Experimental Testing and Numerical Modelling of Honeycomb Structural Fuse

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Abstract

This thesis presents a novel metallic damper, called Honeycomb Structural Fuse (HSF), for seismic applications. HSF utilizes commonly available welded wide flange sections with honeycomb-shape perforations on web. It is designed to dissipate earthquake energy through plastic deformation of the web in shear, while the flanges remain elastic. The HSF can be fabricated into different shapes to fit different structural demands. To investigate the seismic behavior of the HSF, a total of 12 specimens with different honeycomb cell wall aspect ratios (wall thickness to central length) and honeycomb cell combinations (rows and columns) were manufactured and tested under displacement-based static cyclic loads. The influence of the different geometry parameters on the initial stiffness, yield force, yield drift, force-drift relationship, buckling, and failure modes are summarized in this thesis. Finally, a robust finite element model was built to simulate the hysteretic behavior of the HSF. The effectiveness of the proposed model was validated using experimental results. The study shows that the newly proposed HSF has stable energy dissipation, which can be used as an efficient metallic damper for seismic applications.
Lay Summary

Earthquake is a large and devastating disaster causing significant loss of human lives and property damage. The aim of this research project is to develop an innovative, versatile, and highly efficient structural fuse, called Honeycomb Structural Fuse (HSF), for seismic applications. In this work, detailed experimental tests were conducted. In addition, an advanced numerical study was carried out. The results show that the newly proposed HSF has stable energy dissipation capacity and can be used as an efficient damper for seismic applications.
Preface

This thesis is an original and independent work submitted as a requirement for the Master of Applied Science in Civil Engineering degree’s completion at the University of British Columbia. The initial idea for this research was proposed by Professor Tony T.Y. Yang and the author. The author was responsible for the literature review, experimental test, numerical simulation, data processing, results, and conclusion. The thesis was drafted by the author and revised based on comments from Professor Yang. Part of this thesis will be rewritten as a peer-reviewed journal paper following the thesis’ publication.
Table of Contents

Abstract ........................................................................................................................................ iii
Lay Summary ................................................................................................................................. iv
Preface ........................................................................................................................................... v
Table of Contents ........................................................................................................................... vi
List of Tables ................................................................................................................................. x
List of Figures ............................................................................................................................... xi
List of Symbols .............................................................................................................................. xv
List of Abbreviations ..................................................................................................................... xvii
Acknowledgements ....................................................................................................................... xviii
Dedication ....................................................................................................................................... xix
Chapter 1: Introduction .................................................................................................................. 1
  1.1 Overview ................................................................................................................................ 1
  1.2 Types of Structural Fuses ........................................................................................................ 2
    1.2.1 Viscous Fluid Dampers .................................................................................................... 3
    1.2.2 Viscoelastic Dampers ..................................................................................................... 4
    1.2.3 Friction Dampers ............................................................................................................. 5
    1.2.4 Metallic fuses .................................................................................................................. 6
  1.3 A Review of Previous Study on the Steel Shear Yielding Fuses ......................................... 8
    1.3.1 Steel Shear Link Beam in Eccentrically Braced Frame ................................................. 9
    1.3.2 Steel Plate Shear Wall .................................................................................................... 10
    1.3.3 Steel Shear Damper ........................................................................................................ 11
Chapter 2: Experimental Program of HSF ................................................................. 23
  2.1 Introduction ........................................................................................................ 23
  2.2 Test Setup ........................................................................................................... 23
    2.2.1 Tensile Coupon Test Setup ......................................................................... 23
    2.2.2 Shear Damper Test Setup .......................................................................... 25
  2.3 Loading Mechanism .............................................................................................. 26
  2.4 Test Specimen’s Notation and Design ................................................................ 27
  2.5 Test Instruments .................................................................................................. 29
  2.6 Loading Protocol .................................................................................................. 30
  2.7 Test Procedure ..................................................................................................... 31

Chapter 3: Experimental Results of the HSF ............................................................ 32
  3.1 Introduction .......................................................................................................... 32
  3.2 Tensile Coupon Test Results .............................................................................. 32
  3.3 Cyclic Loading Performance .............................................................................. 34
    3.3.1 a0.3r3c4 ........................................................................................................ 34
    3.3.2 a0.5r3c4 ........................................................................................................ 35
    3.3.3 a0.7r3c4 ........................................................................................................ 36
    3.3.4 a0.3r3c3 ........................................................................................................ 37
    3.3.5 a0.5r3c3 ........................................................................................................ 38
    3.3.6 a0.7r3c3 ........................................................................................................ 39
    3.3.7 a0.3r3c2 ........................................................................................................ 40
3.3.8  a0.5r3c2.................................................................41
3.3.9  a0.7r3c2.................................................................42
3.3.10 a0.3r2c3.................................................................43
3.3.11 a0.5r2c3.................................................................44
3.3.12 a0.7r2c3.................................................................45
3.4  Discussion on Buckling Behavior..................................................46
3.5  Discussion on Failure Mode .........................................................47
3.6  Discussion on Force-Drift Relationship.........................................50
3.7  Discussion on Energy Dissipation .................................................54
3.8  Discussion.................................................................................56

Chapter 4: Numerical Study of HSF ......................................................57
4.1  Introduction.................................................................................57
4.2  Finite Element Model Description..............................................57
4.3  Material Modelling .................................................................58
4.4  Simulation Validation...............................................................59
  4.4.1 Force-Drift Relationship Validation ........................................59
  4.4.2 Buckling Behaviour Validation ..............................................61
  4.4.3 PEEQ Distribution ..............................................................62
4.5  Comparison with WWFF............................................................63
  4.5.1 Buckling Shape Comparison..................................................63
  4.5.2 Force-Drift Relationship Comparison......................................64
  4.5.3 Stiffness and Yielding Force Comparison..................................65

Chapter 5: Parametric study ...............................................................67
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Introduction</td>
<td>67</td>
</tr>
<tr>
<td>5.2</td>
<td>Finite Element Model Matrix</td>
<td>67</td>
</tr>
<tr>
<td>5.3</td>
<td>Simulation Results</td>
<td>68</td>
</tr>
<tr>
<td>5.3.1</td>
<td>Yielding Force and Initial Stiffness</td>
<td>69</td>
</tr>
<tr>
<td>5.3.2</td>
<td>Yielding Drift</td>
<td>70</td>
</tr>
<tr>
<td>6.1</td>
<td>Summary and Conclusion</td>
<td>71</td>
</tr>
<tr>
<td>6.2</td>
<td>Recommendations for Future Research</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td><strong>Chapter 6: Summary and Conclusion</strong></td>
<td>71</td>
</tr>
<tr>
<td></td>
<td><strong>Bibliography</strong></td>
<td>75</td>
</tr>
<tr>
<td></td>
<td><strong>Appendices</strong></td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>Appendix A</td>
<td>80</td>
</tr>
</tbody>
</table>
List of Tables

Table 2.1 Test specimen matrix ................................................................. 28
Table 2.2 Loading protocol matrix ............................................................ 30
Table 3.1 Summary of the experimental results ......................................... 53
Table 4.1 Material parameters used in ABAQUS model ............................. 59
Table 5.1 FEA matrix in parametric study ................................................ 68
Table 5.2 Parametric study results ............................................................ 68
List of Figures

Figure 1-1 (a) Typical viscous fluid damper (Constantinou and Symans, 1992) (b) idealized hysteresis loop (Constantinou and Symans, 1992) ................................................................. 3

Figure 1-2 (a) Viscoelastic solid damper (Keel and Mahmoodi, 1986) (b) typical hysteretic loop (Constantinou and Symans, 1992) .................................................................................... 4

Figure 1-3 (a) Pall's friction device (Constantinou et al., 1998) (b) uniaxial friction damper (Constantinou et al., 1998) (c) idealized hysteresis loop (Constantinou and Symans, 1992) ....... 6

Figure 1-4 The typical configuration and application of the buckling restrained brace (Clark et al., 2000) .......................................................................................................................... 7

Figure 1-5 The behavior and configuration of (a) ADAS damper (b) TADS damper (Alehashem et al., 2008) .................................................................................................................. 8

Figure 1-6 The typically configured EBFs with link beams (Mansour et al., 2011) .............. 10

Figure 1-7 Configuration of the steel plate shear wall (Caccese et al., 1993) ...................... 11

Figure 1-8 Braced frame with shear panel fuses .................................................................. 11

Figure 1-9 Slit damper test with (a) fractures at the two ends (b) hysteresis loop (Chan and Albermani, 2008) ................................................................................................................ 13

Figure 1-10 (a) Honeycomb damper in test (b) hysteresis response (Kobori et al., 1992) .... 14

Figure 1-11 (a) Butterfly fuse specimen (b) hysteresis loop (Ma et al., 2011) .................... 14

Figure 1-12 Non-uniform steel strip damper drawings (Lee et al., 2015) ......................... 15

Figure 1-13 Failure modes of uniform and non-uniform steel strip dampers (Lee et al., 2015) 16

Figure 1-14 (a) Tested block slit damper (b) hysteresis curve (Amiri et al., 2018) .............. 16

Figure 1-15 (a) The PYSPD specimen (b) the FE model of the PYSPD (Chan et al., 2013) .... 17
Figure 1-16 (a) The WWFF specimen (b) the hysteresis loop (c) the FE model (Banjuradja, 2018) ........................................................................................................................................ 18

Figure 1-17 Specimen 3D concept.................................................................................................. 19

Figure 1-18 Potential applications of the HSF............................................................................. 20

Figure 2-1 The Baldwin Tate-Emery testing machine.................................................................... 24

Figure 2-2 The key components used in the tensile coupon test .................................................. 24

Figure 2-3 Experimental test setup .............................................................................................. 25

Figure 2-4 Loading mechanism of the specimen ........................................................................... 26

Figure 2-5 Specimen notation of HSF .......................................................................................... 27

Figure 2-6 Connection plate types .............................................................................................. 28

Figure 2-7 Actuator and loading cell in test.................................................................................. 29

Figure 2-8 Placement of the linear pots ....................................................................................... 30

Figure 3-1 (a) Initial state (b) necking state (c) failure state of the tensile coupon test.............. 32

Figure 3-2 Stress-strain relationships from the tensile coupon test ............................................ 33

Figure 3-3 Force-drift relationship of a0.3r3c4 .............................................................................. 34

Figure 3-4 Specimen a0.3r3c4 at different drift ratios ................................................................. 34

