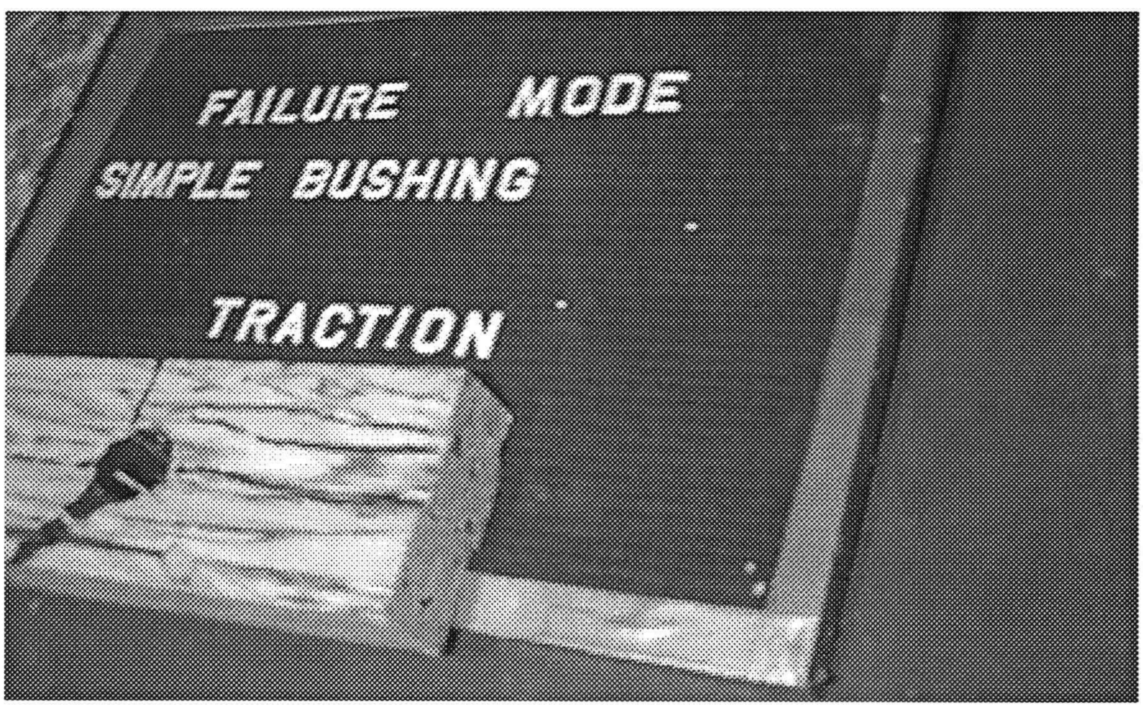


Fig. B.2.: Bolt-Bushing Connection – Failure Mode

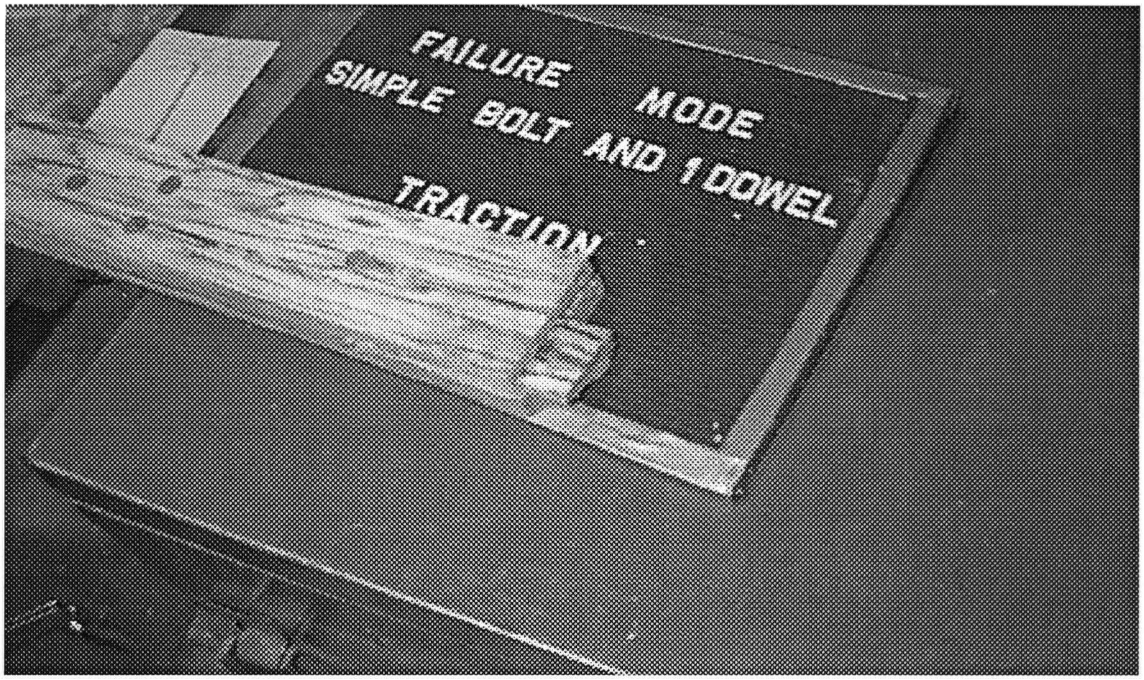


