AN EXPERIMENTAL STUDY ON STRAP TENSION-ONLY BRACE

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Masters of Applied Science

by

Mani Razavi Aghdam

Department of Civil and Environmental Engineering
Carleton University

Ottawa-Carleton Institute of Civil and Environmental Engineering

September, 2009

©2009 Mani Razavi Aghdam

Library and Archives
Canada

Published Heritage
Branch

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque et
Archives Canada

Direction du
Patrimoine de l'édition

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence
ISBN: 978-0-494-60231-7
Our file Notre référence
ISBN: 978-0-494-60231-7

NOTICE:

The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protègent cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

■ ■ ■
Canada

ABSTRACT

An Experimental study has been carried out to evaluate the feasibility of using flat bars in a tension-only bracing system for seismic design. Flexible steel straps (flat bars) with the slenderness ratio between 200 and 800 were tested under cyclic loading. Various slenderness ratios and connection details were investigated. Three bolted connection details were considered in the study: no reinforcement, clamped with an extra plate and welded with an extra plate.

In National Building Code of Canada 2005, a normal building is permitted to deflect up to 2.5% in storey drift due to seismic load. Ideally, a brace in a Seismic Force Resisting System should be able to sustain this deformation under cyclic condition without any significant loss of strength. None of the specimens tested experienced any loss of strength with the increasing cyclic deformation until fracture occurred. Based on the maximum extension observed in the tests, a flat bar brace with the welded plate reinforcement can achieve the ductility required for 2.5% storey drift at a slenderness ratio as low as 200. On the other hand the ductility of the flat bar brace with either of the other two connection details was found to be greatly dependent on its slenderness ratio, length and net section fracture to gross section yielding strength ratio. Specimens with the net section fracture to gross section yielding strength ratio at around 1.20 were able to meet the ductility requirement.

ACKNOWLEDGMENTS

The author wishes to thank Dr. Heng Aik Khoo, supervisor of this thesis for his guidance, advice and support through out project.

I also would like to thank those people who helped me perform the tests, Zhiqi Wen, Jianwei Chen and Civil and Environmental Engineering laboratory technicians at Carleton University.

This research project is funded by Steel Structures Education Foundation and the Natural Sciences and Engineering Research Council of Canada (NSERC).

Last but not the least, I would like to thank my parents, in-law family, my wife (Shirin) and new born daughter (Sarina) for their understanding and encouragement during the period of this research.

TABLE OF CONTENTS

Chapter	Page
CHAPTER 1 INTRODUCTION	1
1.1 Objective of the Thesis	2
1.2 Methodology Used in the Research	2
1.3 Organization of the Thesis	4
CHAPTER 2 LITERUTURE REVIEW	6
2.1 Research on Bracing	6
2.1.1 General Behaviour of Bracing.....	7
2.1.2 Experimental Studies.....	8
2.1.3 Analytical and Numerical Studies	11
2.2 Design Requirements	13
CHAPTER 3 TESTING PROGRAM.....	17
3.1 Objective	17
3.2 Test Matrix	18
3.3 Description of Test Specimens.....	20
3.4 Specimen Preparation and Measurement.....	22
3.5 Test Setup and Instrumentation.....	23
3.5.1 Test Setup	23
3.5.2 Instrumentation.....	23
3.6 Test Procedure.....	24

3.7	Material Properties.....	27
CHAPTER 4	TEST RESULTS	48
4.1	Test Results.....	48
4.1.1	Direction of Buckling and Fracture Location.....	50
4.1.2	Out-of-plane Deformation of a Buckled Strap.....	52
4.1.3	Comparison of Monotonic and Cyclic Tests	54
4.1.4	Effects of A_n/A_g and A_nF_u/A_gF_y Ratios.....	56
4.1.5	Influence of Connection Details.....	57
4.1.6	Effects of Slenderness Ratio	58
4.2	Guidelines and Recommendations on Using Strap Tension-only Brace in SFRS.....	60
CHAPTER 5	SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS.....	82
5.1	Summary	82
5.2	Conclusions.....	83
5.3	Recommendations.....	85
	REFERENCES.....	87
	APPENDIX A: MATERIAL PROPERTIES	91
	APPENDIX B: LOAD VERSUS DEFORMATION CURVES	96
	APPENDIX C: PICTURES OF SPECIMEN FRACTURE AND BUCKLING.....	121

LIST OF TABLES

Table	Page
3.1 Test matrix.	29
3.2 Measured dimensions.	30
3.3 Nominal and expected net section to gross section yielding strength ratio for Type A and B specimens.	32
3.4 Loading rate for different specimen length.....	33
3.5 Material properties.	34
3.6 Material dynamic to static yield and ultimate strength ratios.....	36
4.1 Test results.	63
4.2 Normalized test results.....	67
4.3 Ratios of average cross-section area and tension capacity for Type A and B specimens.....	69
4.4 Horizontal deflection.	70
4.5 Monotonic tests.....	71
4.6 Comparison of monotonic and cyclic tests.....	72
4.7 Average normalized maximum extension and hysteretic energy for Type A specimens.....	72
4.8 Comparison of average normalized maximum extension for various connection details.	73
4.9 Comparison of average normalized hysteretic energy for various	

	connection details.	73
A.1	Material ductility and elastic modulus.....	91
A.2	Material yield and ultimate strengths at various loading rates.	93
A.3	Average specimen strength for various loading rates.	95

LIST OF FIGURES

Figure	Page
1.1 Steel strap specimen with various connection details.....	5
2.1 Bracing systems.	16
3.1 Strap with no reinforcement, Type A.....	37
3.2 Strap clamped with reinforcement plate, Type B.....	38
3.3 Strap welded with reinforcement plate, Type C.....	39
3.4 Test setup.	40
3.5 Picture of test setup.....	41
3.6 Loading frame.....	42
3.7 Bottom connection.....	43
3.8 Top connection.....	44
3.9 Positions of cable transducer	45
3.10 Location of strain gauges.....	46
3.11 Example of a Type C specimen with strain gauges.	47
4.1 Test with a regular rod.	74
4.2 Test with a wide regular rod.	74
4.3 Test with a very wide regular rod.	75
4.4 Fracture for Type A specimens.	76
4.5 Fracture of C2078a and C2108a.	77
4.6 Out-of-plane deformation for fixed end elastic buckling.	78

4.7	Out-of-plane deformation for pinned end elastic buckling.....	78
4.8	Comparison of A2078c (cyclic) and A2078e (monotonic).....	79
4.9	Comparison of A2128b (cyclic) and A2128e (monotonic).....	79
4.10	Normalized maximum tension versus slenderness ratio for Type A specimens.....	80
4.11	Normalized maximum extension load versus slenderness ratio for Type A specimens.....	80
4.12	Normalized maximum tension versus slenderness ratio for Type C specimens.....	81
4.13	Normalized maximum extension load versus slenderness ratio for Type C specimens.....	81
B.1	Axial load versus axial deformation for A8075a specimen.....	96
B.2	Axial load versus axial deformation for A8075b specimen.....	96
B.3	Axial load versus axial deformation for A6075a specimen.....	97
B.4	Axial load versus axial deformation for A6075b specimen.....	97
B.5	Axial load versus axial deformation for A4075a specimen.	98
B.6	Axial load versus axial deformation for A4075b specimen.	98
B.7	Axial load versus axial deformation for A4075c specimen.....	99
B.8	Axial load versus axial deformation for A4078a specimen.	99
B.9	Axial load versus axial deformation for A4078b specimen.	100
B.10	Axial load versus axial deformation for A2078a specimen.	100

B.11	Axial load versus axial deformation for A2078b specimen.	101
B.12	Axial load versus axial deformation for A2078c specimen..	101
B.13	Axial load versus axial deformation for A2078d specimen.	102
B.14	Axial load versus axial deformation for A2078e specimen.	102
B.15	Axial load versus axial deformation for A4108a specimen.	103
B.16	Axial load versus axial deformation for A4108b specimen.	103
B.17	Axial load versus axial deformation for A2108a specimen.	104
B.18	Axial load versus axial deformation for A2108b specimen.	104
B.19	Axial load versus axial deformation for A4128a specimen.	105
B.20	Axial load versus axial deformation for A4128b specimen.	105
B.21	Axial load versus axial deformation for A2128a specimen.	106
B.22	Axial load versus axial deformation for A2128b specimen.	106
B.23	Axial load versus axial deformation for A2128c specimen.	107
B.24	Axial load versus axial deformation for A2128d specimen.	107
B.25	Axial load versus axial deformation for A2128e specimen.	108
B.26	Axial load versus axial deformation for A2128f specimen.	108
B.27	Axial load versus axial deformation for B8075a specimen.	109
B.28	Axial load versus axial deformation for B8075b specimen.	109
B.29	Axial load versus axial deformation for B2078a specimen.	110
B.30	Axial load versus axial deformation for B2078b specimen.	110
B.31	Axial load versus axial deformation for B2128a specimen.	111

B.32	Axial load versus axial deformation for B2128b specimen.	111
B.33	Axial load versus axial deformation for B2128c specimen.	112
B.34	Axial load versus axial deformation for B2128d specimen.	112
B.35	Axial load versus axial deformation for C8075a specimen.	113
B.36	Axial load versus axial deformation for C8075b specimen.	113
B.37	Axial load versus axial deformation for C6075a specimen.	114
B.38	Axial load versus axial deformation for C6075b specimen.	114
B.39	Axial load versus axial deformation for C4075a specimen.	115
B.40	Axial load versus axial deformation for C4075b specimen.	115
B.41	Axial load versus axial deformation for C4078a specimen.	116
B.42	Axial load versus axial deformation for C4078b specimen.	116
B.43	Axial load versus axial deformation for C4108a specimen.	117
B.44	Axial load versus axial deformation for C4108b specimen.	117
B.45	Axial load versus axial deformation for C2078a specimen.	118
B.46	Axial load versus axial deformation for C2078b specimen.	118
B.47	Axial load versus axial deformation for C2108a specimen.	119
B.48	Axial load versus axial deformation for C2108b specimen.	119
B.49	Axial load versus axial deformation for C2108c specimen.	120
C.1	Failure of A8075a and A8075b.	121
C.2	Failure of A6075a and A6075b.	121
C.3	Failure of A4075a and A4075b.	122