Figure 3-5 Force-drift relationship of a0.5r3c4 .............................................................................. 35

Figure 3-6 Specimen a0.5r3c4 at different drift ratios .................................................................. 35

Figure 3-7 Force-drift relationship of a0.7r3c4 .............................................................................. 36

Figure 3-8 Specimen a0.7r3c4 at different drift ratios ................................................................. 36

Figure 3-9 Force-drift relationship of a0.3r3c3 .............................................................................. 37

Figure 3-10 Specimen a0.3r3c3 at different drift ratios ............................................................ 37

Figure 3-11 Force-drift relationship of a0.5r3c3 ............................................................................ 38
Figure 3-12 Specimen a0.5r3c3 at different drift ratios................................................................. 38
Figure 3-13 Force-drift relationship of a0.7r3c3 ................................................................. 39
Figure 3-14 Specimen a0.7r3c3 at different drift ratios................................................................. 39
Figure 3-15 Force-drift relationship of a0.3r3c2 ................................................................. 40
Figure 3-16 Specimen a0.3r3c2 at different drift ratios................................................................. 40
Figure 3-17 Force-drift relationship of a0.5r3c2 ................................................................. 41
Figure 3-18 Specimen at a0.5r3c2 different drift ratios................................................................. 41
Figure 3-19 Force-drift relationship of a0.7r3c2 ................................................................. 42
Figure 3-20 Specimen a0.7r3c2 at different drift ratios................................................................. 42
Figure 3-21 Force-drift relationship of a0.3r2c3 ................................................................. 43
Figure 3-22 Specimen a0.3r2c3 at different drift ratios................................................................. 43
Figure 3-23 Force-drift relationship of a0.5r2c3 ................................................................. 44
Figure 3-24 Specimen a0.5r2c3 at different drift ratios................................................................. 44
Figure 3-25 Force-drift relationship of a0.7r2c3 ................................................................. 45
Figure 3-26 Specimen a0.7r2c3 at different drift ratios................................................................. 45
Figure 3-27 Buckling behavior of HSF .................................................................................. 47
Figure 3-28 Failure modes of HSF ......................................................................................... 49
Figure 3-29 Force-drift relationship of HSF ............................................................................. 51
Figure 3-30 Backbone properties of HSF .............................................................................. 52
Figure 3-31 Normalized energy plot for different cell combination......................................... 55
Figure 4-1 Proposed ABAQUS model .................................................................................... 58
Figure 4-2 Comparison between the experimental and FE model under cyclic loading .......... 60
Figure 4-3 Buckling shapes from experiment and FEA .......................................................... 61
Figure 4-4 PEEQ distribution and corresponding test pictures .............................................. 62
Figure 4-5 Out-of-plane deformation of corresponding FEM of WWFFs ............................... 63
Figure 4-6 Force-drift relationship of corresponding FEM of WWFFs .................................. 64
Figure 4-7 (a) Initial stiffness comparison (b) yielding drift comparison .............................. 66
Figure 5-1 (a) Normalized yield force (b) normalized initial stiffness ................................. 70
Figure 5-2 Yielding drift ratio .................................................................................................. 70
List of Symbols

a: Cell wall aspect ratio
A: Overall aspect ratio
c: Cell columns
\( C_k \): Parameters of material kinematic model
h: Center line length of cell wall
H: Net height of honeycomb shear fuse
H: Overall net height
K: Initial stiffness
L: Overall length
M: Moment
N: Number of back stresses
r: Cell rows
t: Cell wall thickness
V: Shear force
\( V_p \): Pure shear force
\( V_u \): Ultimate force
\( V_y \): Yielding force
W: Plate thickness
\( \alpha \): Overall back stress
\( \gamma \): Drift ratio
\( \gamma_y \): Yielding drift
\( \gamma_u \): Ultimate drift ratio

\( \gamma_k \): Parameters of material kinematic model

\( \varepsilon^{pl} \): Equivalent plastic strain

\( \sigma_y \): Yielding stress
List of Abbreviations

ADAS: Added Damping and Stiffness
BRB: Buckling Restrained Brace
DOF: Degree of Freedom
EBF: Eccentrically Braced Frame
FEA: Finite Element Analysis
HSF: Honeycomb Structural Fuse
HSS: Hollow Steel Section
LVDT: Linear Variable Differential
LP: Linear Pot
PEEQ: Equivalent Plastic Strain
PYSPD: Perforated Yielding Shear Panel Device
SPSW: Steel Plate Shear Wall
TADAS: Triangle-Added Damping and Stiffness
WWFF: Welded Wide Flange Fuse
YSPD: Yielding Shear Panel Device
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Finally, I would very much like to show my gratitude to my parents for their immeasurable love and support for my studies. Many thanks to them for always encouraging me when I most needed it.
Dedication

I dedicated this research to my parents, Weixin Li and Yanwei Zhu, for their unconditional love and support.
Chapter 1: Introduction

1.1 Overview

Earthquake is the shaking of the surface of Earth caused by the sudden release of energy stored in the Earth’s interior. As an unpredictable natural disaster, earthquakes cause enormous life threats, economic loss and homelessness to human life. In 2011, the Christchurch earthquake in New Zealand caused great destruction, resulting in up to 50% of the buildings demolition in the central business district, 184 confirmed deaths and an estimated economic loss of over $20 billion NZ (Eguchi et al., 2012). In the same year, a moment magnitude 9.0 Tohoku earthquake struck at the subduction zone interface plate boundary between the North American and Pacific plates off the coast of Eastern Japan, killing 15,703 people, with 4,647 missing, 5,314 injured and over 130,927 Japanese displaced. In total, approximately 332,000 buildings, 2,100 roads, 56 bridges, and 26 railroads were either destroyed or damaged, totaling an economic loss of over $300 billion, making this the most expensive disaster of all time (Eguchi et al., 2012). Thus, the continued optimization of buildings’ seismic design and performance is highly essential so as to minimize earthquake-induced losses to inhabitants.

The traditional method for seismic design mainly takes advantage of the appropriate strength, stiffness, and natural ductility of main building structures, including beams and columns, to resist earthquake-induced ground shaking, where earthquake load is considered an equivalent static lateral force. Since structures’ primary design objective is to ensure life safety and collapse prevention, a certain level of damage, particularly under strong earthquake shock, with its resultant
enormous economic loss and homelessness, is inevitable. Over the past decades, the popular concept of structural fuse has been widely adopted in next-generation earthquake engineering design. This concept is similar to the electrical fuse applied to buildings that can cut off the entire circuits when overcurrent occurs and otherwise provide protection for electrical circuits. Similarly, the idea of structural fuse is to limit earthquake-induced damage within the designed damping device through its energy absorption or transformation, thus minimizing the degree of damage to the main structure. After earthquakes, the designed structural fuse can be conveniently inspected and replaced, with the parent structure can efficiently recovering full function, making it resilient towards future earthquake shaking. Unlike the active and semi-active earthquake system, the structural fuse as a passive energy dissipator does not require an external source of power, eliminating the reliability problem in connection with power supply and computer control systems during fierce ground shaking.

1.2 Types of Structural Fuses

A good fuse must possess: 1) stable and advanced hysteretic performance, 2) proper stiffness and strength, 3) economical and practical fabrication and 4) good environmental factor resistance. Currently, the main structural fuses include viscous fluid, viscoelastic and friction dampers, and metallic fuses.
1.2.1 Viscous Fluid Dampers

The viscous fluid dampers evolved from the shock isolation damping device originally developed for military hardware which utilizes the flow of fluid through orifices and is applied widely in recent years within structures as an energy dissipation device. A few well-known applications can be found, for instance, in: The New York Power Indian Point 3 Nuclear Power Plant, the Virginia Power North Ana Nuclear Station and the West Seattle Swing Bridge. The typical construction of a tested specimen is shown in Figure 1-1(a). It mainly consists of a stainless-steel piston, with a bronze orifice head and an accumulator. It is filled with silicone oil. The orifice flow is compensated for by a passive bimetallic thermostat that allows operation of the device over a temperature range of -40°F to 160°F (-40°C to 70°C) (Constantinou and Symans, 1992). The idealized force-displacement relationship of a viscoelastic fluid damper is shown in Figure 1-1(b).

![Figure 1-1 (a) Typical viscous fluid damper (Constantinou and Symans, 1992) (b) idealized hysteresis loop (Constantinou and Symans, 1992)](image-url)
1.2.2 Viscoelastic Dampers

Viscoelastic dampers have been applied to high-rise buildings as an efficient energy dissipating device to resist wind- and earthquake-induced shaking. Examples of structures with such dampers include the World Trade Center in New York City (110 stories), the Columbia Sea First Building in Seattle (73 stories) and the Number Two Union Square Building in Seattle (60 stories) (Constantinou and Symans, 1992). A typical viscoelastic damper installed in buildings usually consists of two viscoelastic layers bonded between three rigid metallic plates, as shown in Figure 1-2(a). The layers can be made of copolymers or glassy materials which can transfer mechanical energy into heat when subjected to shear deformation. The response is frequency dependent, as the outer steel flanges move with the motion of a building. The energy is dissipated by the viscoelastic layers rubbing against the steel centerplate. When mounted in a structure, shear deformation and, hence, energy dissipation take place when the structural vibration induces relative motion between the outer steel flanges and the centerplate (separated by viscoelastic layers). A typical hysteresis curve for a viscoelastic damper is shown in Figure 1-2(b).

![Figure 1-2](image_url)

**Figure 1-2** (a) Viscoelastic solid damper (Keel and Mahmoodi, 1986) (b) typical hysteretic loop

(Constantinou and Symans, 1992)
1.2.3 Friction Dampers

Pall and Marsh (1982) proposed the idea of installing fractional devices at the intersection of buildings’ X bracing to improve structural seismic performance. The mechanism for this type of damper utilizes the friction resistance between two solid objects when they slide relative to one another to dissipate the excessive energy produced from the ground shaking in an earthquake. In this way, the inelastic yielding of the parent structure can be minimized. Figure 1-3 (a) shows the configuration of Pall’s friction damper. Aiken and Kelly (1990) investigated a uniaxial friction damper, as shown in Figure 1-3 (b), where copper alloy friction pads slide along the inner surface of the cylindrical steel casting to convert the mechanical energy induced by an earthquake into heat. These fictional devices were initially developed by Sumitomo Metal Industries, Ltd., in Japan for application in railway engineering and subsequently extended to structural engineering applications. Instances of use was found in two high-rise building in Japan, the Sonic City Office Building in Omiya City and the Asahi Beer Azumabashi Building in Tokyo. These devices have high-performance characteristics, with their behavior being negligibly affected by amplitude, frequency, temperature or the number of applied loading cycles. Figure 1-1 (c) illustrates the typical idealized hysteretic curve of a fraction damper under cyclic loading, which approximates a perfect rectangle.
1.2.4 Metallic fuses

Over the past decades, metallic fuses have been studied extensively and applied worldwide in earthquake engineering, which can be mainly classified into three focal categories according to their working mechanism, namely, axial, flexural and shear yielding fuses. Shear yielding fuses will be further discussed in the next section.