Fig. B.3.: Simple Bolt Reinforced with 1 Dowel - Failure Mode

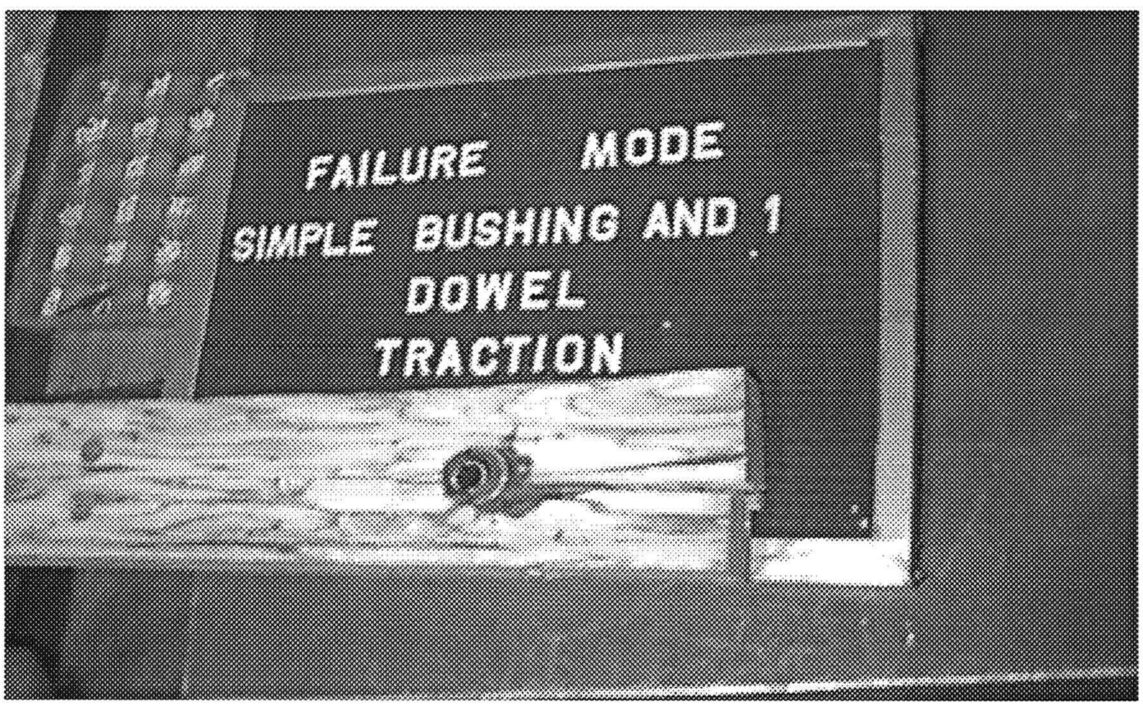


Fig. B.4.: Bolt-Bushing Reinforced with 1 Dowel – Failure Mode