C.4	Failure of A4075c and A4078a.	122
C.5	Failure of A4078b and A2078a.	123
C.6	Failure of A2078b and A2078d.....	123
C.7	Failure of A2078e and A4108a.	124
C.8	Failure of A4108b and A2108a.....	124
C.9	Failure of A2108b and A4128a.....	125
C.10	Failure of A4128b and A2128a.....	125
C.11	Failure of A2128b and A2128c.....	126
C.12	Failure of A42128e and A2128f.....	126
C.13	Failure of B8075a and B8075b.	127
C.14	Failure of B2078a and B2078b.....	127
C.15	Failure of B2128a and B2128b.....	128
C.16	Failure of B2128c and B2128d.....	128
C.17	Buckling of C8075a and C8075b.....	129
C.18	Buckling of C6075a and C6075b.....	129
C.19	Buckling of C4075a and C4075b.....	130
C.20	Buckling of C4078a and C4078b.....	130
C.21	Failure of C2078a and C2078b.....	131
C.22	Buckling of C4108a and C4108b.....	131
C.23	Failure of C2108a and C2108b.....	132
C.24	Failure of C2108c.	132

LIST OF SYMBOLES

a	-	maximum out-of-plane deformation
A	-	cross-section area
A_f	-	average cross-section area at fracture
A_g	-	measured gross cross-section area
A_n	-	measured net cross-section area
A_o	-	undeformed cross-section area
b	-	deformed length
b_o	-	relaxed length at zero load
E	-	measured elastic modulus
E_h	-	average hysteretic energy
E_n	-	average normalized energy
F	-	measured force in the member
FB	-	flat bar
F_m	-	maximum tension force up to the time of consideration
F_u	-	nominal ultimate strength
F_y	-	nominal yield strength
F_{ys}	-	measured static yield strength
h	-	vertical distance between horizontal cable transducers
h_s	-	interstorey height

I	-	moment of inertia
K	-	effective length factor
KL/r	-	effective or nominal slenderness ratio
L	-	nominal length of specimen measured between the middle bolt holes
L_d	-	undeformed centre-to-centre distance of the innermost bolt holes
LD	-	limited-ductility frame
L_o	-	specimen overall length
L_r	-	reinforcement plate length
MD	-	moderately ductile frame
$NBCC$	-	National Building Code of Canada
$OCBF$	-	Ordinary Concentrically Braced Frame
r	-	radius of gyration
R	-	force modification factor
R_d	-	ductility-related force modification factor
R_o	-	over strength-related force modification factor
R_y	-	ratio of the expected yield stress to the specified minimum yield stress
$SFRS$	-	Seismic Force Resisting System
t	-	specimen thickness
t_r	-	reinforcement plate thickness
T_{max}	-	maximum tension force
T_{nmax}	-	maximum normalized tension force

w	- specimen width
w_r	- reinforcement plate width
x	- horizontal deflection variable
y	- vertical deflection variable
Z	- plastic section modulus
δ	- half of the applied deformation range
δ_y	- yield deformation
Δ	- axial deformation from the original undeformed position
$\Delta_{\max}$	- maximum extension
Δ_m	- maximum extension up to the time of consideration
$\Delta_{n\max}$	- maximum normalized extension
λ	- non-dimensional slenderness ratio
μ_f	- maximum normalized deformation range
Φ	- resistance factor

CHAPTER 1 INTRODUCTION

Bracing is commonly used in buildings to provide lateral support. During an earthquake, a brace can help dissipating energy through inelastic deformation. When cycling through tension and compression, plastic hinges can form in the brace and at the connection. The formation of these hinges lead to strain localization that accelerates the failure of the bracing system. Instead of using stocky braces, very flexible braces that buckle elastically can be used to delay the formation of plastic hinge and improve the ductility of the bracing system. At a moderate compression deformation, a flexible brace with a high slenderness ratio will be able to accommodate the compressive deformation by buckling elastically, while a stockier brace may have to accommodate the deformation through the rotation at plastic hinges.

With a very flexible brace, the end of brace and the gusset plate at the connection can be easily designed to be stiffer than the brace member to ensure that plastic hinge and fracture do not occur at the gusset plate and the connection. Thus by avoiding and delaying the formation of the plastic hinge, fracture of the brace and connection may be prevented, and only the brace may have to be replaced after a severe earthquake as a result of inelastic extension.

A very flexible brace can be constructed with a steel strap. Unlike cables and round rods, there is no special detailing required for connecting a steel strap. A number of

studies have been carried out on very flexible light gage steel straps in cold-formed structures under cyclic loading. Results from these studies showed that very flexible braces can be used satisfactory in low-rise steel frame buildings. The slenderness ratio of the braces investigated in these studies were generally larger than 800, while in the other studies, the focus was mainly on braces of other structural shapes with the slenderness ratio less than 200. Thus, it is useful to have more information on the performance of braces with slenderness ratio from 200 to 800.

1.1 Objective of the Thesis

The primary objective of this research project is to investigate the performance of flexible steel straps with the slenderness ratio between 200 and 800 under cyclic loading. Various slenderness ratios and connection details will be investigated. The feasibility of using various steel strap configurations will be investigated experimentally. These tests will also provide the data for the validation of finite element model to be developed for the parametric finite element study on the strap tension-only bracing system that is to be carried out in a separate study.

1.2 Methodology Used in the Research

The total of nineteen combinations of brace and connection detail with at least two specimens for each combination were tested. Flat bars were used as the bracing

member. The braces are considered to be fixed supported at both ends. The general configuration of the experiment along with the three different bolted connection details investigated are shown in Fig. 1.1.

These details consist of the connection with no reinforcement, and with reinforcement of either clamping or welding an additional plate. The test specimens have been designed to investigate effects of slenderness ratio and connection detail. The slenderness ratio investigated varies from 200 to 800 by changing the specimen length and thickness. Various net to gross cross-section area ratios at the connection were tested by using straps of different width.

A thick gusset plate was used to connect the brace in order to prevent any plastic hinge from forming in the gusset plate. The loading sequence of the test was conducted according to Guidelines for Cyclic Seismic Testing of Components of Steel Structures ATC-24 (ATC 1992) for single specimen testing program, but with some modifications for the later stages of the loading cycle. A small number of monotonic tests were also carried out to compare the response between monotonic and cyclic loading sequences.

All the tests were conducted under deformation control. Mechanical properties from tension coupon tests were used in analyzing the data in the test program. The hysteretic energy, maximum load and deformation, were determined for the tests. These values were normalized with respect to the yield load and yield deformation to allow for a better comparison between specimens of different lengths and material properties. Equations to predict the out-of-plane deflection of a buckled strap were developed and

verified. Based on the test data, effects of slenderness ratio and connection detail were assessed and recommendations provided on using strap tension-only bracing in a Seismic Force Resisting System.

1.3 Organization of the Thesis

Chapter 2 presents a brief literature review of previous studies on structural bracing systems. Provisions in design standards for the tension-only bracing system are presented.

In Chapter 3, the experimental program is presented. This chapter describes the test setup, testing procedure, test matrix and specimen geometry. A brief description of the tension coupon tests is provided.

Test results are presented in Chapter 4. Effects of slenderness ratio and connection detail on the ductility and the energy dissipation capability of the specimen are discussed. Discussions of the test results with respect to the design provisions for the tension-only bracing systems are presented, together with the recommendations.

Chapter 5 consists of the summary of the thesis, and as well as the conclusions and recommendations.

Additional test data are presented in appendices.

Figure 1.1 Steel strap specimen with various connection details.

CHAPTER 2 LITERATURE REVIEW

Vertical bracing is commonly used in non-moment-resisting steel frames to provide lateral support. When designed as members of a Seismic Force Resisting System (SFRS), the bracing member helps dissipate energy through plastic deformation during an earthquake. A compact bracing member can resist both compression and tension loads, while a very slender bracing member is only effective in providing resistance in tension. Figure 2.1 shows various bracing configurations that can be used in a structure. Among these, only X and diagonal bracing configurations are permissible when using a slender tension-only bracing member in a concentrically braced frame.

Many studies have been carried out to investigate the performance of bracing in an earthquake. Most of these studies focused on hollow structural sections, angles and sheet-metal strips. A brief review of bracing design and research is provided. Only some of the studies are discussed.

2.1 Research on Bracing

A number of tests have been carried out on the bracing member either individually, in a frame or in a building. Some of these tests were carried out by Astaneh-Asl et al. (1985) on angles, Kahn and Hanson (1976) on flat bars, Popov and Black (1981) on various structural sections, Tremblay et al. (2003) on rectangular HSS, Shaback and

Brown (2003) on square HSS, Al-Kharat and Rogers (2007) on cold-formed steel straps, and Filiatrault and Tremblay (1998) on tie-rods. Various numerical studies on seismic response of concentric braced frames have been carried out by Tremblay et al. (1997), and Tremblay (2000, 2001). Analytical studies of the bracing response have also been conducted by Tremblay (2002), El-Tayem and Geol (1986), Higginbotham and Hanson (1976), and Dewolf and Pelliccione (1979). Slenderness ratio, width to thickness ratio, ultimate to yield strength ratio, and deformation rate are some of the factors that have been found to affect the performance of the brace.