The common axial yielding fuse is the Buckling Restrained Brace (BRB) (Suzuki et al., 1994; Takeda et al., 1976), designed to dissipate seismic energy by the axial yielding of its steel core when under earthquake induced ground motion. It is generally made up of a slender steel core, an encasing mortar for restraining the buckling behavior of the steel core when under axial
compression, and an interface region that prevents undesired interactions between the two, as shown in Figure 1-4. Structures with BRBs can be easily and efficiently constructed using bolted or pinned connections and can be more easily replaced following severe earthquake shaking, which makes them more resilient towards earthquakes (Figure 1-4).

![Figure 1-4 The typical configuration and application of the buckling restrained brace (Clark et al., 2000)](image)

First proposed by Whittaker et al. (1988), the Added Damping and Stiffness (ADAS) is a metallic fuse which is constructed based on the flexural yielding mechanism. As shown in Figure 1-5 (a), the ADAS is made up of several X-shaped steel plates applied braced system. This configuration is designed such that yielding can occur along the entire length of the device by double curvature inelastic deformation (fixed boundary conditions) under fierce shaking. Shake table tests by Whittaker et al. (1988) of a 3-storeyed steel model structure demonstrate that the ADAS elements improved the behavior of the moment resisting frame to which they were installed by increasing a) stiffness, b) strength and c) ability to dissipate energy. However, since the ADAS devices are designed to bolt together through two ends of each plate, the stiffness is highly sensitive to the tightness of the bolts and is generally less than that of the predicted value due to the two fixed ends (Whittaker et al., 1988). Aiming to solve this uncertainty, Triangle-Added Damping and Stiffness (Figure 1-5 (b)), called TADAS, was studied by researchers (Tsai et al., 1993). Based on its
triangular plate design, TADAS can yield along nearly the length of the entire device without curvature concentration providing adequate stiffness and strength.

Figure 1-5 The behavior and configuration of (a) ADAS damper (b) TADS damper (Alehashem et al., 2008)

1.3 A Review of Previous Study on the Steel Shear Yielding Fuses

The aforementioned flexural yielding dampers are designed to absorb seismic energy through inelastic out-plane flexural deformation according to weak axes. Since very thin steel plates are the main elements which result in low out-plane stiffness, flexural dampers usually consist of multiple steel plates bolted together to achieve the stiffness demand for the main structural design. During the past decades, another important type of metallic fuse, the Steel Plate Shear Device, has been studied and developed by researchers and engineers; this fuse utilizes the shear capacity of
steel plates to dissipate seismic energy. The main advantages of using the shear yielding mechanism include the attainment of adequate stiffness with an effective utilization of the material. Main steel plate shear devices include steel shear link beams, steel plate shear walls and steel shear dampers.

1.3.1 Steel Shear Link Beam in Eccentrically Braced Frame

Steel plates yielding in shear have been studied extensively in the 1970's to 1980's for their application as steel shear link beams for eccentrically braced frames (EBFs) (Engelhardt and Popov, 1989; Hjelmstad and Popov, 1983; Mansour et al, 2011; Roeder and Popov, 1977; Roeder and Popov, 1978). Figure 1-6 illustrates the typical configuration of the EBF and its link beam in a test. Researchers from the US and Canada conducted experimental tests at both the component and systems level, demonstrating that the steel shear link, when acting as a fuse based on steel plate shear yielding, can efficiently dissipate large amounts of earthquake energy. EBFs with shear link beams are well suited for applications in seismic regions based on their high elastic stiffness and good ductility.
1.3.2 Steel Plate Shear Wall

The steel plate shear wall (SPSW) is another popular application of the concept of steel plate shear yielding in seismic engineering (Figure 1-7). Extensive numerical and experimental studies on SPSWs were initiated in the early 1970’s. In 1973, Takahashi et al. (1973) first conducted a series of 12 single plate tests and two single bay, two-storied full-scale stiffened steel plate shear walls with and without reinforced openings, demonstrating that the steel plate shear wall with ribbed plates had good hysteretic behavior compared with unstiffened ones and both its rigidity and strength could be calculated with the shear theory. Afterwards, Caccese et al. (1993), Driver et al. (1998) and Lubell et al. (2000) conducted a systems-level study whereby a thin plate shear wall with beam-column boundary members was tested. The research demonstrated the effectiveness of the steel plate shear wall as a lateral load resisting system with distinct advantages including its enhanced stiffness, strength and ductility, stable hysteretic characteristics and advanced energy absorption capability. A fracture was found at the corner of a storey due to local buckling behavior.
1.3.3 Steel Shear Damper

Shear panel fuses and their corresponding ramifications have been widely studied in the past few years; their construction is based on the mechanism of steel plate shear yielding and has normally been applied to such bracing systems as hysteretic damping devices, as shown in Figure 1-8.

Based on previous studies on steel plate shear walls and link beams, the steel shear fuse has the advantages of high stiffness and strength. However, it has also been found that, due to thin plate
utilization, it’s out-plane buckling behavior is quite severe, causing, for instance, sudden drops in shear force, pinching hysteresis loops and low ductility. Such behavior is undesirable for the energy dissipation of fuses and the main structural design. To solve this problem, two main approaches have been adopted: 1) adding stiffeners to the plates or at boundaries, and 2) center weaknesses (openings cut into its plates).

In 1994, Nakashima (1995) and Nakashima et al. (1994) explored the energy dissipation behavior of shear panels made of 120 MPa low yield stress steel and compared the effectiveness of different stiffener arrangements and boundary conditions, with or without the application of axial loads. The test results revealed that shear panels with two-way stiffeners had the highest energy dissipation capacity, followed by vertical stiffeners. Specimens without stiffeners displayed the lowest energy dissipation performance. It was also found that these stiffeners could restrain with greater stability out-plane buckling behavior and hysteresis loops. In 2009, Chan et al. (2009) developed the Yielding Shear Panel Device (YSPD), where a steel plate was cut and welded within hollow steel sections (HSS). YSPD was designed to dissipate earthquake energy through the shear yielding of the welded plate simultaneously with flexural deformation of the HSS. Meanwhile the HSS can also provide buckling restriction for the shear web. The results showed that YSPD can work effectively, with high initial stiffness, as an energy dissipater. However, the fabrication and design of the YSPD is relatively difficult to achieve, due to the precision required to cut and weld the steel plate within the HSS and the highly nonlinear coupling that needs to be performed between the steel plate and the HSS under cyclic load.
Another approach to achieving high ductility is that of cutting holes into the plates, referred to as “center weakness”. Chan and Albermani (2008) conducted an experimental study on cutting slits into solid steel shear plates. Through this procedure, the plates are divided into a number of parallel links which exhibit flexural mode behavior rather than the predominant shear mechanism of the original solid plate. Each individual link is more compact than the high width-to-thickness ratio solid plates. Thus, the buckling resistance is enhanced. Additionally, after the slits are cut, the initial stiffness is reduced, which can alleviate demand on the supporting elements. The test results confirmed the conceptual design whereby the fracture was concentrated on the two ends of the “beam” since the flexural working mechanism and buckling behavior was somehow restrained. Figure 1-9 illustrates the fracture and hysteresis loop of slit damper.

![Slit damper test with (a) fractures at the two ends (b) hysteresis loop (Chan and Albermani, 2008)](image)

Kobori et al. (1992) proposed construction of a honeycomb damper plate using steel plates with honeycomb-shaped openings, as shown in Figure 1-10 (a), which left butterfly-shaped links. This kind of design led to a more distributed yielding along the length of the links because of the resemblance of its geometry to the moment diagram of the beams deforming into a double curvature. The test results showed that the damper can reach a 30% shear deformation without degradation (Figure 1-9(b)).
Based on this idea, some similar hysteresis dampers are widely studied from other aspects. In 2011, Ma et al. (2011) conducted tests on geometric variations, including the ratio of link width to the thickness and slenderness ratio, which was 2-10 and 14-56, respectively, to provide greater flexibility to design (Figure 1-11(a)). The test further explored the performance of much thinner butterfly links (of mainly 6 mm) which may be adequate for applications of small ductility demand. The force-deformation relationship showed that the fuses fractured at a shear deformation of 35% with pinching hysteresis behavior, as shown in Figure 1-11(b).
In 2015, Lee et al. (2015) described the cyclic performance of non-uniform and uniform steel strip dampers. The shapes proposed are (a) a dumbbell-shaped strip, (b) a tapered strip, and (c) an hourglass-shaped strip, as shown in Figure 1-12. The test results showed that, compared with the uniform specimen, the damage was not concentrated at the ends in the crack propagation stage, but the cracks were instead widely distributed along the height (Figure 1-13). The proposed dampers significantly improved cumulative ductility by 1.13–1.75 and energy dissipation by 1.27–2.36, as compared to the conventional uniform strip damper (Lee et al., 2015).

Figure 1-12 Non-uniform steel strip damper drawings (Lee et al., 2015)
In 2017, Amiri et al. (2018) conducted experimental and analytical studies of block slit dampers. This is based on the aforementioned butterfly damper with its very low height to thickness ratios, which has a high shear capacity (Figure 1-14(a)). The researcher demonstrated that the width of the middle to bottom portion, equaling 0.45, showed the best hysteresis performance. The force-displacement curves of the tested specimens were stable with advanced energy dissipation capacities due to the specimens being resistant to buckling as well as the development of plastic strains throughout the heights of the specimens (Figure 1-14(b)).
(3mm) steel plate was welded from hollow sections, but with circular perforations, as shown in Figure 1-15 (a). The idea was to alleviate demand on the supporting elements through perforations which could thus reduce undesirable local deformations near connections. Through the cyclic test, the researchers drew the conclusion that the proposed fuse had stable hysteretic behavior and qualified low-cyclic fatigue. The perforations in the diaphragm plates reduced the elastic stiffness and yield force, and the demand on the supporting elements. Also, a more stable hysteresis loop was observed (Chan et al., 2013). The corresponding FE element model was built based on the shell element (S4R) to acquire an initial understanding of the mechanism (Figure 1-15(b)). However, the fabrication and design of a YSPD is relatively difficult, due to the precision required to cut and weld the steel plate within the HSS and the highly nonlinear coupling between the steel plate and HSS under cyclic load.