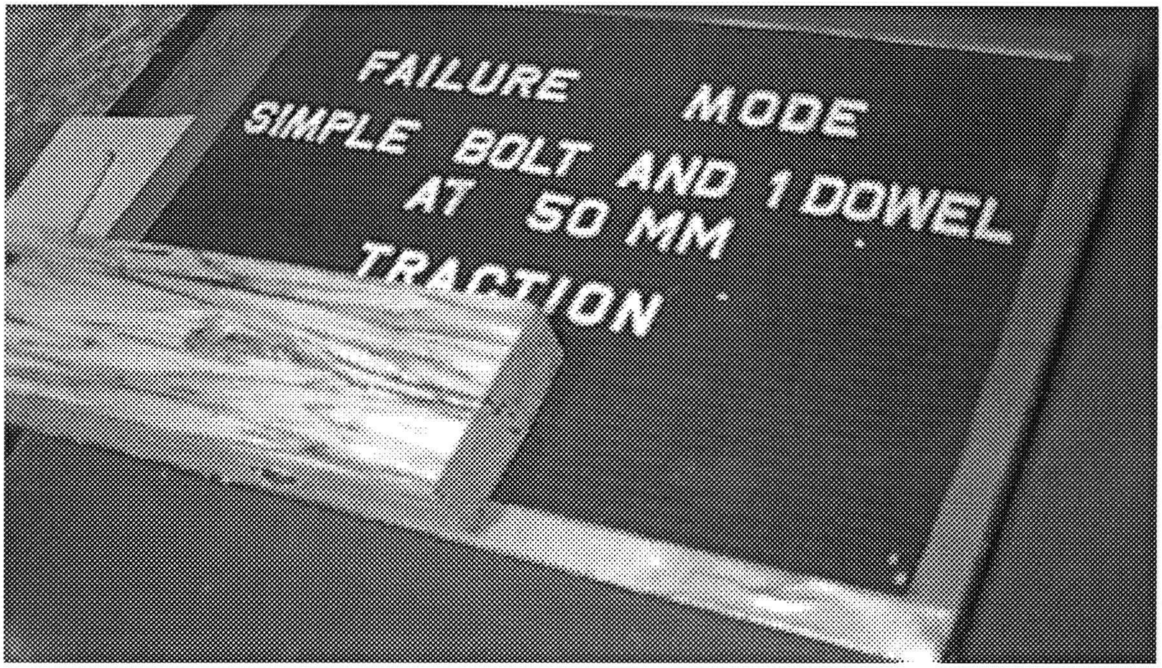


Fig. B.5.: Simple Bolt Reinforced with 1 Dowel at 50 mm – Failure mode

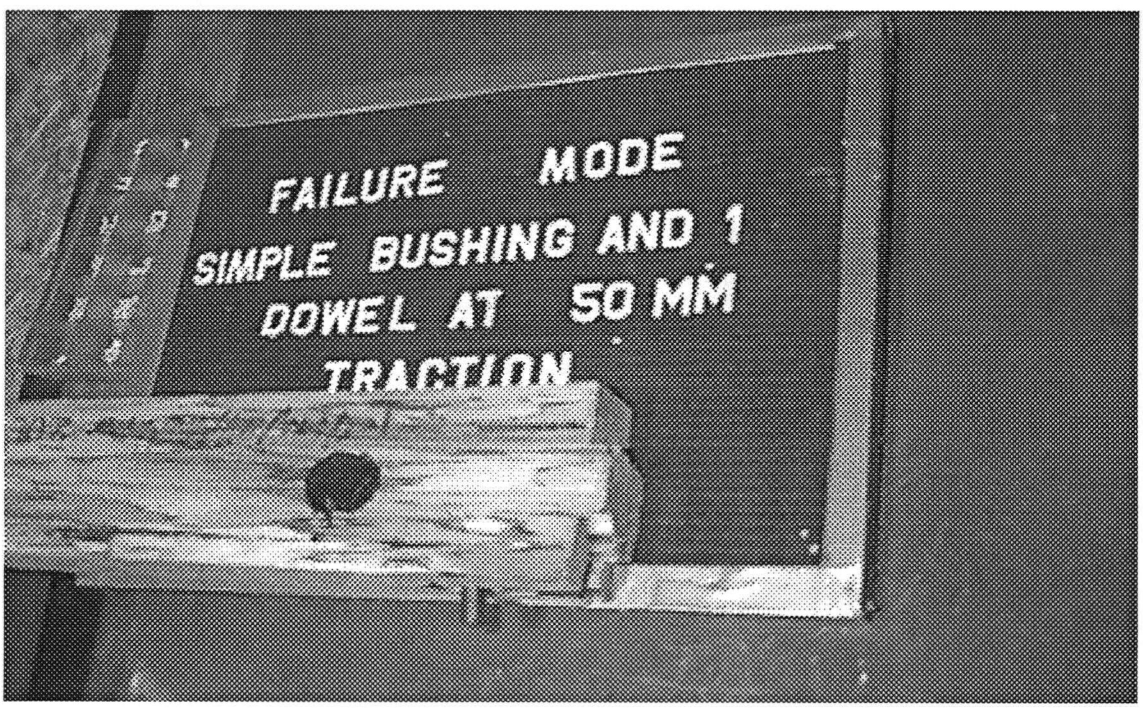