2.1.1 General Behaviour of Bracing

Generally, a bracing member will buckle under severe compressive deformation. For the configuration with a diagonal or a cross bracing without the mid-length attached, the initial buckled shape of the brace is between half and full sine curve depending on the end constraint. The deformed shape normally generates the largest curvature at the ends and the mid-span of the brace. Inelastic buckling eventually develops with the increase in the cyclic deformation.

Tests on various structural shapes by Kahn and Hanson (1976), Popov and Black (1981), Astaneh-Asl et al. (1985), Shaback and Brown (2003) and Tremblay et al. (2003) have shown that all specimens formed plastic hinges at these three locations. The formation of plastic hinges accelerates the strength degradation and fracture of the

member under cyclic loading since almost all the cyclic deformation is accommodated through the strain reversal at the plastic hinge. This eventually leads to fracture of the member at one of these locations.

2.1.2 Experimental Studies

There have been many tests on bracing under cyclic loading. Kahn and Hanson (1976) tested steel bars with slenderness ratios ranging from 85 to 210 and two loading rates. The fast rate was approximately 100 times faster than the slow rate. As anticipated, shorter specimens were found to have dissipated greater energy than larger specimens under the same relative deflection cycle. The maximum compressive buckling load was also found to decrease with increasing number of cycle, with a greater decrease after the first cycle than subsequent cycles. The hysteresis response was nearly identified under the two loading rates, with the response slightly stiffer in the tension region at the faster loading rate.

Popov and Black (1981) also tested different structural shapes with slenderness ratios from 40 to 120. The slenderness ratio was found to be the single most important parameter in determining the hysteretic behavior. Members with the lower slenderness ratio generate fuller loop than those with a higher ratio. The hysteretic performance of a member was also found to be influenced by the structural shape with respect to its susceptibility to local buckling. Local buckling occurred in the regions of plastic hinges

in advanced stages of cyclic load application. Normalized values of the load and displacement were used in order to make the comparison between members with different material properties. The normalized force and displacement are the corresponding measured force and displacement divided by the yield force and yield displacement respectively.

An experimental study was carried out by Astanek-Asl et al. (1985) on double-angle bracing in a hinged frame. The overall ductility and cyclic behavior of out-of-plane buckling double-angle members are greatly affected by the stitches and end gusset plates. It was recommended that stitches stronger than nominal stitches should be provided. A minimum free length equal to twice the thickness of the gusset plate beyond the angles is necessary to allow the free formation of plastic hinges and to improve the ductility.

Jain et al. (1978), Shaback and Brown (2003), and Tremblay et al. (2003) tested tubular members under cyclic loading. While Jain et al. (1978) only tested for two cycles, Shaback and Brown (2003) and Tremblay et al. (2003) tested the specimens until fracture. Similar to other studies, slenderness ratio has been found to be the single most important parameter influencing hysteric behavior of the specimen. Shaback and Brown (2003) found that the width to thickness ratio of the cross-section has a great influence on the brace fracture life, but has minimal effect on the hysteretic behavior. Both Tremblay (2002) from examining results from tubular members including tests by others, and Goggings et al. (2005) from tests on cold-formed tubes, concluded that the ductility of the

brace is strongly dependent on the slenderness ratio, and to a lesser extent, the width-to-thickness ratio of the cross-section. Equations in terms of slenderness ratio and width-to-thickness ratio were proposed to predict the fracture life of the brace by Shaback and Brown (2003) and Tremblay et al. (2003). Tremblay et al. (2003) proposed a simple fracture life equation defined for the maximum normalized deformation range.

$$\mu_f = 8.3\lambda + 2.4 \quad \text{with} \quad (2.1)$$

$$\lambda = \frac{KL}{r} \sqrt{\frac{F_y}{\pi^2 E}} \quad (2.2)$$

where KL is the effective length, r is the radius of gyration, F_y is the yield strength and E is the elastic modulus. Shaback and Brown (2003) also proposed two equations to predict the out-of-plane deflection of the brace. A number of lateral brace deflection equations have also been proposed by Tremblay (2002) from initial buckling to the formation of plastic hinges.

Most cyclic tests on the structural sections have been limited to specimens with the slenderness ratio less than 200. Some tests have been carried out on specimens with the slenderness ratio greater than 200 using round steel bars and thin straps as tension-only bracing. Filiatrault and Tremblay (1996, 1998) tested a frame braced with tie-rods under various seismic ground excitations. It was found that the frame response exhibited severe pinching in the hysteretic loop. The maximum force in the bracing was equivalent to approximately 1.14 times that at yielding for the rod. This was attributed to the increase in the yield strength of the rod as the deformation rate increases.

Kim et al. (2006) carried out shake table tests on cold-formed steel shear panel. The shear panel braced with the thin steel straps performed satisfactory for the ground motion considered in the test. Al-Kharat and Rogers (2007, 2008) also tested cold-formed steel strap braced walls. The force demand due to brace yielding was found to be higher than anticipated partly due to the strain rate effect increase in the yield strength. As the strain rate increases, the ultimate to yield strength ratio of the material decreases. This has been noted to affect the capacity design requirement of the connection for the test specimen to ensure gross section yielding of the brace before net section fracture occurs. All cold-formed steel strap braced walls by Kim et al. (2006), and Al-Kharat and Rogers (2007, 2008) exhibited severe pinching in the hysteretic loop. There were also significant slack in the braces at the end of the tests.

2.1.3 Analytical and Numerical Studies

Besides experimental studies, analytical studies have been conducted to study the effective length factor of bracing systems and to model their axial hysteretic behaviour. Numerical studies have also been conducted on seismic response of concentrically braced steel frames.

In the analytical and experimental studies of X-bracing system of single angle, El-Tayem and Goel (1986) recommended that an effective length of 0.85 times the half diagonal length can be considered for X-bracing systems made from single equal-leg

angles. An analytical study by Picard and Beaulieu (1987) showed that the effective length of the diagonal brace in a X-bracing system can be taken as 0.5 times the diagonal length when the diagonals are continuous and attached at the intersection point without including the rotation constraint provided by the complementary member and gusset plate considered by El-Tayem and Geol (1986). The results were further extended by Sabelli and Hohbach (1999) for other additional end restraints. Upper bound and lower bound in-plane and out-of-plane effective length factors were established by Sabelli and Hohbach (1999).

Davaran (2001) carried out an analytical study to investigate the effect of having a discontinuous brace in X-bracing systems. Various details were suggested to improve the rotational stiffness of center connection to increase the load carrying capacity of X-bracing systems with discontinuous brace. Jain et al. (1978) also provided a procedure to calculate the effective length factor for a single diagonal tubular member slotted into the gusset plate. In a X-bracing system, the peak compression force and tension force do not occur at the same time. Dewolf and Pelliccione (1979) in the analytical and experimental studies of the X-bracing frame found that when the compression force was at its maximum, the capacity of the frame was only between 40% to 70% of the test failure load. Both Tremblay (2002) and Shaback and Brown (2003) proposed equations to calculate the post-buckling strength of the compression brace so that the bracing capacity can be accounted for at the instance of the tension brace yielding. Performing the numerical analysis to investigate the seismic response of the braced frame requires the

knowledge of the axial hysteretic behaviour of the brace. This behaviour is normally represented by mathematical models to be incorporated into the numerical analysis. Some of these models have been proposed by Higginbotham and Hanson (1976) and Prathuangsit et al. (1978). Using a mathematical hysteretic model, Tremblay et al. (1997) and Tremblay (2000) studied the influence of brace slenderness on the seismic response of concentrically braced frames including tension-only braced frame. Tremblay et al. (1997) suggested that the tension-only braced frame should be limited to 4 storeys even if it is designed with a force modification factor R of 2. Tremblay (2000) also recommended that tension-only braced frame should be permitted up to four storeys, but with some limitations on the maximum slenderness ratio.

2.2 Design Requirements

Both Canadian and American design standards, Limit States Design of Steel Structures CSA-S16-01 (CSA 2005) and Seismic Provisions for Structural Steel Buildings ANSI/AISC 341-05 (AISC 2005) permit the use of tension-only brace in the Seismic Force Resisting Systems (SFRS). Since the complete design requirements are extensive, only a brief summary of bracing system design requirements are discussed.

In CSA-S16-01 (CSA 2005), tension-only bracing systems can be used in both moderately ductile (MD) and limited-ductility (LD) concentrically braced frames as well as in conventional construction. A height limit of 20 m for MD frame and 40 m for LD

frame are prescribed when tension-only bracing systems are used. However, there is a difference in the slenderness ratio (KL/r) limit for each type of these frames, where K is the effective length factor, L is the brace length and r is the radius of gyration. Due to the higher expected capability to dissipate energy through inelastic behavior, the slenderness ratio of the brace in MD Type braced frames has an upper limit 200. This is followed by LD Type braced frames with a higher upper limit of 300, and conventional construction where the limit can be waived if other means are provided to control the brace flexibility, sag, vibration, and slack in a member that is in line with the service conditions of the structure or if it can be shown that such factors are not detrimental to the performance of the structure.