![Figure 1-15 (a) The PYSPD specimen (b) the FE model of the PYSPD (Chan et al., 2013)](image)

Recently, a more practical metallic damper called the Welded Wide Flange Fuse (WWFF) was proposed by Banjuradja (2018), as shown in Figure 1-16 (a), which utilized commonly available welded wide flange section to dissipate earthquake energy through shear yielding of the web in the longitudinal direction, with the flanges remaining elastic. The advantages of the WWFF mainly
include its economic fabrication, versatile design, and efficient energy dissipation capability. In the study, an analytical equation was proposed and detailed parameters such as size ($f_{sc}$), aspect (A: web width to the clear depth of the web) and slenderness ratios (S: clear depth of the web to plate thickness) were experimentally tested. Each of the parameters, namely, A=0.75, 1.5 and 2; $f_{sc}$=1, 1.3, and 2; and S= 22, 32, 43 were included in the study. The cyclic test showed that, as the aspect ratio increased, the buckling shape changed from two parallel lines in the loading direction to a diagonal buckling shape. However, the hysteretic shape was not significantly influenced by the aspect ratio. The WWFF, with its low slenderness ratio, revealed a failure mode with pure shear yielding and fracture near the welding zone. As the slenderness ratio increased, plate buckling and yielding through the tension field action occurred, moving the fracture to the center of the web. The buckling behavior caused severe pinching (Figure 1-16(b)). To assist in understanding the proposed WWFF, the robust FE model was constructed based on the shell element (Figure 1-16(c)).

![Figure 1-16](image)

*Figure 1-16* (a) The WWFF specimen (b) the hysteresis loop (c) the FE model (Banjuradja, 2018)
1.4 Research Motivation and Objectives

In this study, a novel steel plate damper called, Honeycomb Structural Fuse (HSF), is proposed based on the previous study of WWFF (Banjuradja, 2018). Figure 1-7 shows the 3D concept of the HSF. The HSF uses the same configuration as the WWFF with the addition of honeycomb-shape perforations in the web. The perforations provide designers with more freedom in selecting initial stiffness and yielding drift by changing parameters, when compared with a solid web. Also, out-plane buckling is somehow inhibited, thus obtaining full hysteresis preformation.

In this work, cyclic quasi-static tests were conducted on 12 HSFs in the Structural Engineering Laboratory at the University of British Columbia, Vancouver. The effects of honeycomb cell wall aspect ratio and row and column combination of honeycomb cells were extensively examined. A robust finite element model was built, and the numerical results were validated with the experimental results. Based on the validated model, further parametric studies were performed to identify the trends of key design parameters and to provide better understanding of HSFs behavior.
Finally, the comparison with WWFF was conducted to investigate the effect of honeycomb perforation.

Thus, the objectives of this study were to investigate the effectiveness of honeycomb perforation and the influence of different geometry parameters on the performance, and to prepare a correspondingly reliable FE model in the interest of future engineering designs. The potential applications are shown in Figure 1-18.

Figure 1-18 Potential applications of the HSF
1.5 Organization of the Thesis

Chapter 2 of the thesis describes the experimental program used for testing the proposed HSF. The test setups including the tensile coupon and shear damper test setups are introduced. Then, the corresponding test specimen’s design and matrix are shown. Following this, the loading protocol and test procedure for the cyclic test are explained.

In Chapter 3 of the thesis, the specimen’s performance in the tensile coupon and cyclic loading tests are described in detail. HSF behavior, including buckling and failure modes, the force-drift relationship and energy dissipation efficiency are the key trends demonstrated in this chapter.

The focus of Chapter 4 is to create a robust FE model in ABAQUS for a comprehensive understanding of the performance of HSFs. First, the detailed modelling approach is described, including material law, element selection, boundary conditions. Then, the simulation results are compared with the test results to validate its effectiveness. Finally, the comparison with WWFF is conducted to investigate the effect of honeycomb perforation.

In Chapter 5, with the robust FE model, the parameter study is then conducted to complete the trends followed in Chapter 4. Also, with more reliable results, other trends related to the key characteristics of HSF are summarized, including yielding force, initial stiffness, ultimate drift. The chapter closes with a discussion.
In the final chapter of the thesis, a summary and conclusion of the entire work are prepared, and recommendations for future work to explore the HSF in greater depth are also presented.
Chapter 2: Experimental Program of HSF

2.1 Introduction

The experimental program includes the 12 proposed HSF tests and corresponding tensile coupon test. The tests were conducted at the Structural Laboratory, at the University of British Columbia, Vancouver. The aim of the test was to investigate the hysteretic behavior of the HSF. Tests can provide references to later Finite Element Analysis in Abaqus. In this chapter, the test setup, specimen description, loading protocol and test procedure are discussed.

2.2 Test Setup

Two main test setups were employed to test the HSFs. For material property testing, the tensile coupon test setup was provided by the Structural Laboratory of UBC. To test the proposed HSFs, the corresponding shear damper setup designed by the Smart Structures Group at UBC was employed.

2.2.1 Tensile Coupon Test Setup

The Baldwin Tate-Emery testing machine manufactured by the Baldwin Lima Hamilton corporation was used for the tensile coupon test. It was provided by the Structural Lab at UBC to test the steel material law, as show in Figure 2-1. This type of machine is universal and has a capacity of 400,000 lbs.
The holding brackets had been manufactured to hold the LVDTs, and its spring load provided the clamping force that prevented instruments falling off due to the gradual narrowing of coupon cross-section when stretching. The LVDTs held by the brackets were used to measure the deformation of coupon’s gage length. The key components used in the tensile coupon test are showed in Figure 2-2.
2.2.2 Shear Damper Test Setup

The experimental setup was designed to generate pure shear loading in the specimen. Figure 2-3 details the testing apparatus for this experiment, which consists of five main parts: the loading beam, pantograph, mounting platform, out-of-plane support, and fin extension. The pantograph was designed to prevent the setup from rotating in plane without restraint in the U2 direction. The use of the out-of-plan restraint and the fin prevented the setup from translating and rotating out of plane. The specimens were connected to the loading beam and the reaction frame using bolts connections through the HSF flanges. An actuator with a capacity of 1000 kN and stroke limit of +/- 150 mm was placed at the top of the testing frame. The actuator was designed to push and pull the specimen in the U1 direction.

Figure 2-3 Experimental test setup
2.3 Loading Mechanism

The setup was designed to provide a pure shear loading mechanism. The support reactions and the internal force diagrams due to this loading are presented on Figure 2-4. The shear force of the specimen was uniform throughout the element with the same magnitude as the actuator force. The moment reaction (M) at both ends was assumed to have the value of $M = 0.5VH$, with an inflection point at its center.

![Diagram showing Loading mechanism of the specimen](image)

**Figure 2-4 Loading mechanism of the specimen**

As shown in Figure 2-4, the actuator’s central line coincided with the specimen’s centre. This was to eliminate eccentricity between the actuator and specimen’s centre and thus minimize the axial demands on the pantograph. Any accidental eccentricity caused by additional moment to the specimen would be balanced by the axial force from the pantograph.
2.4 Test Specimen’s Notation and Design

Twelve specimens with different honeycomb cell wall aspect ratios (a) and honeycomb cell row and column combinations (r-c) were systematically tested at the University of British Columbia. Each of the HSF was fabricated using 3 plates (two flanges and one web). Honeycomb shape perforations were completed using laser cut on the 4.8mm thickness (\(t_w\)) plates with 5mm fillet at corners. The honeycomb shear web was then fillet-welded using E49XX weld at the center line of the flanges. Figure 2-5 and Table 2.1 show the summary of the specimen notations and dimensions used in this study. The aspect ratio (a) is defined as the ratio of honeycomb cell wall thickness (t) to center line length (h). Similarly, four row (r) and column (c) combinations of honeycomb cell were investigated. Three honeycomb cell wall aspect ratios, \(a = 0.3, 0.5\) and 0.7, were included in this study. Three different number of columns, \(c = 2, 3, \) and 4, and two different number of rows, \(r = 2 \) and 3, were investigated. Two different flange types A and B were used to match different shear web geometry of the HSF, as shown in Error! Reference source not found.a and b.

Figure 2-5 Specimen notation of HSF
Table 2.1 Test specimen matrix

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Cell wall Thk.</th>
<th>Cell wall (center) length</th>
<th>Cell wall aspect ratio</th>
<th>Cell Rows</th>
<th>Cell Columns</th>
<th>Plate Thk.</th>
<th>Overall Height</th>
<th>Overall Length</th>
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<td>l (mm)</td>
<td>a=t/l</td>
<td>r</td>
<td>c</td>
<td>W (mm)</td>
<td>H (mm)</td>
<td>L (mm)</td>
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<td>0.3</td>
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<td>4.8</td>
<td>203.2</td>
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<td>0.7</td>
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<td>4</td>
<td>4.8</td>
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<td>4.8</td>
<td>139</td>
<td>302.0</td>
</tr>
</tbody>
</table>

(a) Bolt pattern A  
(b) Bolt pattern B

Figure 2-6 Connection plate types
2.5 Test Instruments

In this study, an actuator with a capacity of 1000 KN and +/- 200 mm was adopted. The used load cell was mounted between the actuator’s end and the L-beam, which is MTS 661.31 with a capacity of 100 kN. Two adapter plates were used to connect the load cell to the load beam and actuator.