Fig.B.6.: Bolt-Bushing Reinforced with 1 Dowel at 50 mm – Failure Mode

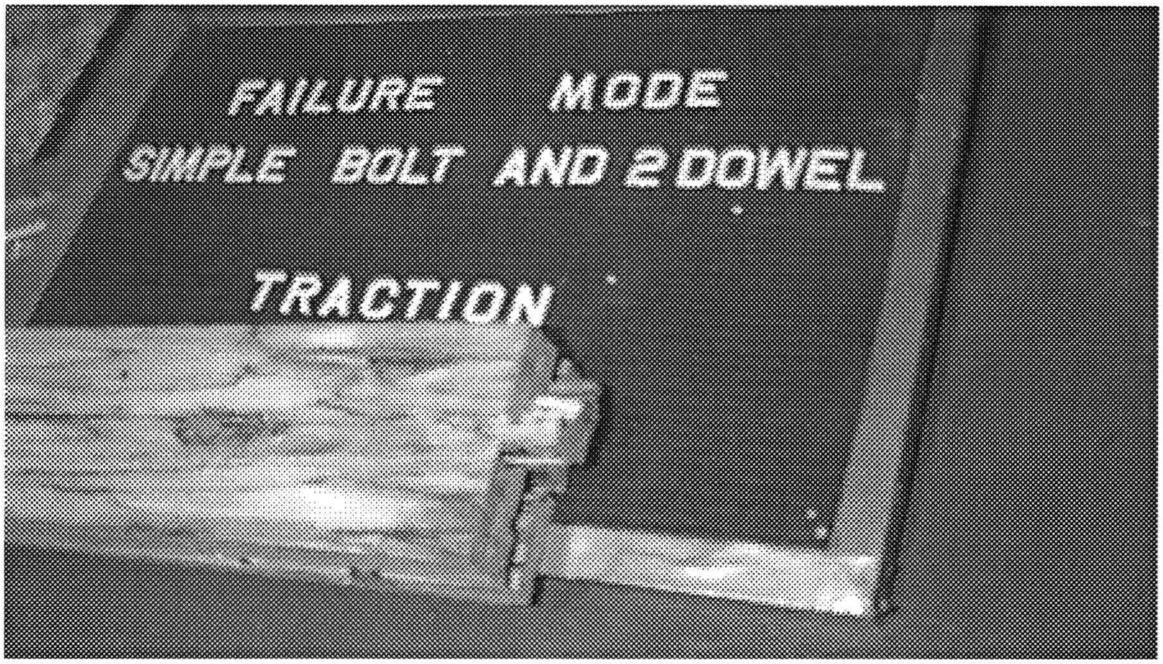


Fig. B.7.: Simple Bolt Reinforced with 2 Dowels – Failure Mode