For MD and LD Type braced frames, the brace connections shall be designed to resist at least both $A_g R_y F_y$ in tension and 1.2 times the probable compressive resistance of the bracing members, where A_g is the gross area and R_y is the ratio of the expected yield stress to the specified minimum yield stress, F_y . The net section factored resistance of an unreinforced brace may be increased by a factor R_y/Φ with R_y not greater than 1.1 and Φ is the resistance factor. However for conventional construction, the braced connections are required only to be proportioned so that the expected failure mode is ductile. Nevertheless in all cases, the maximum design tensile force need not exceed the combined effect of gravity load and effects of seismic loads corresponding to $R_d R_o = 1.3$, where R_d is ductility-related force modification factor and R_o is the over-strength related force modification factor. The brace members or connections must also have ductile

rotational behavior in MD and LD Type braced frames. When rotation is expected in the bracing member, the connections shall have a factored flexural resistance of at least $1.1ZR_yF_y$ of the bracing member where Z is the plastic section modulus. Besides the strength requirements in CSA-S16-01, the largest calculated interstorey drift due to the seismic load is also limited to $0.01h_s$ for post-disaster buildings, $0.02h_s$ for schools, and $0.025h_s$ for all other buildings by the National Building Code of Canada 2005 (NRCC 2005), where h_s is the interstorey height.

ANSI/AISC 341-05 (AISC 2005) also has connection design requirements for Ordinary Concentrically Braced Frames (OCBF) that are similar to MD and LD Type braced frames in CSA-S16-01 (CSA 2005). While CSA-S16-01 (CSA 2005) places some limits on the KL/r ratio of tension-only brace, no KL/r ratio limit has been specified for tension-only brace in ANSI/AISC 341-05 (AISC 2005) for OCBF.

K bracing

V bracing

Inverted-V bracing

X bracing

Diagonal bracing

Figure. 2.1 Bracing systems.

CHAPTER 3 TESTING PROGRAM

Although many experimental studies have been carried out on bracing systems, there have been only a few studies conducted on braces with the slenderness ratio between 200 and 800 under cyclic loadings. Tests on specimens with the slenderness ratio greater than 200 have mainly been limited to tie-rods and thin cold-formed steel straps.

This experimental study focused on steel straps with the slenderness ratio between 200 and 800 using hot-rolled flat bars. Tests were conducted in the Civil and Environmental Engineering Laboratory at Carleton University under displacement control. Strain gauges were instrumented to measure the strain distribution and cable transducers employed to record the transverse and axial deformations. A series of cyclic loading tests were carried out on flat bars with various slenderness ratios and three connection details in order to gain a better understanding of the ductility and performance of tension-only steel straps at this range of slenderness ratios, and eventually developing the corresponding design recommendations and guidelines for steel straps.

3.1 Objective

The objective of the testing program is to investigate the feasibility of using high slenderness ratio flat bar braces in steel structures for seismic design requirements. Effects of slenderness ratio and connection detail on the ductility and performance of the

braces will be studied experimentally. In addition, data obtained from this experimental study will be used in the validation of the finite element models developed for the parametric finite element analysis to be carried out that is outside the scope of this thesis.

3.2 Test Matrix

A total of 49 hot-rolled flat bar specimens were tested. Four cross-section sizes of flat bar specimens were used. They were FB 76x4.8 (3"x3/16"), FB 76x7.9 (3"x5/16"), FB 102x7.9 (4"x5/16"), and FB 127x7.9 (5"x5/16"). In addition, FB 64x4.8 (2-1/2"x3/16") and FB 64x7.9 (2-1/2"x5/16") were also used as the reinforcement plate. All flat bars were CAN/CSA G40.20/21 (CSA 2004) 300W (44W) steel, except for FB 76x7.9 and FB 127x7.9, which met the specifications for both 300W (44W) and 345W (50W) grades. Welding was carried out using E49XX electrodes. Effects of slenderness ratio, connection detail and ultimate to yield load ratio were investigated. Even though not ideal, the different ultimate to yield load ratio was obtained indirectly by using the flat bar of various width to achieve the different net to gross section area ratio. The parameters considered are described below.

1) Slenderness ratio

For a bracing member, one of the most important parameters is the slenderness ratio. With a flat bar brace, the bending strain due to buckling at the same axial deformation decreases with a higher slenderness ratio. In the test program,

nominal slenderness ratios of 200, 400, 600, and 800 were considered. These ratios were achieved changing the specimen length and thickness. The calculation of the nominal slenderness ratio adopted will be described later.

2) Connections

The energy dissipating capability of a SFRS requires the proper design of the connections to control the location of the plastic deformation. Figures 3.1 to 3.3 show the three connection types investigated. Type A connection in Fig. 3.1 has no reinforcement where the plastic deformation localization due to axial extension and buckling occurs at the section across the bolt hole. In Type B, the connection is stiffened by clamping an additional plate so that the plastic deformation due to buckling occurs away from the bolt hole in order to improve the ductility of the brace. Type C connection is welded with an additional plate to further improve the ductility of the brace by ensuring the connection is stronger than the rest of the brace in bending and tension.

3) Net to gross section area ratio

Three net to gross section area ratios were considered in order to investigate the effect of the ultimate to yield capacity ratio. Having the same material properties, the ductility of the flat bar brace is expected to improve with a higher net to gross section ratio at the connection. Three net to gross section area ratios of 0.71, 0.78, and 0.83 were considered. Even though the holes were punched, the net area is calculated by removing only 22 mm width.

3.3 Description of Test Specimens

The following notation was adopted to identify the test specimen:

$\alpha\beta\chi\chi\eta\tau$

a) α

The first letter α denotes the type of connection used for the specimen.

A = Type A connection with no reinforcement plate.

B = Type B connection clamped with a reinforcement plate.

C = Type C connection with a welded reinforcement plate.

b) β

The second digit represents the nominal slenderness ratio from 200 to 800 with 2, 4, 6, 8 representing 200, 400, 600, and 800 respectively.

c) $\chi\chi$

The third and fourth digits identify the specimen width with 07 for 76, 10 for 102, and 12 for 127 mm.

d) η

The fifth digit indicates the thickness of the specimen. It is either 5 for 4.8 mm or 8 for 7.9 mm.

e) τ

Finally the last letter, which is a, b, c, and so on, represents duplicate specimens.

The nominal and measured dimensions of the specimen are presented in Tables 3.1 and 3.2 respectively. Table 3.3 shows the nominal and expected net section fracture to gross section yielding strength ratio for Grade 300W Type A and B straps, where $R_y F_y$ is taken as 385 MPa and the expected F_u is taken as 1.1 times the nominal as according to CSA-S16-01 (CSA 2005). The following symbols are adopted to represent dimensions of the specimen according to Figs. 3.1 to 3.3.

- 1) Specimen overall length (L_o).

Five different lengths between 1120 and 2510 mm were used in the test to achieve the nominal slenderness ratio between 200 and 800.

- 2) Specimen thickness (t).

Flat bar thicknesses of 4.8 and 7.9 mm were used.

- 3) Specimen width (w).

The specimens have three widths of 76, 102, and 127 mm.

- 4) Nominal slenderness ratio (KL/r).

Four nominal slenderness ratios of 200, 400, 600, and 800 were tested. To simplify the discussion, the nominal slenderness ratio of the specimen is henceforth referred to as the slenderness ratio. The slenderness ratio of the specimen is calculated as

$$\frac{KL}{r} = \frac{KL}{\sqrt{\frac{I}{A}}} = \frac{KL}{\sqrt{\frac{\left(\frac{wt^3}{12}\right)}{wt}}} = 3.46 \frac{KL}{t}, \quad (3.1)$$

where K is the effective length factor is taken as 0.5 for both ends fixed condition, L is the distance between the middle bolt holes (second bolt hole), r is the radius of gyration, I is the moment of inertia, and A is the cross-section area.

- 5) Reinforcement plate length x width x thickness ($L_r \times w_r \times t_r$).

Specimens with Type B and C connection details have reinforcement plates either clamped or welded to the ends. All reinforcement plates were 200 mm long. For Type B specimens, the reinforcement plates were of the same width and thickness as the main specimen. In Type C specimens, 64 mm wide reinforcement plates were used with 76 mm wide straps and 76 mm wide plates with 102 mm wide straps, but the same thickness was maintained for the main specimen and reinforcement plate.

3.4 Specimen Preparation and Measurement

The contact surface of the specimen at the connection was cleaned to Class A, clean mill scale surface in accordance to SSPC (2004) Solvent Cleaning, Hand Tool Cleaning, and Power Tool Cleaning Specifications. The specimen width and thickness, and its reinforcement plate length, width and thickness were measured with a digital caliper. A digital micrometer was also used in measuring the thickness of the specimen. A measuring tape was used in measuring the length of the specimen. Average measured dimensions of each specimen and its corresponding reinforcement plate are shown in

Table 3.2.

3.5 Test Setup and Instrumentation

Tests were carried out using a 1000 kN hydraulic jack with a 450 mm stroke limit. The machine stroke, cable transducer, load cell, and strain gauge readings were recorded continuously through the data acquisition system during the test.

3.5.1 Test Setup

Figures 3.4 to 3.8 show details of the fixtures for attaching the specimen and the general test setup. The end fixtures were reinforced and rigidly connected to the base plate and the head of the loading jack to prevent the ends from rotating about horizontal axis. Even though each end of the specimens was connected with only three M20 ASTM A490M bolts, four bolt holes were provided on the gusset plate to minimize the frequency of lifting of the loading cross beam needed to accommodate the different specimen length. All bolts were pre-tensioned using the turn-of-nut method. Figure 3.8 shows the loading frame used in the test.

3.5.2 Instrumentation

Strain gauges and cable transducers were used in the tests to measure the

deformation of the specimen. Figure 3.9 shows locations of the cable transducers. The horizontal cable transducers were always positioned on the side away from the gusset plate such that the specimen was always between the gusset plate and horizontal cable transducer. All cable transducers have a 500 mm extension range. Two cable transducers measured the vertical deformation, and the other two measured the horizontal deflection at the mid-length. The actuator stroke was used in the deformation control. It is expected that the actuator stroke and axial deflection measured by the cable transducer to be close. In some tests, the horizontal cable transducers may have to be removed in the middle of the test because either the deflection has exceeded the range of the cable transducer or the attachment for the cable connection was interfering with the vertical cable transducer.