Since there was no displacement or force feedback, the control was conducted based on displacement from the linear pots. In other words, three linear pots (LPs) were used to record the displacements of the setup. In order to eliminate the bolt slippage measurement, two linear pots (LP1 and LP2) were placed between the flanges of the HSF (Figure 2-8). Using nonlinear geometric transformation, the exact deformation of the HSF in the U1 and U2 directions could be calculated. An additional linear pot was placed at Location B to compare the displacement of Location A in the U2 direction so as to ensure that the setup did not rotate in the in-plan direction.
2.6 Loading Protocol

The AISC 341-16 (2016) loading protocol for the beam-to-column connections was adopted with minor modifications. The loading protocol was defined using drift ratio, which was calculated by dividing the displacement in the U1 direction by the clear distance of the web (H). The loading protocol consisted of two cycles of $\gamma = 0.002$, followed by six cycles of $\gamma = 0.00375$, $\gamma = 0.005$ and $\gamma = 0.0075$; four cycles of $\gamma = 0.01$ and two cycles of $\gamma = 0.015$ and $\gamma = 0.02$, and increments of $\gamma = 0.01$, until the stroke limit of the testing apparatus’ deformation limit was reached. Table 2.2 illustrate the loading protocol applied to the test.

<table>
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<tr>
<th>No.</th>
<th>Number of cyclic</th>
<th>Drift ratio $\gamma$</th>
<th>No.</th>
<th>Number of cyclic</th>
<th>Drift ratio $\gamma$</th>
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</thead>
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<td>2</td>
<td>0.02</td>
<td>14</td>
<td>2</td>
<td>0.09</td>
</tr>
</tbody>
</table>
2.7 Test Procedure

The specimen was temporarily braced by long struts at each of its 4 corners to prevent accidental out-plane buckling during transportation. The struts were then removed when they were ready to be tested. Some preparation work had already been performed before the tests:

1. Three sets of bolt holes were drilled on the sides of the specimens to install linear pots, which were then mounted on the back of the specimen, while the front of the web was white washed.
2. The linear pots were calibrated, and the control system was well tuned prior to testing.
3. The specimen was carefully mounted to the designated bolt holes using 7/8” bolts. Adapter plates were used to adjust the space between the bolts if necessary. After the specimen and the displacement sensors were installed properly, the test was conducted.

The test was conducted until the failure of the specimen or until the limit of the instrumentation was achieved. The entire procedure was recorded on camera. The data was analyzed following the test.
Chapter 3: Experimental Results of the HSF

3.1 Introduction

This chapter first presents the results of the tensile coupon test. The detailed strain-stress relationships were plotted and summarized. After obtaining the material law, the cyclic test results of the 12 HSFs described in Chapter 2 are presented and the hysteresis behavior including buckling and failure modes described in detail. The chapter ends with a discussion on the tests’ experimental behavior and data.

3.2 Tensile Coupon Test Results

The tensile test of the steel coupons was conducted to determine the stress-strain relationship of the source steel. The coupon specimen was designed and tested following the standard of ASTM A370-17 (2017). The coupons from the same plate were tested under monotonic loading, as shown in Figure 3-2; these are the initial, necking, and failure states, respectively.

(a) Initial state (b) necking state (c) failure state of the tensile coupon test
Figure 3-2 describe the strain-stress relationship and corresponding results obtained in the test, where the Young’s Modulus and the yield stress are 210 GPa and 256 Mpa, with maximum elongation of 42%.

![Stress-strain relationships from the tensile coupon test](image-url)
3.3 Cyclic Loading Performance

3.3.1 a0.3r3c4

Specimen a0.3r3c4 has a honeycomb cell wall aspect ratio of 0.3, with 3 rows and 4 columns. Its shear force versus drift ratio relationship is presented in Figure 3-3, while Figure 3-4 shows its deformation at different drift ratios. Yielding occurred at the drift ratio of 0.5%. It was found that the force began to drop when the specimen reached its peak force at the 5% drift ratio, but no obvious out-plane buckling was observed at this state during the test, meaning that the force drop was caused by the specimen’s fracture rather than its buckling. The test was halted at the 13% drift ratio, where the specimen fractured severely. Due to the stress concentration, the fracture was mainly located at the two ends of the honeycomb cell walls.

![Figure 3-3 Force-drift relationship of a0.3r3c4](image)

![Figure 3-4 Specimen a0.3r3c4 at different drift ratios](image)
3.3.2 a0.5r3c4

Specimen a0.5r3c4 with 3 rows and 4 columns has a honeycomb cell wall aspect ratio of 0.5. Figure 3-5 and Figure 3-6 show the hysteresis curve and deformation at different drift ratios respectively. The specimen yielded at a drift ratio of 0.47%. At around a 3% drift ratio, the specimen reached peak force, accompanied by a slight bucking. The force degradation became increasingly noticeable with drift ratio increasing and specimen buckling. The specimen exited working at drift ratio of 13% when the test apparatus reached its limit. At this state, fractures were found at both ends of the honeycomb cell wall and buckling zones, as shown in Figure 3-6, implying that the working mechanism under these conditions is a combination of local honeycomb cell wall bending and global honeycomb web shear.

![Figure 3-5 Force-drift relationship of a0.5r3c4](image)

![Figure 3-6 Specimen a0.5r3c4 at different drift ratios](image)
3.3.3 a0.7r3c4

Specimen a0.7r3c4 with 3 rows and 4 columns has a high honeycomb cell wall aspect ratio of 0.7. Figure 3-7 and Figure 3-8 illustrate the hysteresis curve and deformation at different drift ratios. The specimen yielded at a drift ratio of 0.45%. The specimen could not take on higher forces at a 2% drift ratio due to obvious out-of-plane buckling. The tension and compression fields were observable when the specimen was in this state, which is similar to the solid plates’ behavior (Banjuradja, 2018). When reaching a 13% drift ratio, severe fracture was found at the diagonal buckling zones, as shown in Figure 3-8, which means that the working mechanism is the global plate shear dominant for this case. The test was halted at the 13% drift ratio, although the specimen was believed capable of continuing to further levels.

![Figure 3-7 Force-drift relationship of a0.7r3c4](image)

![Figure 3-8 Specimen a0.7r3c4 at different drift ratios](image)
3.3.4 a0.3r3c3

Figure 3-9 reveals the force-drift relationship of specimen a0.3r3c3, which has a 0.3 honeycomb cell wall aspect ratio and cell combination of 3*3. Figure 3-10 shows deformed specimen moments at different drift ratios. It was noted that the force began to decrease when reaching its peak force at the 6% drift ratio. No obvious out-plane buckling was found at this state, which means that the force drop was caused by specimen fracture rather than buckling. The specimen demonstrated serious failure with several honeycomb cell wall fractures at a drift ratio at 11%. Due to the stress concentration, the fracture was mainly located at the two ends of the honeycomb cell walls. This behavior resembles that of a0.3r3c4.

![Force-drift relationship of a0.3r3c3](image)

**Figure 3-9 Force-drift relationship of a0.3r3c3**

![Specimen a0.3r3c3 at different drift ratios](image)

γ=0.5%  γ=6%  γ=11%

**Figure 3-10 Specimen a0.3r3c3 at different drift ratios**
3.3.5 a0.5r3c3

Specimen a0.5r3c3 with 3 columns and 3 rows has a mid-honeycomb cell wall aspect ratio. Figure 3-11 illustrates the force-drift relationship under cyclic loading. The force began to drop at the drift ratio of 4% where the peak force was reached. After this point, the force degradation became increasingly noticeable. At the same time, out-plan-buckling behavior was found. The test was halted at a drift ratio of 13%, when the linear pots reached their limit. At the final point, the specimen did not show obvious factures as it behaved like a “spring”. The final bucking mode, as in Specimen a0.5r3c4, was diagonal, as shown in Figure 3-12.

![Figure 3-11 Force-drift relationship of a0.5r3c3](image)

![Figure 3-12 Specimen a0.5r3c3 at different drift ratios](image)
3.3.6 a0.7r3c3

Specimen a0.7r3c3 with its cells in 3 columns and 3 rows has a high honeycomb cell wall aspect ratio of 0.7. Figure 3-13 shows the hysteresis curve. The specimen yielded at 0.5%. The force began to drop from 80 KN at the drift ratio of 4%. Out-plane-buckling behavior was realized at this point. After this, the force degradation became increasingly noticeable. Meanwhile, out-plane-buckling behavior increased in severity. Finally, the test was halted at drift ratio of 13%, with obvious tears being located at the buckling zone of the honeycomb shear web, as shown in Figure 3-14. From the figures, it can be observed that shear deformation (tension-compression mode) was the dominant working mechanism.

![Figure 3-13 Force-drift relationship of a0.7r3c3](image)

![Figure 3-14 Specimen a0.7r3c3 at different drift ratios](image)
3.3.7  a0.3r3c2

Specimen a0.3r3c2 with cells in 3 columns and 3 rows has a low honeycomb cell wall aspect ratio of 0.3. Figure 3-15 shows its force-drift relationship. The specimen reached its yielding point at 0.5%. The force began to drop from around 10 KN at a drift ratio of 2.5%. At this state, there was no obvious out-plane deformation, while white wash began to drop from the ends of the local honeycomb cell wall. After this point, the force degradation became increasingly noticeable. Finally, the test was halted at the drift ratio of 11%, when very severe fractures became concentrated at the ends of the cell walls, as shown in Figure 3-16. It was concluded that the HSF was based on the local beam bending working mechanism.

![Figure 3-15 Force-drift relationship of a0.3r3c2](image)

![Figure 3-16 Specimen a0.3r3c2 at different drift ratios](image)
3.3.8  a0.5r3c2

Specimen a0.5r3c2 with 3 columns and 2 rows has a mid-honeycomb cell wall aspect ratio. Figure 3-17 shows the force-drift relationship for the specimen when under cyclic loading. The force began to drop at the drift ratio of 2.5% when a peak force of 27KN was reached. After this point, the shear force continued to decrease, while out-plan-buckling behavior was not obvious. At the end of test, specimen did not display obvious factures as it had behaved like a “spring”, but the sensors had reached their limit. At the final point, it was noted that the specimen had two obvious parallel bucking lines (Figure 3-18). This is similar to the case of a0.7r3c2 in the next section. The specimen exhibited global plate bending behavior.

![Figure 3-17 Force-drift relationship of a0.5r3c2](image)

![Figure 3-18 Specimen at a0.5r3c2 different drift ratios](image)
3.3.9  a0.7r3c2

The cyclic behavior of Specimen a0.5r3c2 is outlined in this section. The specimen has 3 columns and 2 rows of cells and high honeycomb cell wall aspects with a ratio of 0.7. Figure 3-19 shows the force-drift relationship curve. The force began to drop at a drift ratio of 3% when a peak force of 35KN was reached. At this point, slight out-plan buckling behavior was displayed. Two parallel buckling lines extended from the two free ends. When reaching the final drift ratio, no fractures were found but severe buckling behavior was quite obvious, as shown in Figure 3-20. The specimen exhibited global plate bending behavior.