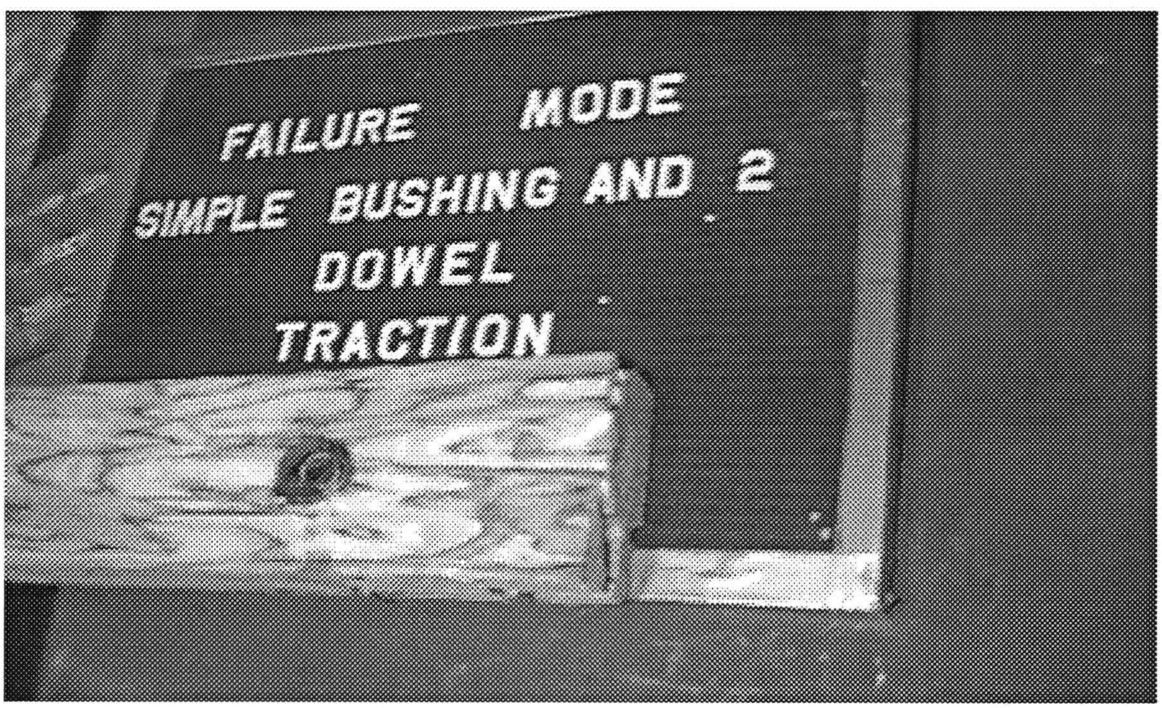


Fig. B.8.: Bolt-Bushing Reinforced with 2 Dowels – Failure Mode

Fig. B.9.: Simple Bolt Connection – Cyclic Test Failure Mode