Depending on the connection type, two or three strain gauges were instrumented on the specimen. Locations of the strain gauges are shown in Fig. 3.10. These strain gauges are numbered G1 to G3 as shown in the Figure. Figure 3.11 illustrates the layout of strain gauges on Type C specimens. In the test, the primary data collected were the axial deformation and load. For this reason, mainly one specimen in each configuration has been instrumented with strain gauges.

3.6 Test Procedure

All specimens were tested under cyclic deformation except specimens A2078e, A2078d, A2128f, and A2128e, which were tested under monotonic tension at a

displacement control loading rate of 5 mm/min. In the monotonic test, static readings were taken after the loading crosshead was paused for 30 seconds at a displacement interval of about 2 mm.

For the cyclic tests, the loading sequence was conducted according to ATC-24 Guidelines for Cyclic Seismic Testing of Components of Steel Structures (ATC 1992) for single specimen testing program with some modifications for the later stages of the loading cycle. The following loading pattern was used in the test:

- 1) Three cycles at $\delta = 0.25\delta_y$
- 2) Three cycles at $\delta = 0.5\delta_y$
- 3) Three cycles at $\delta = 0.6\delta_y$
- 4) Three cycles at $\delta = 0.8\delta_y$
- 5) Three cycles at $\delta = \delta_y$
- 6) Three cycles at $\delta = 2\delta_y$
- 7) Three cycles at $\delta = 3\delta_y$
- 8) Two cycles at $\delta = 4\delta_y$

After $\delta = 4\delta_y$ the applied deformation increased by δ_y for every two cycles. δ is half of the applied deformation range and δ_y is the yield deformation taken as

$$\delta_y = \frac{F_y L}{E} \quad (3.2)$$

where F_y is the nominal yield strength taken as 300 MPa, E is the elastic modulus taken as 200000 MPa and L is the nominal length of the specimen measured between the

middle bolt holes. ATC-24 specifies at least six cycles should be at $\delta < \delta_y$. In the tests, twelve cycles and four loading ranges at $\delta < \delta_y$ were specified with the loading range δ at the bounds suggested in Appendix S 1997 Seismic Provisions for Structural Steel Buildings (AISC 1997). All specimens were tested under displacement control. Since the specimen has a high slenderness ratio, the buckling load of the specimen is very small. For this reason, load control was not used in the elastic cycle even though that has been suggested by ATC-24 (ATC 1992). A number of static readings were also taken during the cyclic test of at least one specimen for each test configuration after pausing the loading crosshead for 30 seconds.

Further modifications were made to the testing protocol suggested by ATC-24 (ATC 1992) due to constraints in the loading control and testing time. In the beginning of the test, the loading range is small. Thus, a low loading rate was used in order to better control the applied displacement. However, maintaining the same low loading rate throughout the test will make the test prohibitory long. Thus, a variable loading rate was adopted for the test. Table 3.4 shows the loading (strain) rates applied at different stages of the test for various specimen lengths. For a small number of tests where a large number of applied cycles were required, the increment step for the loading displacement range was increased to $5 \delta_y$ after the half loading displacement range $\delta = 50\delta_y$. However, the number of loading cycle per displacement range remained at two cycles. Due to the high slenderness ratio of some of the specimens, the specimens may not fail before the actuator stroke limit has been exceeded. For these specimens, the loading were carried

out for 30 cycles at the maximum stroke before the test was terminated even if fracture has not occurred.

NBCC 2005 (NRCC 2005) limits the storey drift due to seismic load to 2.5% at near collapse state for ordinary buildings. A 2.5% storey drift with the brace at 45° is equal to 1.25% strain in the brace, which is at $\delta = 8.3\delta_y$ for $F_y = 300\text{MPa}$. The ductility demand is the greatest when the brace is at 45° . Thus changing the deformation increment from δ_y as specified in ATC-24 loading protocol to $5\delta_y$ after $\delta = 50\delta_y$ does not affect validity of using the test data to assess the specimen suitability to be used in a seismic design since the deformation at $\delta = 50\delta_y$ has far exceeded the ductility requirement for 2.5% storey drift.

3.7 Material Properties

Actual material properties of the flat bars are required to evaluate the test results. The tension coupon tests were conducted by another student as part of a separate study in strain rate dependent material properties. Thus, only a brief description of the coupon test is provided here. Coupons were cut and machined according to ASTM-E8-04 (ASTM 2004). For every flat bar size, two coupons were tested in tension at the strain rate of 0.0001, 0.01, and 0.5s^{-1} for a total of six coupons. In addition, static readings were also taken during the 0.0001s^{-1} strain rate test after pausing machine crosshead for around 90 seconds during the test at 0.0001s^{-1} strain rate, at which point the cross-section

dimensions were also measured manually with a caliper and a micrometer.

Results of the coupon tests are listed in Appendix A with the summarized averages in Table 3.5. The elastic modulus E , yield strength F_y , ultimate strength F_u , elongation of 50 mm gauge length and ratio of undeformed over average cross-section area at fracture (A_o/A_f) are listed in the Table 3.5. The average cross-section area at fracture is the product of the average of the maximum and minimum width and thickness at the location of fracture. The ultimate to yield strength (F_u/F_y) ratio varies with the material and decreases with a higher loading rate. Among the flat bars, the static F_u/F_y ratio varies from a low of 1.43 for FB 76x4.8 to 1.74 for FB 76x7.9, while the ratio ranges from 1.26 to 1.57 at the $0.5s^{-1}$ strain rate. The F_u/F_y ratio affects the design that requires gross section yielding before net section fractures. At the strain rate of $0.5s^{-1}$, the yield strength of all six flat bars also exceeds the expected yield strength of 385 MPa in CSA S16-01 for Grade 300W and 350W steels. Unlike the F_u/F_y ratio, the yield and ultimate strength increase with the strain rate. Material dynamic to static yield and ultimate strength ratios for the flat bar specimens are shown in Table 3.6. The rate of increase for yield strength is faster than the ultimate strength, which corresponds to the reduction in the F_u/F_y ratio with a higher strain rate.

Table 3.1 Test matrix.

Specimen no.	Length x width x thickness $L_o \times w \times t$ (mm)	Reinforcement $L_r \times w_r \times t_r$ (mm)	$\frac{KL}{r}$	$\frac{A_n}{A_g}$	Connection type
A8075a-b	2510 x 76 x 4.8	-	800	0.71	A
A6075a-b	1930 x 76 x 4.8	-	600	0.71	A
A4075a-c	1360 x 76 x 4.8	-	400	0.71	A
A4078a-b	2050 x 76 x 7.9	-	400	0.71	A
A2078a-e	1120 x 76 x 7.9	-	200	0.71	A
A4108a-b	2050 x 102 x 7.9	-	400	0.78	A
A2108a-b	1120 x 102 x 7.9	-	200	0.78	A
A4128a-b	2050 x 127 x 7.9	-	400	0.83	A
A2128a-f	1120 x 127 x 7.9	-	200	0.83	A
B8075a-b	2510 x 76 x 4.8	200 x 76 x 4.8	800	0.71	B
B2078a-b	1120 x 76 x 7.9	200 x 76 x 7.9	200	0.71	B
B2128a-d	1120 x 127 x 7.9	200 x 127 x 7.9	200	0.83	B
C8075a-b	2510 x 76 x 4.8	200 x 64 x 4.8	800	-	C
C6075a-b	1930 x 76 x 4.8	200 x 64 x 4.8	600	-	C
C4075a-b	1360 x 76 x 4.8	200 x 64 x 4.8	400	-	C
C4078a-b	2050 x 76 x 7.9	200 x 64 x 7.9	400	-	C
C4108a-b	2050 x 102 x 7.9	200 x 76 x 7.9	400	-	C
C2078a-b	1120 x 76 x 7.9	200 x 64 x 7.9	200	-	C
C2108a-c	1120 x 102 x 7.9	200 x 76 x 7.9	200	-	C

Table 3.2 Measured dimensions.

Specimen no.	Length, L_o (mm)	Width, w (mm)	Thickness, t (mm)	Top reinforcement plate, $L_r \times w_r \times t_r$ (mm)	Bottom reinforcement plate, $L_r \times w_r \times t_r$ (mm)
A8075a	2510	75.9	4.67	-	-
A8075b	2509	76.0	4.64	-	-
A6075a	1931	76.1	4.66	-	-
A6075b	1930	76.0	4.65	-	-
A4075a	1358	76.1	4.68	-	-
A4075b	1359	76.1	4.68	-	-
A4075c	1360	76.2	4.65	-	-
A4078a	2050	76.4	7.89	-	-
A4078b	2049	76.3	7.87	-	-
A2078a	1120	76.3	7.86	-	-
A2078b	1119	76.4	7.87	-	-
A2078c	1120	76.2	7.87	-	-
A2078d	1121	76.2	7.91	-	-
A2078e	1120	76.3	7.87	-	-
A4108a	2050	101.9	7.88	-	-
A4108b	2050	101.9	7.89	-	-
A2108a	1120	101.9	7.87	-	-
A2108b	1120	102.0	7.90	-	-
A4128a	2049	127.5	7.76	-	-
A4128b	2049	127.5	7.78	-	-
A2128a	1118	127.2	7.72	-	-
A2128b	1119	127.0	7.68	-	-
A2128c	1118	126.9	7.74	-	-
A2128d	1119	126.9	7.70	-	-
A2128e	1118	127.4	7.80	-	-
A2128f	1120	126.9	7.69	-	-

Table 3.2 Continue.