![Figure 3-19 Force-drift relationship of a0.7r3c2](image)

![Figure 3-20 Specimen a0.7r3c2 at different drift ratios](image)
3.3.10 a0.3r2c3

Specimen a0.3r2c3 has a low honeycomb cell wall aspect ratio of 0.3 with 2 columns and 3 rows of cells. Its force-drift relationship is shown in Figure 3-21. The specimen reached the yielding point at 0.5%. The maximum shear force was 19 KN, and the corresponding drift ratio 6%. At this state, there was no obvious out-plane deformation, while whitewash had begun to drop from the ends of the local honeycomb cell walls. Finally, the test was halted at the drift ratio of 11%, where very severe fractures were found concentrated on the ends of the cell wall, as shown in Figure 3-22. It can be concluded that the HSF was based on the local beam bending working mechanism.

![Figure 3-21 Force-drift relationship of a0.3r2c3](image1)

![Figure 3-22 Specimen a0.3r2c3 at different drift ratios](image2)
3.3.11 a0.5r2c3

Specimen a0.5r2c3 has a middle honeycomb cell wall aspect ratio of 0.5, and 2 columns and 3 rows of cells. Its force-drift relationship is shown in Figure 3-23. The specimen yielded at a drift ratio of 0.5% The maximum shear force is 58 KN, and the corresponding drift ratio is 5%. The specimen fractured at a drift ratio of 15% at the two ends of its cell walls, as shown in Figure 3-24.

![Figure 3-23 Force-drift relationship of a0.5r2c3](image1)

![Figure 3-24 Specimen a0.5r2c3 at different drift ratios](image2)
3.3.12 a0.7r2c3

Specimen a0.7r2c3 has a high honeycomb cell wall aspect ratio of 0.7, along with 2 columns and 3 rows of cells. Figure 3-25 displays its force-drift relationship. The specimen yielded at a drift ratio of 0.46% and reached its peak force of 87 KN at a 3% drift ratio. After its ultimate point, the force began to degrade, and diagonal buckling lines were found on the honeycomb shear web. The test stopped at the 11% drift ratio when the sensors’ limits was reached. The behavior is more like the global plate shear.

![Figure 3-25 Force-drift relationship of a0.7r2c3](image)

![Figure 3-26 Specimen a0.7r2c3 at different drift ratios](image)
3.4 Discussion on Buckling Behavior

Figure 3-27 shows the buckling behavior of the HSFs, at the drift ratio when specimens were about to fracture (a, b, c and d) or significant out-plane-deformation was observed (e, f, g and h). The experimental results show that the buckling behavior of the HSFs was highly influenced by the cell wall aspect ratio (a). As shown in Figure 3-27a, b, c, and d, no obvious out-plane buckling was observed before specimen began to fracture. The behavior was mostly confined by flexural yielding of the wall cells. However, with a high cell wall aspect ratio ($a = 0.7$), the specimens buckled severely before fracture as shown in Figure 3-27e, f, g, h. This triggering condition of out-plane buckling appeared to be independent of the cell row (r) and column (c) combination. However, the cell row (r) and column (c) combinations had significant effect on the buckling mode. When the number of columns was equal to or higher than the number of rows (Figure 3-27e, f, h), diagonal buckling lines were found on the honeycomb shear web. The specimen with more honeycomb cell rows than columns (Figure 3-27g) buckling appeared with two parallel lines across the web (from free end to free end).
3.5 Discussion on Failure Mode

The failure modes of the specimens are shown in Figure 3-28. Specimens with a low cell wall aspect ratio (a = 0.3) exhibited local fracture concentrated at the ends of the cell wall (Figure 3-28a, d, g, and j). This behavior is similar to yielding and fracture of flexural beam. Specimens with a high cell wall aspect ratio (a = 0.7) and that have a number of columns (c) greater than or equal to the number of rows (r) showed tension field action like shear plate. This resulted in fracture occurring in a diagonal line across the web (Figure 3-28c, f, and l). Specimens with a medium cell
wall aspect ratio \((a = 0.5)\) and that had a number of columns \((c)\) greater than or equal to the number of rows \((r)\) exhibited failure modes that seem to be a combination of global shear buckling and local flexural cell wall yielding (Figure 3-28b, e, and k). This behavior was particularly evident in Figure 3-28k, where the central cell wall links yielded and fractured, and global buckling can also be observed across the web. Specimens with medium and high cell wall aspect ratios \((a = 0.5\) and \(a = 0.7)\) and that have less columns \((c)\) than rows \((r)\) exhibited extensive global flexural buckling, however, fracture was not observed when specimens behaved as a “spring” (Figure 3-28e, h). The testing was halted due to the limitation of the instrumentation.
(a) a0.3r3c4  (b) a0.5r3c4  (c) a0.7r3c4

(d) a0.3r3c3  (e) a0.5r3c3  (f) a0.7r3c3

(g) a0.3r3c2  (h) a0.5r3c2  (i) a0.7r3c2

(j) a0.3r2c3  (k) a0.5r2c3  (l) a0.7r2c3

Figure 3-28 Failure modes of HSF
3.6 Discussion on Force-Drift Relationship

Figure 3-29 shows the results of the force-drift relationship of specimens with different cell wall aspect ratios (a) and different number of rows (r) and columns (c). Overall, the results show that as the cell wall aspect ratio (a) increased, the ultimate force increased and the drift at which force begins to degrade decreases. The force-drift response of specimens with medium and high cell wall aspect ratios (a = 0.5 and a = 0.7) have a more pinched hysteresis and the force dropped much earlier and more severely, when compared to specimens with a low cell wall aspect ratio (a=0.3).
Figure 3.29 Force-drift relationship of HSF
In addition to the hysteresis loops presented in Figure 3-29, the backbone curves of the HSFs were obtained from the envelope of the hysteretic curve. Figure 3-30 shows an example of the backbone curve obtained from a0.5c3r4 HSFs. Several key parameters such as the yielding force ($V_y$), yielding drift ($\gamma_y$), ultimate force ($V_u$), ultimate drift ratio ($\gamma_u$) were determinate from the backbone curve. The summary of the key backbone parameters is presented in Table 3.1. Overall, the results show that as the cell wall aspect ratio ($a$) increases the stiffness and force also increase. Specimens with a low cell wall aspect ratio ($a=0.3$) show higher yield drifts and ultimate drifts. Specimens with medium cell wall aspect ratios ($a = 0.5$) show higher yield drifts and ultimate drifts when compared with the high aspect ratio ($a = 0.7$), with the exception of a0.5r3c2 which exhibits a slightly lower ultimate drift value.

**Figure 3-30 Backbone properties of HSF**
Table 3.1 Summary of the experimental results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Yield force $V_y$ [kN]</th>
<th>Initial stiffness $K$ [kN/rad]</th>
<th>Ultimate force $V_u$ [kN]</th>
<th>Yield drift ratio $\gamma_y$ [%]</th>
<th>Ultimate drift ratio $\gamma_u$ [%]</th>
<th>Buckling shape</th>
<th>Fracture location</th>
</tr>
</thead>
<tbody>
<tr>
<td>a0.3r3c4</td>
<td>20</td>
<td>6269</td>
<td>28</td>
<td>0.51%</td>
<td>5.07%</td>
<td></td>
<td>Two ends of cell wall</td>
</tr>
<tr>
<td>a0.5r3c4</td>
<td>54</td>
<td>19850</td>
<td>70</td>
<td>0.47%</td>
<td>2.95%</td>
<td>Diagonal</td>
<td>Buckling zone</td>
</tr>
<tr>
<td>a0.7r3c4</td>
<td>89</td>
<td>35777</td>
<td>107</td>
<td>0.45%</td>
<td>2.00%</td>
<td>Diagonal</td>
<td>Buckling zone</td>
</tr>
<tr>
<td>a0.3r3c3</td>
<td>14</td>
<td>4199</td>
<td>18</td>
<td>0.52%</td>
<td>5.95%</td>
<td></td>
<td>Two ends of cell wall</td>
</tr>
<tr>
<td>a0.5r3c3</td>
<td>38</td>
<td>13433</td>
<td>50</td>
<td>0.48%</td>
<td>3.79%</td>
<td>Diagonal</td>
<td>No obvious fracture</td>
</tr>
<tr>
<td>a0.7r3c3</td>
<td>62</td>
<td>24327</td>
<td>78</td>
<td>0.46%</td>
<td>3.58%</td>
<td>Diagonal</td>
<td>Buckling zone</td>
</tr>
<tr>
<td>a0.3r3c2</td>
<td>8</td>
<td>2122</td>
<td>11</td>
<td>0.53%</td>
<td>7.00%</td>
<td></td>
<td>Two ends of cell wall</td>
</tr>
<tr>
<td>a0.5r3c2</td>
<td>19</td>
<td>70513</td>
<td>27</td>
<td>0.48%</td>
<td>2.67%</td>
<td>Horizontal</td>
<td>No obvious fracture</td>
</tr>
<tr>
<td>a0.7r3c2</td>
<td>35</td>
<td>13024</td>
<td>44</td>
<td>0.46%</td>
<td>2.98%</td>
<td>Horizontal</td>
<td>No obvious fracture</td>
</tr>
<tr>
<td>a0.3r2c3</td>
<td>15</td>
<td>4672</td>
<td>19</td>
<td>0.51%</td>
<td>5.76%</td>
<td></td>
<td>Two ends of cell wall</td>
</tr>
<tr>
<td>a0.5r2c3</td>
<td>39</td>
<td>14295</td>
<td>58</td>
<td>0.47%</td>
<td>4.87%</td>
<td>Diagonal</td>
<td>Two ends of cell wall</td>
</tr>
<tr>
<td>a0.7r2c3</td>
<td>66</td>
<td>25581</td>
<td>87</td>
<td>0.46%</td>
<td>2.95%</td>
<td>Diagonal</td>
<td>Buckling zone</td>
</tr>
</tbody>
</table>
3.7 Discussion on Energy Dissipation