Fig. B.10.: Bolt-Bushing Connection – Cyclic Test Failure Mode

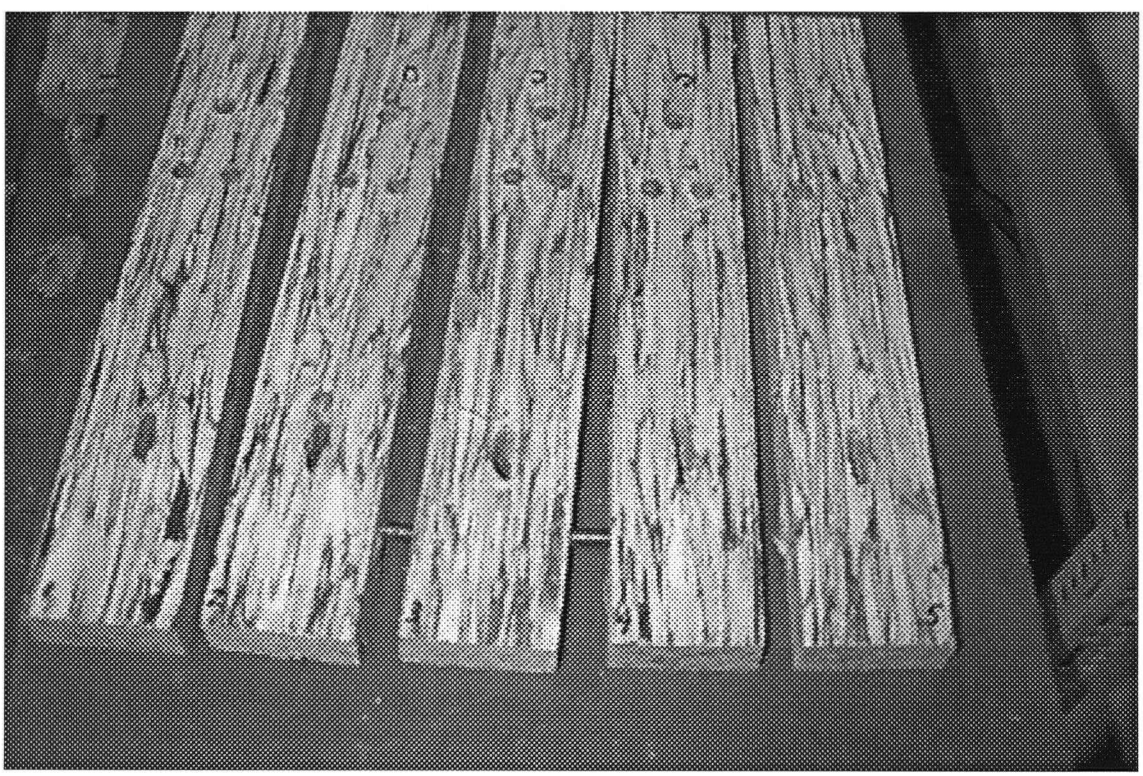
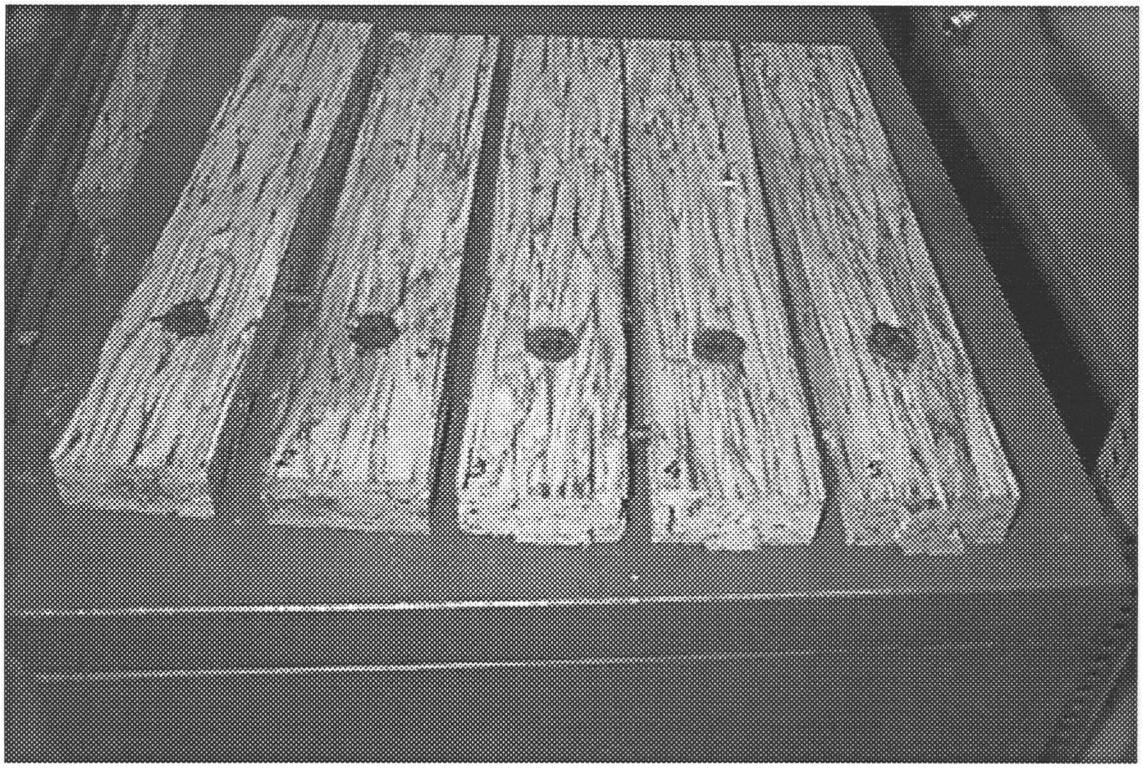