Specimen no.	Length L_o (mm)	Width, w (mm)	Thickness, t (mm)	Top reinforcement plate, $L_r \times w_r \times t_r$ (mm)	Bottom reinforcement plate, $L_r \times w_r \times t_r$ (mm)
B8075a	2510	75.9	4.64	199 x 76.1 x 4.72	199 x 76.1 x 4.73
B8075b	2510	76.0	4.65	198 x 76.0 x 4.72	198 x 76.0 x 4.70
B2078a	1120	76.4	7.88	198 x 76.3 x 7.95	199 x 76.3 x 7.95
B2078b	1119	76.3	7.85	200 x 76.2 x 7.95	199 x 76.3 x 7.96
B2128a	1119	127.1	7.76	204 x 126.9 x 7.70	204 x 127.1 x 7.70
B2128b	1117	127.8	7.72	203 x 126.9 x 7.96	204 x 126.9 x 7.78
B2128c	1120	126.8	7.70	203 x 127.1 x 7.73	203 x 126.8 x 7.80
B2128d	1120	126.8	7.77	200 x 127.7 x 7.80	199 x 127.3 x 7.81
C8075a	2509	76.0	4.65	198 x 62.5 x 4.84	198 x 62.7 x 4.86
C8075b	2509	76.1	4.62	198 x 62.8 x 4.91	198 x 62.7 x 4.89
C6075a	1928	75.9	4.73	198 x 62.1 x 4.76	198 x 62.3 x 4.83
C6075b	1928	76.0	4.68	198 x 62.0 x 4.81	198 x 62.2 x 4.64
C4075a	1358	76.0	4.67	198 x 62.6 x 4.82	198 x 62.6 x 4.77
C4075b	1358	76.2	4.67	198 x 62.6 x 4.79	198 x 62.0 x 4.73
C4078a	2049	76.2	7.89	198 x 63.4 x 8.01	198 x 63.3 x 7.96
C4078b	2048	76.3	7.89	199 x 63.3 x 7.96	196 x 63.3 x 7.95
C4108a	2049	101.9	7.87	199 x 76.3 x 7.93	199 x 76.3 x 8.00
C4108b	2050	101.9	7.86	199 x 76.3 x 7.93	199 x 76.5 x 8.00
C2078a	1116	76.4	7.95	198 x 63.7 x 7.96	198 x 63.7 x 7.96
C2078b	1118	76.5	7.92	198 x 63.4 x 7.90	198 x 63.6 x 7.88
C2108a	1119	101.9	7.87	198 x 76.4 x 7.98	199 x 76.6 x 7.98
C2108b	1120	101.9	7.86	199 x 76.5 x 7.95	199 x 76.6 x 7.95
C2108c	1119	101.8	7.86	199 x 76.9 x 7.97	199 x 76.5 x 7.99

Table 3.3 Nominal and expected net section fracture to gross section yielding strength ratio for Type A and B specimens.

Strap	$\frac{A_n}{A_g}$	Nominal $\frac{A_n F_u}{A_g F_y}$	Expected $\frac{1.1 A_n F_u}{R_y A_g F_y}$
76 mm x 4.8 mm	0.71	1.07	0.91
76 mm x 7.9 mm	0.71	1.07	0.91
102 mm x 7.9 mm	0.78	1.18	1.01
127 mm x 7.9 mm	0.83	1.24	1.06

Table 3.4 Loading rate for different specimen length.

Target displacement	Displacement rate, (mm/min)	Strain rate, (s ⁻¹)	Gusset plate bolt hole	30 cycles at
Specimen length, L _o = 1120 mm (KL/r = 200)				
δ ≤ 10 δ _y	15	0.00027	Closest	-
10 δ _y < δ ≤ 21 δ _y	30	0.00054		
21 δ _y < δ ≤ 40 δ _y	60	0.00109		
40 δ _y < δ	120	0.00218		
Specimen length, L _o = 1360 mm (KL/r = 400)				
δ ≤ 8 δ _y	15	0.00022	Farthest	-
8 δ _y < δ ≤ 17 δ _y	30	0.00044		
17 δ _y < δ ≤ 34 δ _y	60	0.00088		
34 δ _y < δ	120	0.00176		
Specimen length, L _o = 1930 mm (KL/r = 600)				
δ ≤ 11 δ _y	30	0.00029	Closest	90 δ _y ¹
11 δ _y < δ ≤ 23 δ _y	60	0.00058		
23 δ _y < δ ≤ 40 δ _y	120	0.00116		
40 δ _y < δ	240	0.00232		
Specimen length, L _o = 2050 mm (KL/r = 400)				
δ ≤ 10 δ _y	30	0.00027	Farthest	75 δ _y
10 δ _y < δ ≤ 21 δ _y	60	0.00054		
21 δ _y < δ ≤ 40 δ _y	120	0.00108		
40 δ _y < δ	240	0.00216		
Specimen length, L _o = 2510 mm (KL/r = 800)				
δ ≤ 17 δ _y	60	0.00043	Farthest	65 δ _y
17 δ _y < δ ≤ 34 δ _y	120	0.00086		
34 δ _v < δ	240	0.00172		

Notes:

¹ Only for specimen C6075b.

Table 3.5 Material properties.

Strap	Strain rate (s ⁻¹)	Yield strength, F _y (MPa)	Ultimate strength, F _u (MPa)	$\frac{F_u}{F_y}$	$\frac{A_o}{A_f}$	Elongation (%)	Elastic modulus, E (MPa)
76 mm x 4.8 mm	Static (0.0001)	308.0	440.9	1.43	-	-	210700
	0.0001	326.1	466.6	1.43	2.71	34.7	
	0.01	356.8	472.3	1.32	2.52	31.9	
	0.5	387.2	489.1	1.26	2.55	38.1	
76 mm x 7.9 mm	Static (0.0001)	318.2	553.8	1.74	-	-	205100
	0.0001	342.6	577.6	1.69	2.33	28.5	
	0.01	369.3	589.7	1.60	2.46	29.2	
	0.5	394.3	619.7	1.57	2.41	28.1	
102 mm x 7.9 mm	Static (0.0001)	348.1	562.1	1.61	-	-	204200
	0.0001	375.1	586.3	1.56	2.44	31.9	
	0.01	394.8	596.9	1.51	2.54	30.7	
	0.5	422.6	628.0	1.49	2.44	30.7	
127 mm x 7.9 mm	Static (0.0001)	328.5	494.2	1.50	-	-	208300
	0.0001	345.9	518.4	1.50	2.59	33.5	
	0.01	361.7	524.2	1.45	2.50	31.2	
	0.5	408.7	552.8	1.35	2.54	34.1	

Table 3.5 Continue.

Strap	Strain rate (s ⁻¹)	Yield strength, F _y (MPa)	Ultimate strength, F _u (MPa)	$\frac{F_u}{F_y}$	$\frac{A_o}{A_f}$	Elongation (%)	Elastic modulus, E (MPa)
64 mm x 4.8 mm	Static (0.0001)	337.6	490.7	1.45	-	-	212700
	0.0001	351.5	515.8	1.47	2.23	28.6	
	0.01	373.5	521.6	1.40	2.43	30.9	
	0.5	418.2	547.9	1.31	2.41	32.3	
64 mm x 7.9 mm	Static (0.0001)	325.2	497.4	1.53	-	-	213400
	0.0001	339.9	518.6	1.53	2.36	33.5	
	0.01	363.2	527.8	1.45	2.38	33.0	
	0.5	407.3	555.3	1.36	2.35	34.5	

Table 3.6 Material dynamic to static yield and ultimate strength ratios.

Strap	$\frac{F_y}{F_y(\text{static})}$				$\frac{F_u}{F_u(\text{static})}$			
	Strain rate (s^{-1})				Strain rate (s^{-1})			
	Static	Dynamic			Static	Dynamic		
	0.0001	0.0001	0.01	0.5	0.0001	0.0001	0.01	0.5
76 mm x 4.8 mm	1	1.06	1.16	1.26	1	1.06	1.07	1.11
76 mm x 7.9 mm	1	1.08	1.16	1.24	1	1.04	1.06	1.12
102 mm x 7.9 mm	1	1.08	1.13	1.21	1	1.04	1.06	1.12
127 mm x 7.9 mm	1	1.05	1.10	1.24	1	1.05	1.06	1.12

Figure 3.1 Strap with no reinforcement, Type A.

Figure 3.2 Strap clamped with reinforcement plate, Type B.

Figure 3.3 Strap welded with reinforcement plate, Type C.

Figure. 3.4 Test setup.

Figure. 3.5 Picture of test setup.

Figure. 3.6 Loading frame.

Elevation

All dimensions in mm unless specified otherwise

Figure 3.7 Bottom connection.

Figure 3.8 Top connection.

Figure 3.9 Positions of cable transducer.

Figure. 3.10 Locations of strain gauges.

Figure 3.11 Example of a Type C specimen with strain gauges.

CHAPTER 4 TEST RESULTS

Steel straps with various slenderness ratios and connection details have been tested. The response and performance of the strap has been found to change with the slenderness ratio and connection detail. Based on results of the tests, effects of slenderness ratio and connection detail on buckled shape, dissipated energy, load-deformation relationship, location of fracture, and ductility are assessed and discussed. Guidelines and recommendations are also provided on using steel straps as tension-only bracing member in seismic design.