Figure 3-31a, b, c, and d show the cumulative energy dissipation normalized by the volume of web steel. The results only included the first 10% drift ratio although the specimens could sustain larger deformation as the test was halted by the limitation of instruments instead of specimen fracture. HSFs with high cell wall aspect ratio (a=0.7) exhibited highest energy dissipation efficiency for different honeycomb cell combinations (r2c3, r3c2, r3c3, r3c4), which was followed by the specimen with mid cell wall aspect ratio (a=0.5). HSFs exhibited lowest energy dissipation ability when the cell wall aspect ratio (a) equals to 0.3. Furthermore, higher cell wall aspect ratio HSFs can reach the same amount of energy dissipation at lower cumulative drifts. If the cell wall aspect ratio is the same, HSFs with more columns have larger energy dissipation efficiency (Figure 3-31a, b and c). This trend is identical to all three cell wall aspect ratios (a=0.3, 0.5, and 0.7). Specimen a0.3r2c3 and a0.5r2c3 in Figure 3-31d showed highest energy dissipation capacity per volume in all specimens.
Figure 3-31 Normalized energy plot for different cell combination
3.8 Discussion

From the cyclic test on the HSFs, it was found that the HSFs’ hysteresis performance was highly influenced by the honeycomb cell wall aspect ratio (a) and honeycomb cell combination (rows (r) and columns (c)). Some discussions include:

- When the cell wall aspect ratio was low, the working mechanism was based on local cell wall bending; when increasing the aspect ratio, the working mechanism transferred to the global plate shear.
- When the cell wall aspect ratio was low, the out-plane buckling was somehow inhibited; with the aspect ratio increasing, the buckling behavior became severe.
- When the number of cell rows was greater than the columns, the buckling mode was concentrated in two parallel zones (free to free ends); when the number of cell columns was higher than that of the rows, the buckling zone transferred to the diagonal of the entire plate.
- The hysteresis curve was highly influenced by the cell wall aspect ratio: when it was low, the curve was quite stable and full; however, when it was high, the hysteresis curve becomes pinched due to the out-plane buckling, which tended to gradually resemble that of the WWFFs (solid plates).
- HSFs with high cell wall aspect ratio showed the highest energy dissipation efficiency following by mid and low aspect ratios for first 10% drift ratio (4.906 cumulative drift)
Chapter 4: Numerical Study of HSF

4.1 Introduction

This chapter describes the numerical model of the Honeycomb Structural Fuse using Finite Element Software ABAQUS. A graphical user interface program, ABAQUS/CAE with AUTOCAD input and Python programming was used to build the FE models. In this chapter, the modelling approaches, material modeling, element types and imperfection and other details are described. Finally, the numerical models are validated by comparing them with the force-drift relationship and buckling modes from the test results. Furthermore, the comparison with WWFFs with same overall aspect ratio is conducted to investigate the effect of honeycomb perforation.

4.2 Finite Element Model Description

Due to the limited test results, in this stage, the corresponding finite element model, using ABAQUS/CAE, was proposed to provide a comprehensive understanding of HSFs with different parameters. Because the flanges of the HSF were designed to remain elastic with minimal deformation compared to the honeycomb shear web, only the honeycomb shear web was modelled. Figure 4-1 shows the degrees of freedoms (DOFs) used in this study. To simulate the real test conditions, the base of the honeycomb shear web was fixed by restraining all translational and rotational DOFs. The boundary condition of the top face of the honeycomb shear web was modelled using coupling constraints, where all the DOFs were constrained to that of the master node. Displacement loading history was applied at the master node in the x-direction, while the y-
direction was left free. 3D-stress, 8-node, nonlinear solid elements (C3D8R) were used to mesh the specimens (Section 4.2.1), while nonlinear geometric transformation was accounted for by using the \textit{NL Geom} option. Meshing size and geometric imperfections recommended by Banjuradja (2018), were used.

\textbf{Figure 4-1 Proposed ABAQUS model}

### 4.3 Material Modelling

It is known that steel material has different mechanical properties under cyclic and monotonic loading (Black \textit{et al.}, 2004); to accurately consider the metallic nonlinearities, a material law provided by ABAQUS was adopted in this study. Previous studies (Deng \textit{et al.}, 2015; Deng \textit{et al.}, 2014) had proved its effectiveness. The integration equation 4.1 for the back-stress evolution laws in ABAQUS is

\[
a = \sum_{k=1}^{N} \alpha_k = \sum_{k=1}^{N} \frac{C_k}{Y_k} \left(1 - e^{-\gamma_k \bar{\varepsilon}_p^2}\right) \quad (4.1)
\]
where $\alpha$ represents the overall back stress, which indicates the movement of the yield surface, $N$ is the number of back stresses, $\varepsilon^{pl}$ is the equivalent plastic strain, and $C_k$ and $\gamma_k$ ($k = 1, 2, 3$) are the parameters of the model. In this study, based on coupon tests, the initial yield stress was 256 MPa. Young's modulus and Poisson's ratio were 210 GPa and 0.3, respectively. The associated $C_k$ and $\gamma_k$ ($k = 1, 2, 3$) were determined based on the stress-strain curve obtained from the coupon test results, the details about the parameters were given in Table 4.1.

<table>
<thead>
<tr>
<th>$C_1$</th>
<th>$\gamma_1$</th>
<th>$C_2$</th>
<th>$\gamma_2$</th>
<th>$C_3$</th>
<th>$\gamma_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975</td>
<td>55</td>
<td>500</td>
<td>220</td>
<td>1100</td>
<td>7.3</td>
</tr>
</tbody>
</table>

### 4.4 Simulation Validation

Along with the proposed modelling approaches described in Section 4.3, the developed FE model in ABAQUS needed to be validated by comparing it with the experimental results to ensure its efficiency.

#### 4.4.1 Force-Drift Relationship Validation

Based on the modelling approaches stated in the previous sections, the ABAQUS models were used to simulate the hysteresis behavior of the HSFs. Figure 4-2 provides a comparison of the force-drift relationship between the experimental test and the finite element simulation. The results present the desired agreement as shown and thus validate the effectiveness of the proposed ABAQUS modelling approaches.
Figure 4.2 Comparison between the experimental and FE model under cyclic loading
4.4.2 Buckling Behaviour Validation

The out-plane buckling behavior was compared between the FE analysis and the experimental test, as shown in Figure 4-3. It was found that, when the number of cell rows was greater than the columns, the buckling zones were concentrated in the two parallel lines on the honeycomb shear web. And when the number of cell columns was higher than that of the rows, a diagonal buckling zone occurred. The FEA results reveal that the proposed ABAQUS model is able to reflect real buckling behavior in tests.

Figure 4-3 Buckling shapes from experiment and FEA
4.4.3 PEEQ Distribution

Figure 4-4 shows the results of the equivalent plastic strain (PEEQ) from FEM compared with the experimental tests. As shown in Figure 4-4a, when the cell wall aspect ratio was low (a= 0.3), the PEEQ distribution was concentrated on two ends of honeycomb cell walls due to local beam flexural yielding mechanism. A high cell wall aspect ratio (a=0.5-0.7) resulted in the PEEQ more uniformly dispersing over the web, as shown in Figure 4-4b and c. This trend indicated that failure mechanism of HSFs transferred from local cell wall flexural yielding to global plate shear yielding as the cell wall aspect ratio increases. In the medial range, the HSF worked under combined mechanisms.

![Figure 4-4 PEEQ distribution and corresponding test pictures](image)
4.5 Comparison with WWFF

To compare the effects of honeycomb perforation, the corresponding WWFF model, S23FEA, S34FEA, S33FEA and S32FEA, with same overall aspect ratio (A=L/H) were built. For instance, S32FEA has same geometry size with corresponding to the HSF of r3c2. The WWFF modelling approaches were described by Banjuradja (2018), validated by the experimental test results.

4.5.1 Buckling Shape Comparison

Figure 4-5 shows the out-of-plane deformation of WWFFs. The WWFF with overall aspect ratio of 1 showed out-of-plane buckling at the free edges (Figure 4-5c). When the overall aspect ratio was high (A=1.5, 2, 2.15), the diagonal tension field started to form in the web (Figure 4-5a, b, and d). This trend was identical to HSFs by comparing with the analysis in Figure 4-3, illustrating that the bucking shape of HSFs was highly influenced by the overall aspect ratio A, which is the same as WWFFs.

(a) S34  (b) S33  (c) S32  (d) S23

Figure 4-5 Out-of-plane deformation of corresponding FEM of WWFFs
4.5.2 Force-Drift Relationship Comparison

Figure 4-6 illustrates the force-drift relationship of WWFFs for 5% drift ratio. The ultimate drift ratios determined from backbone curves were 0.50%, 0.72%, 0.97%, 1.96% respectively. Compared with ultimate drift ratio of HSFs in Table 3.1, the results are much lower. The shear force of WWFFs dropped much earlier than the HSFs, which resulted in more severely pinched behavior. Honeycomb perforation on web can inhibit out-plane-buckling behavior.

![Figure 4-6 Force-drift relationship of corresponding FEM of WWFFs](image)

(a) S34FEA  (b) S33FEA  
(c) S32FEA  (d) S23FEA
4.5.3 Stiffness and Yielding Force Comparison

Figure 4-7a shows the initial stiffness comparison between HSFs from test and WWFFs from numerical study. The results showed that the honeycomb perforation significantly reduced the initial stiffness. With the overall aspect ratio increasing, the perforation effects to stiffness became more obvious. The stiffness of WWFFs increased more steeply compared with HSFs as overall aspect ratio \( A \) increasing. The initial stiffness of HSFs with same cell wall aspect ratio (\( a = 0.3, 0.5, \) and 0.7) and WWFF can be linearly fitted. Figure 4-7b compared the yielding drift ratios between WWFFs and HSFs. It demonstrates that with the same overall aspect ratio, HSFs had larger yielding drift than corresponding WWFFS. As the cell wall aspect ratio (\( a \)) increasing, the HSFs exhibited increasingly low yielding drift (\( \gamma_{0.3} = 0.52\%, \gamma_{0.5} = 0.48\%, \gamma_{0.7} = 0.45\% \)). WWFFs had lowest yielding drift of 0.41\%. As shown in Figure 4-7b, overall aspect ratio did not influent the yielding drift significantly for each group of specimens.
Figure 4-7 (a) Initial stiffness comparison (b) yielding drift comparison

$$K_s = 382.4 \pm 162.1$$

$$K_{07} = 106.8 \pm 41.5$$

$$K_{05} = 60.4 \pm 25.1$$

$$K_{03} = 20.2 \pm 9.7$$

$$\gamma_s = 0.41\%$$

$$\gamma_{0.3} = 0.52\%$$

$$\gamma_{0.5} = 0.48\%$$

$$\gamma_{0.7} = 0.45\%$$

$$\gamma_s = 0.41\%$$
Chapter 5: Parametric study

5.1 Introduction

In this chapter, the parametric study based on the verified ABAQUS model was conducted. The objective of this study was to provide more reliable analysis results to understand the performance of the HSFs. The parametric results were then used to complete the proposed trend, including yielding force and initial stiffness, yielding drift, and other elements.