Fig. B.11.: Simple Bolt Reinforced with 1 Dowel – Cyclic Test Failure Mode



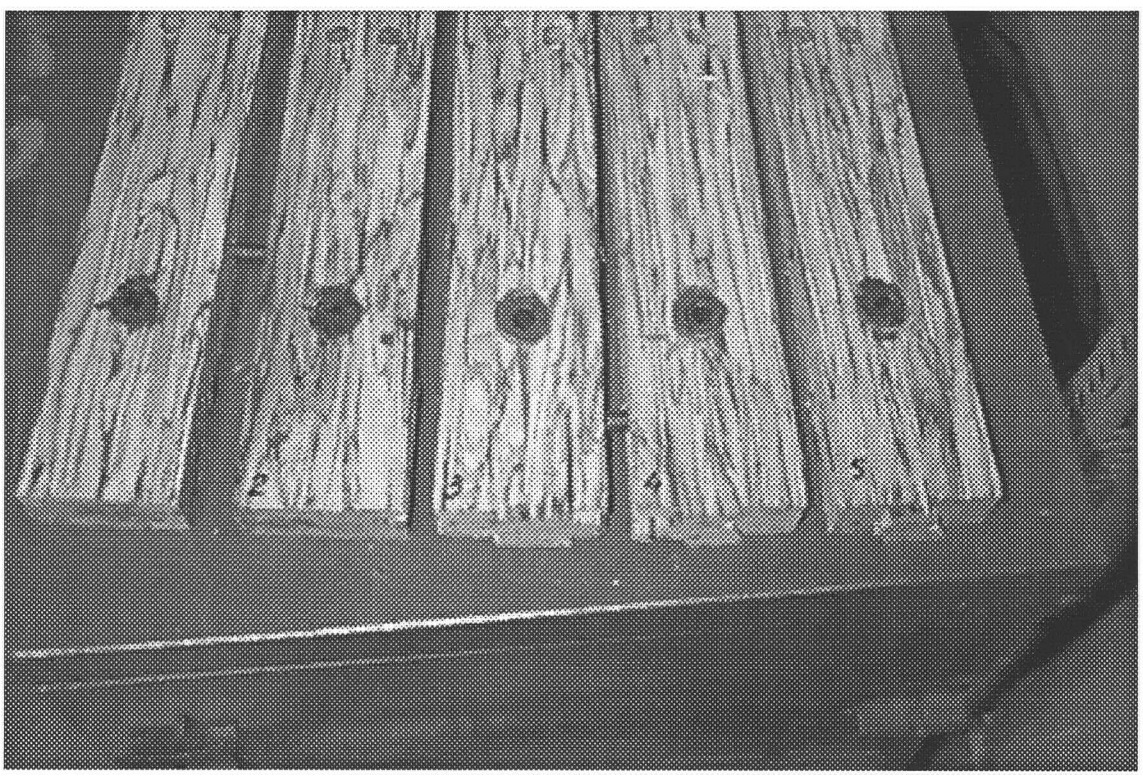


Fig. B.12.: Bolt-Bushing