4.1 Test Results

Results of the test are summarized in Tables 4.1 and 4.2. The following parameters are adopted for the discussion. In Table 4.1, the hysteretic energy is calculated as the energy dissipated up to fracture or when the test stopped. It is defined as

$$E_h = \int F d\Delta \quad (4.1)$$

where F is the measured force in the member and Δ is the average measured displacement from the two axial cable transducers. In order to allow for a better comparison between specimens with different material and length, normalized values of test results similar to Popov and Black (1981) are also presented in Table 4.2. Since the loading rate varied in the test, the static yield strength has been adopted in calculating the normalized value in

the discussion even though the maximum load in Table 4.1 is the dynamic load. The normalized maximum tension load, $T_{n\max}$ is taken as

$$T_{n\max} = \frac{T_{\max}}{A_g F_{ys}} \quad (4.2)$$

where $T_{\max}$ is the maximum tension force recorded until the test was stopped or the specimen fractured, A_g is the measured gross cross-section area of the specimen, and F_{ys} is the measured static yield strength. The normalized maximum extension, $\Delta_{n\max}$ is defined as

$$\Delta_{n\max} = \frac{\Delta_{\max} E}{F_{ys} L} \quad (4.3)$$

where $\Delta_{\max}$ is the maximum extension recorded until the test was stopped or the specimen fractured, E is the measured elastic modulus and L is the distance between the middle bolt holes. Finally the normalized hysteretic energy is defined as

$$E_n = \frac{E_h E}{A_g F_{ys}^2 L} \quad (4.4)$$

The loading strain rate of the test in Table 3.4, which is an average over the specimen length, L ranges from 2×10^{-4} to 2×10^{-3} . From results of the material test shown in Table 3.6, the dynamic to static yield strength rate was found to vary from 1.10 to 1.16 at 10^{-2}s^{-1} . In Table 4.2, the normalized maximum tension load ($T_{n\max}$) is at least 1.05 for all specimens. However, this does not imply that gross section yielding has been achieved in all specimens since static yield strength was used in calculating the normalized values. Based on the dynamic material properties, it is difficult to assess conclusively if gross

section yielding has occurred in the test using T_{nmax} alone when T_{nmax} has a value between 1.10 and 1.16.

The average net to gross section area and the net section fracture to gross section yielding strength ratios for Type A and B specimens are shown in Table 4.3. Only FB 76x4.8 specimens have the $(A_n F_u / A_g F_y)$ ratio close to or less than 1.0. Other specimens have a ratio that is significantly greater than 1.0 even up to a strain rate of $0.5s^{-1}$, and thus would be expected to exhibit considerable ductility in the test. The load versus deformation curves for all tests are shown in Appendix B. There was no deterioration in the load with the increase range in deformation until fracture occurred.

4.1.1 Direction of Buckling and Fracture Location

In the test, the specimen can buckle either towards or away from the cable transducers. The direction towards the cable transducers is the direction away from the gusset plate. As shown in Figs 3.5 and 3.8, the specimen was always in between the gusset plate and horizontal cable transducer. Table 4.1 lists the direction of buckling observed in the test, with "+" indicating the direction towards the cable transducer and "-" in the opposite direction. There is no preferred buckling direction observed in the test. In order to ensure and force the buckling to go in one direction, a strut (rod) (not connected to the specimen) was positioned at the mid-length of the specimen as shown in Figs. 4.1 to 4.3. Despite using the strut, buckling direction can still swing back and forth from one

cycle to another at the late stages of loading.

All Type A specimens fractured across the innermost bolt hole except for A2128c, where fracture occurred across a section close to the end of the gusset plate. Figure 4.4 shows the typical fracture across the innermost bolt hole and that for A2128c. For Type A specimens, the largest cumulative strain due to axial extension occurred at the innermost bolt hole. When the specimen buckled towards the cable transducers and away from the gusset plate, the largest cumulative bending strain due to the buckling and straightening also occurred at the innermost bolt hole. For these reasons, all Type A specimens fractured across the innermost bolt hole when buckling was away from the gusset plate. However, when the specimen buckled towards the gusset plate as in A4075c and A2128c, the largest cumulative bending strain occurred close to the end of the gusset plate instead of innermost bolt hole because the buckled configuration has to go around the gusset plate. Generally, the cumulative strain due to axial extension reduces with a higher $A_n F_u / A_g F_y$ ratio at the bolt hole. Similarly, the cumulative bending strain due to buckling also reduces with a higher slenderness ratio with other things being equal. For this reason, A4075c, which has a higher slenderness ratio and lower $A_n F_u / A_g F_y$ ratio compared to A2128c, fractured across the innermost bolt hole while A2128c fractured close to the end of the gusset plate.

In Type B specimens, the extra plate shifted the location of the largest cumulative bending strain away from the innermost bolt hole to a section close to the end of the reinforcement plate. This increases the ductility of a Type B specimen compared to a

similar Type A specimen, as can be seen in Table 4.1. While all specimens in B8075 and B2078 series fractured across the innermost bolt hole, some specimens in B2128 series fractured at the mid-length. There is an interplay of many factors, such as clamping force, slenderness ratio, $A_n F_u / A_g F_y$ ratio and material properties, that influence where fracture occurs. It is not possible to draw a conclusion on the fracture location based on the limited test results available.

For Type C specimens with welded plate reinforcement, the stroke limit of the actuator was exceeded in many tests before fracture occurred due to the higher ductility compared to Type A and B specimens. Since the section at the bolt hole was no longer the weakest, fracture occurred in these specimens either at the mid-length or close to the end of the reinforcement plate. Figure 4.5 shows the typical fracture locations of Type C specimens of either close to the end of the reinforcement plate in C2078a or at the mid-length for C2108a. Pictures of fracture location and/or buckling shape for all specimens are shown in Appendix C.

4.1.2 Out-of-plane Deformation of a Buckled Strap

The out-of-plane elastic buckling deformation is given by Fig. 4.6 for fixed end condition and Fig. 4.7 for pinned end condition. Based on the assumed deformation shapes in Figs. 4.6 and 4.7, the maximum out-of-plane deflection for both fixed and pinned end conditions can be simplified to

$$a = 0.64\sqrt{(b_o - b)b} \quad (4.5)$$

where a is the maximum out-of-plane or lateral deflection, b_o is the relaxed length at zero load and b is the deformed length. Equation (4.5) is similar to that derived by Tremblay (2002) for fixed end condition, but differs for pinned end condition. In an actual buckling, the end condition is between fixed and pinned. Thus, Eq. (4.5) appears to be the particularly suitable to estimate the maximum out-of-plane buckling deformation. Three relaxed lengths may be considered in using Eq. (4.5). Assuming that all deformations are elastic, the relaxed length can be assumed to be equal to the original undeformed length as

$$b_o = L_d \quad \text{with} \quad (4.6a)$$

$$b_o - b = -\Delta \quad (4.6b)$$

where L_d is the undeformed centre-to-centre distance of the innermost bolt holes for Type A specimens and the inner distance between ends of reinforcement plate for Type C specimens, and Δ is the axial deformation from the original undeformed position taking as negative in compression. If the maximum extension up to the time of consideration is assumed to be fully plastic, the relaxed length can be taken as

$$b_o = L_d + \Delta_m \quad \text{with} \quad (4.7a)$$

$$b_o - b = \Delta_m - \Delta \quad (4.7b)$$

where Δ_m is the maximum extension up to the time of consideration. Finally, the maximum extension up to the time of consideration can be assumed to include some elastic deformation associated with the maximum tension force experienced by the strap

up to then. This gives the relaxed length as

$$b_o = L_d + \Delta_m - \frac{F_m(L_d + \Delta_m)}{A_g E} \quad \text{with} \quad (4.8a)$$

$$b_o - b = \Delta_m - \Delta - \frac{F_m(L_d + \Delta_m)}{A_g E} \quad (4.8b)$$

where F_m is the maximum tension force up to the time of consideration, A_g is the gross section area of the strap and E is the elastic modulus. Predicted values based on Eqs. (4.6) to (4.8) are compared to the measured deformations for some of the tests in Table 4.4. Clearly, Eq. (4.8) gives the most accurate overall predicted deflection with the accuracy improving at a larger cyclic loading range. The predicted deformation by Eq. (4.8) is within 10 % of the measured values in Table 4.4, except for A4075a at a low deformation range of $\delta = \delta_y$. Equation (4.6) generally underestimates and Eq. (4.7) overestimates the deformation. As expected, since Eq. (4.6) assumes fully elastic extension while Eq. (4.7) assumes fully plastic extension, the accuracy of Eq. (4.6) deteriorates as the loading range increases and the reverse applies to Eq. (4.7).

4.1.3 Comparisons of Monotonic and Cyclic Tests

Monotonic tests were carried out for A2078 (FB 76x4.8) and A2128 (FB 127x7.9) specimens in addition to the cyclic tests. As can be seen in Table 4.3, both specimen groups have a comparable capacity ($A_n F_u / A_g F_y$) ratio, but A2128 specimens have a higher cross section A_n / A_g ratio. This implies that the side of the A2128 extends further out from

the centerline than A2078, which translates to a higher stress concentration or a more non-uniform stress and strain distributions across the section at the bolt hole for A2128. Table 4.5 shows results of monotonic tests as compared to the ideal net section capacity at various strain rates. Based on the loading rate of 5 mm/min, the monotonic test has a overall loading strain rate of around 0.00009s^{-1} . A2078 specimens achieved the ideal full net section capacity for the strain rate of 10^{-4}s^{-1} , but the capacity for A2128 specimens was about 5% lower. This can be attributed to the higher stress concentration at the bolt hole for A2128 that causes the specimens to fail before the ideal net section capacity is reached.

Comparisons of monotonic and cyclic test results are shown in Table 4.6. Values from A2128c have been excluded because the specimen buckled away from the cable transducers that have resulted in a less severe strain accumulation at the bolt hole. Figures 4.8 and 4.9 show the load versus deformation curves for one each of the monotonic and cyclic specimens. It can be seen in Figs. 4.8 and 4.9 that the load versus deformation curve for the monotonic test forms the upper envelope and provides a good estimate of the tension half of the load versus deformation curve for the cyclic test. Shown in Table 4.6, the maximum tension load in the cyclic test is 5% lower than the monotonic test for A2128 and 11% lower for A2078, following the same trend as the comparison of the maximum monotonic tension to the ideal net section capacity between the two specimen groups. It is expected that the difference between the maximum monotonic and cyclic tension load to reduce as the slenderness ratio increases. On average, the maximum

extension for A2078 in the cyclic test was about the same as the monotonic test, but it was about 25% lower in the cyclic test for A2128. This may be attributed partly to the higher stress concentration at the bolt hole for A2128 compared to A2078 due to the difference in the specimen width or A_n/A_g ratio.