5.2 Finite Element Model Matrix

To further study the nonlinear behavior of the HSFs with different geometric parameters a detailed parameter study was conducted. Four groups of HSFs with different honeycomb cell rows \((r)\) and columns \((c)\) were used in this study: 1) \(r = 3\) and \(c = 4\); 2) \(r = 3\) and \(c = 2\); 3) \(r = 3\) and \(c = 3\); and 4) \(r = 2\) and \(c = 3\). Each group included six models with cell wall aspect ratios ranging from 0.3 to 0.8. Table 5.1 shows the summary of the parameters included in this study.
5.3 Simulation Results

Table 5.2 summarizes the key results from the parametric study, including yielding force, initial stiffness and yielding drift.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Yielding force $V_y$ (kN)</th>
<th>Initial stiffness K (kN/mm)</th>
<th>Yielding drift $\gamma_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>a0.3r3c4FEA</td>
<td>19.5859</td>
<td>14.9986</td>
<td>0.51%</td>
</tr>
<tr>
<td>a0.4r3c4FEA</td>
<td>35.4618</td>
<td>29.5912</td>
<td>0.49%</td>
</tr>
<tr>
<td>a0.5r3c4FEA</td>
<td>53.7336</td>
<td>48.2390</td>
<td>0.47%</td>
</tr>
<tr>
<td>a0.6r3c4FEA</td>
<td>71.9105</td>
<td>68.1510</td>
<td>0.46%</td>
</tr>
<tr>
<td>a0.7r3c4FEA</td>
<td>89.2165</td>
<td>88.2509</td>
<td>0.45%</td>
</tr>
<tr>
<td>a0.8r3c4FEA</td>
<td>104.4972</td>
<td>106.0016</td>
<td>0.44%</td>
</tr>
<tr>
<td>a0.3r3c2FEA</td>
<td>7.6934</td>
<td>10.8252</td>
<td>0.43%</td>
</tr>
<tr>
<td>a0.4r3c2FEA</td>
<td>12.0134</td>
<td>22.0120</td>
<td>0.49%</td>
</tr>
<tr>
<td>a0.5r3c2FEA</td>
<td>18.5171</td>
<td>35.7209</td>
<td>0.48%</td>
</tr>
<tr>
<td>a0.6r3c2FEA</td>
<td>28.0364</td>
<td>49.8746</td>
<td>0.47%</td>
</tr>
<tr>
<td>a0.7r3c2FEA</td>
<td>35.1024</td>
<td>65.5796</td>
<td>0.46%</td>
</tr>
<tr>
<td>a0.8r3c2FEA</td>
<td>41.0949</td>
<td>77.5238</td>
<td>0.46%</td>
</tr>
<tr>
<td>a0.3r3c3FEA</td>
<td>13.7323</td>
<td>13.6759</td>
<td>0.52%</td>
</tr>
<tr>
<td>a0.4r3c3FEA</td>
<td>24.8482</td>
<td>27.0466</td>
<td>0.50%</td>
</tr>
<tr>
<td>a0.5r3c3FEA</td>
<td>37.6135</td>
<td>44.1301</td>
<td>0.48%</td>
</tr>
<tr>
<td>a0.6r3c3FEA</td>
<td>50.4170</td>
<td>62.2778</td>
<td>0.47%</td>
</tr>
<tr>
<td>a0.7r3c3FEA</td>
<td>62.4619</td>
<td>80.5531</td>
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</tr>
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5.3.1 Yielding Force and Initial Stiffness

Figure 5-1a shows the influence of the honeycomb cell wall aspect ratio on the normalized yielding force of the HSF. The results show that the normalization of the yielding force using the pure shear force \( V_P = \frac{1}{\sqrt{3}} \sigma_y a t_w \) can be linearly fitted. In general, as the cell wall aspect ratio increases, the normalized yield force approaches \( V_P \). Similarly, Figure 5-1b illustrates the initial stiffness...
normalized by the overall aspect ratio, A (L/H), for the HSF at different honeycomb cell wall aspect ratios. The normalized initial stiffness increases as the aspect ratio increases.

![Diagram](image1)

**Figure 5-1** (a) Normalized yield force (b) normalized initial stiffness

### 5.3.2 Yielding Drift

Figure 5-2 shows the yielding drift ratios for the HSFs. The yielding drift ratios ($\gamma_y$) ranged from 0.4% to 0.6% and decreased with increases in the honeycomb cell wall aspect ratio. This relationship could be quadratically fitted, as shown in Figure 5-2.

![Diagram](image2)

**Figure 5-2** Yielding drift ratio
Chapter 6: Summary and Conclusion

6.1 Summary and Conclusion

In this study, a novel steel damper, named the Honeycomb Structural Fuse (HSF), the modified version from the previously developed Welded Wide Flange Fuse (WWFF) was proposed as a structural fuse for seismic application. HSFs were designed to dissipate earthquake energy by the inelastic deformation of honeycomb shear web. In this study, 12 specimens with different cell wall aspect ratios (a), number of cell rows (r), and number of cell columns (c) were experimentally tested. Additionally, a finite element analysis was conducted, and the effectiveness of the proposed model was validated by the test results. The behavior of HSFs and WWFFs with same overall size were compared to study the effect of honeycomb perforation. Finally, the numerical model was further used to conduct parametric analysis and to recommend design equations. Based on the experimental and numerical studies, the following conclusions are made:

1. HSF can efficiently work as an energy dissipation device as it exhibited a stable hysteresis with high energy dissipation.
2. As the cell wall aspect ratio (a) increases from 0.3 to 0.7, the failure mechanism of HSF transferred from local cell wall bending to the global plate shear behavior. In the medial range (a = 0.5), the HSF works under the combination of two mechanisms.
3. The ultimate failure modes vary depending on the geometry. Specimens with a low cell wall aspect ratio (a = 0.3) showed fracture occurring at the ends of the cell walls. Specimens
with a high cell wall aspect ratio (a = 0.7) showed fracture occurring in a diagonal pattern across the plate web.

4. Cell wall bending mechanism (low cell wall aspect ratio) of HSF resulted in no observable global buckling behavior before fracture and hysteresis curve is more stable. On the other hand, the buckling behavior of HSF with high cell wall aspect ratios was more severe, and the force-drift relationship became more pinched.

5. The buckling modes of HSFs were highly influenced by honeycomb cell row (r) and column (c) combinations. When the number of honeycomb cell rows was larger than that of columns, the HSF had lower overall aspect ratio and showed two parallel buckling lines in loading directions. This indicated a flexural global buckling behavior. When the number of honeycomb cell column was equal or larger to that of rows, the buckling zone moved to diagonal lines as overall aspect ratio was high. This indicated a global shear buckling behavior.

6. The numerical modelling with proposed modelling approaches and material property from coupon test can reliably predict the force-drift relationship and the highly nonlinear behavior of the HSFs.

7. HSFs showed the same buckling shapes as the corresponding WWFFs with same overall aspect ratio.

8. Honeycomb perforation inhibited the pinching behavior comping to the solid plate. HSFs with lower cell wall aspect ratio exhibited more stable force-drift relationship.
9. From comparison results, the honeycomb perforation can significantly reduce the initial stiffness. The lower cell wall aspect ratio results in lower initial stiffness but higher yielding drift ratio.

10. With the honeycomb cell wall aspect ratio increasing, the yield force and initial stiffness increased, and the normalized yield force and initial stiffness can be fitted linearly fitted; on contrary, the yielding drift decreased when honeycomb cell wall aspect ratio increasing, which can also be fitted linearly fitted.
6.2 Recommendations for Future Research

This study systematically studied the performance of HSFs based on experimental tests, finite element analysis and a detailed parametric study, providing a solid foundation for future relevant work. The recommendations are as follows:

1. The finite element analysis did not include a fracture simulation. Therefore, to provide a more robust FE model for engineering applications, more advanced modelling approaches considering fracture are recommended;

2. This study mainly focused on a component level investigation. An investigation into the performance of the structural system with HSFs is suggested;

3. This study focused on the study of the uniform cell walls of honeycombs. From the study, it was noted that the PEEQ was almost always concentrated on the two ends of the cell walls instead of uniformly distributed; this finding can be the motivation for future studies to improve the performance of HSFs.
Bibliography


Appendices

Appendix A

The test specimen’s matrix and detailed dimensions
**Nomenclature:**

- **a0.3**
- **r3**
- **c3 - A**

**Cell wall aspect ratio**

**Rows Columns Connection type**

---

**Note:**

1. All thickness of honeycomb (solid web) shear plates is 4.8mm (3/16")
2. Typical specimen connection is shown below. Honeycomb is welded at center of connection plates (not shown here).
3. The top and bottom connection plates must be welded in pair with white arrows inside and in same direction (as different plates have different geometry and drilled holes on certain sides)
4. All laser cut holes and corners have 3mm fillets (round)
5. Stress relief is needed after laser cutting
6. Tack weld 4 vertical studs at 4 corners to prevent buckling in transport
7. Units are mm
8. Fire coupon specimens are needed to cut off from same source plates

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**3D Sketch**

- All laser cut holes and corners have 3mm fillets (round)
All laser cut hole and corners have 5mm fillets (round)

**Notes:**
1. All thickness of plate for laser cutting is 4 mm (1/16")
2. Typical specimen connection is shown below.
3. Honeycomb is welded at center of connection plate.
4. Connection plates have been built. Only need for welding.
5. All corners are filleted with 5mm radius.

3D Sketch
All corners are filleted with 5mm radius
NOTES:

1. ALL THICKNESS OF PLATE FOR LASER CUTTING IS 4.8 MM (3/16")
2. TYPICAL SPECIMEN CONNECTION IS SHOWN BELOW
3. HONEYCOMB IS WELDED AT CENTER OF CONNECTION PLATE
4. CONNECTION PLATES HAVE BEEN BUILT ONLY NEED FOR WELDING
5. ALL CORNERS ARE FILLETED WITH 5MM RADUS