Reinforced with 1 Dowel – Cyclic Test Failure Mode

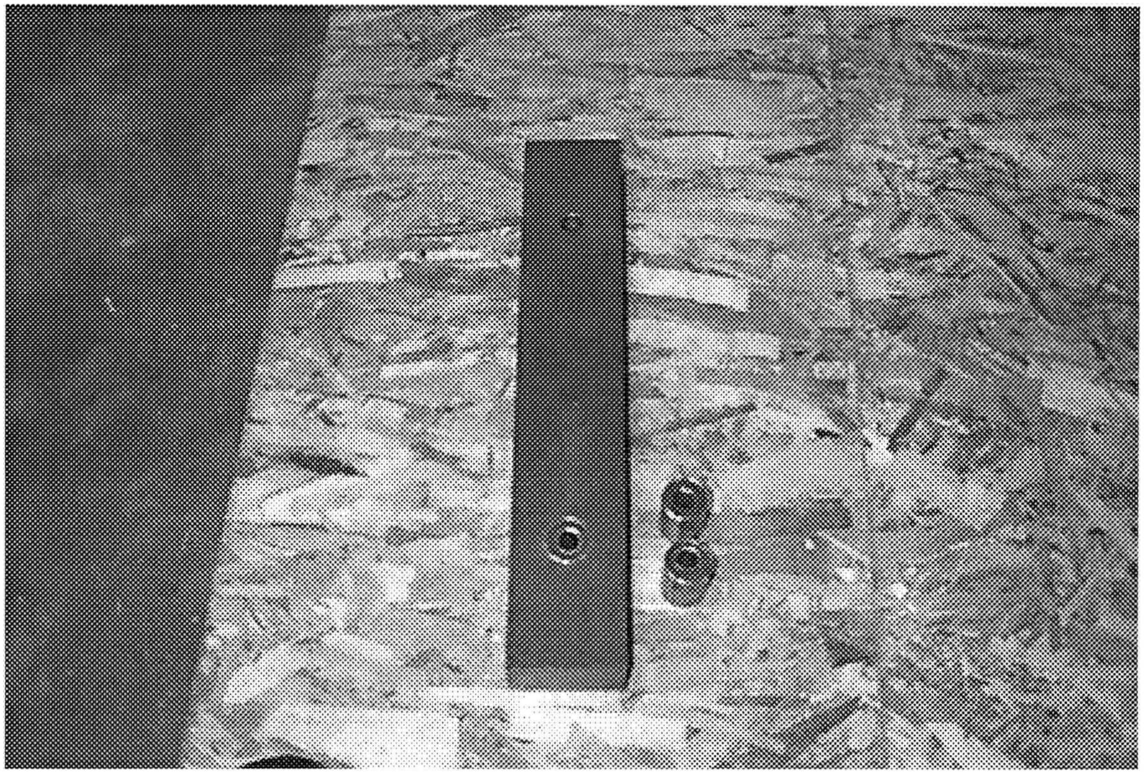


Fig. B.13.: Simple Bushing in Steel Member – Specimens tested.