4.1.4 Effects of A_n/A_g and A_nF_u/A_gF_y Ratios

For the same material, the ductility of the strap is expected to increase with the net to gross section area ratio (A_n/A_g) or the net section fracture to the gross section yielding ratio (A_nF_u/A_gF_y). However, this may not be completely true for straps with different material properties. Excluding tests that buckled away from the cable transducers and loaded monotonically, the average normalized maximum extension and hysteretic energy results for Type A specimens are summarized in Table 4.7.

Due to different material properties, the A_nF_u/A_gF_y ratio for all 7.9 mm thick straps (Axxx8) turns out to be about equal, and is significantly higher than 1.0 even though the A_n/A_g ratio is different. On the other hand, the A_nF_u/A_gF_y ratio for 4.8 mm thick straps (Axxx5) is close to 1.0 up to the strain rate of 10^{-4}s^{-1} . In general, the actual A_nF_u/A_gF_y ratio is significantly different than the nominal and expected net section fracture to gross section yielding strength ratios in Table 3.3. It can be seen in Table 4.7, A2078 and A2108 achieved roughly the same $\Delta_{n\max}$ and E_n while $\Delta_{n\max}$ and E_n for A2128 are about 20% higher, even as all these three Type A specimen series have roughly the

same $A_n F_u / A_g F_y$ ratio. The same can be concluded for A4078, A4108, and A4128. Unlike A4078, A4108 and A4128, the $A_n F_u / A_g F_y$ ratio for A4075 is only around 1.0. As a result, A4075 has a much lower ductility. This is also reflected in the much smaller Δ_{nmax} and E_n in A4075 as compared to any of the 7.9 mm thick straps. As expected, the $A_n F_u / A_g F_y$ ratio can be a good overall indicator on the ductility and energy dissipating capacity of the strap, but not a definitive one.

4.1.5 Influence of Connection Details

Three types of connection details were considered in the test program. Type A detail, having a A_n / A_g ratio of less than 1.0, was expected to be the least ductile. This is followed by Type B detail (clamped with an extra plate), which shifts the largest cumulative bending strain from the innermost bolt hole to a section close to the end of the reinforcement plate while the A_n / A_g ratio is still below 1.0. Type C detail will be the most ductile since the A_n / A_g ratio is 1.0. Tables 4.8 and 4.9 show the comparisons of the average normalized maximum extension and hysteretic energy for various connection details. Type A and B specimens that buckled away from the cable transducers, monotonic tests, and C4075a that has loading control problem have been excluded. All specimens in Tables 4.8 and 4.9 fractured in the test except for C8075 and C4078. It can be seen that the ductility and hysteretic energy improved from Type A to Type B connection detail. The improvement is especially great for A8075 specimen that has a

low normalized maximum extension. Further significant improvement in the ductility and hysteretic energy were achieved from Type B to Type C connection detail. The improvement in the ductility and hysteretic energy by switching from Type A to Type C connection detail increases with the slenderness ratio from x2078 ($KL/r = 200$) to x4078 ($KL/r = 400$). A similar comparison cannot be made for x4075 and x8075 specimens because tests for C8075 were stopped too prematurely due to the actuator stroke limit.

Based on the storey drift limit of 2.5% in NBCC 2005 (NRCC 2005), the ductility requirement for bracing at 45° angle is approximately equal to a normalized maximum extension (Δ_{nmax}) of 8.3 for a yield strength of 300 MPa, or a 1.25% strain in the brace. From Table 4.2, all Type C specimens achieved Δ_{nmax} greater than 30. This means that all Type C specimens will satisfy the ductility demand for a Seismic Force Resisting System. Although most of Type A and B specimens achieved Δ_{nmax} greater than 8.3, some specimens fractured much earlier. For Type A and B specimens, the ductility is greatly influenced by the $A_n F_u / A_g F_y$ ratio.

4.1.6 Effects of Slenderness Ratio

There are two ways to change the slenderness ratio of the strap. One is by changing the length and the other is by changing the thickness. In this study, the length of the specimen was changed to achieve the different slenderness ratio.

Comparisons of normalized maximum tension load and extension versus nominal

slenderness ratio are shown together with the trend lines for Type A specimens in Figs. 4.10 and 4.11, and for Type C specimens in Figs. 4.12 and 4.13. Figures 4.10 and 4.11 exclude data from specimens that buckled away from cable transducers and monotonic tests. Data from Cx075 series of specimens were also not included in Figs. 4.12 and 4.13 because some of the tests in that series were stopped too prematurely due to actuator stroke limit to make any comparison useful. Even though C4xx8 ($KL/r = 400$) specimens did not fracture during the test, they are included in the comparisons because the normalized maximum extension that can be applied was much higher than the normalized maximum extension achieved in the C2xx8 ($KL/r = 200$) specimens.

As shown in Figs. 4.10 and 4.12, the normalized maximum tension load (T_{nmax}) increases slightly with the slenderness ratio for both Type A and C specimens. This is probably due to the reduction in the compression load as the slenderness ratio increases, which in turn induces less plastic stress reversal in compression. The normalized maximum extension (Δ_{nmax}) was also found to increase with the slenderness ratio for Type C specimen. As can be seen in Fig. 4.13, Δ_{nmax} almost double as the nominal slenderness ratio increases from 200 to 400. However, this may be a little misleading because after $\delta=50\delta_y$, the loading range increment rate was changed from δ_y to $50\delta_y$. Nevertheless, there is a significant increase in the ductility. This increase can partly be attributed to the lower bending strain being generated with a higher slenderness ratio for the same applied normalized deformation. However, Δ_{nmax} is shown in Fig. 4.11 to decrease with the slenderness ratio for Type A specimens. Unlike Type C specimens, the

net section area for Type A specimens is less than the gross section area. Thus, any increase in the deformation will localize more at the bolt hole rather than being distributed evenly over the whole member. For the same normalized extension, a longer Type A specimen will experience a higher strain at the bolt hole than a shorter specimen. This is probably the reason why the normalized maximum extension of Type A specimens decreases as the slenderness ratio increases as the slenderness ratio increase was achieved through using a longer specimen. However, if the material properties and length are identical, it would be expected that the ductility will improve with a higher slenderness ratio by changing the thickness. Similar to the normalized maximum extension, Table 4.9 shows that the normalized hysteretic energy increases with the slenderness ratio in Type C specimens, but reduces in Type A specimens.

4.2 Guidelines and Recommendations on Using Strap Tension-only Brace in SFRS

Since objectives of the experimental study were only to investigate the behavior of high slenderness flat bar braces, and provide data for the validation of the finite element analysis models to be developed for the parametric study, only some basic guidelines and recommendations will be provided here. A more comprehensive guidelines and recommendations will be provided through the finite element analysis parametric study that is to be conducted separately.

For a Seismic Force Resisting System (SFRS), it is important that the member has the ability to go through a number of inelastic load reversal cycles without a significant loss of strength. In the test every specimen achieved a higher tension load with increase range of deformation until the last leg of the loading cycle before fracture occurred. This means that the strap tension-only brace will only require to meet the ductility requirement since there is no deterioration of tension strength.

In NBCC 2005 (NRCC 2005), a normal building is required to have a storey drift of less than 2.5% during an earthquake. This translates to a deformation of a 0.0125 strain for a brace at 45° , which is $\delta = 8.3\delta_y$ for $F_y = 300$ MPa or the normalized maximum extension $\Delta_{nmax} = 8.3$. The strap can be considered to have satisfied the ductility requirement if the Δ_{nmax} exceeds 8.3 under the ATC-40 loading protocol. The ductility demand is less if the brace is at an angle of inclination other than 45° .

Based on Δ_{nmax} from the tests, any brace with Type C connection detail and slenderness ratio of greater than 200 can be used safely in SFRS. Although not studied, it would be expected any reinforcement plate with the same grade and thickness as the strap that meets the edge and end distance limits for the bolted connection will satisfy the Type C detail requirement. With the significant excess ductility exhibited by the specimens at $KL/r = 200$, the ductility requirement can probably still be met at a much lower KL/r ratio. This limit will be established through the finite element analysis parametric study, which is outside the scope of this thesis. Conservatively, Eq. (2.1) by Tremblay et al. (2003) can be used to estimate the limit.

Unlike Type C specimens, the ductility of Type A and B specimens are dependent on the member length, A_nF_u/A_gF_y and slenderness ratios. The calculated A_nF_u/A_gF_y ratio at various strain rates is shown in Table 4.3. Three of the flat bar specimen groups have the static A_nF_u/A_gF_y ratio greater than 1.2 achieved the required ductility, while the one specimen group with the static A_nF_u/A_gF_y ratio close to 1.0 only managed to achieve limited ductility. Two of the flat bar specimen groups sized with the expected A_nF_u/A_gF_y ratio greater than 1, as shown in Table 3.3, also achieved the required ductility. However, the performance of the specimen groups that satisfied the ductility requirement still need to be investigated for a longer length. There are insufficient test data to provide any definitive guideline and recommendation for a brace designed with the Type B or C detail. It is possible that the ductility requirement can be met if the brace is designed with the A_nF_u/A_gF_y ratio greater than 1.2 or the expected A_nF_u/A_gF_y ratio greater than 1. The actual A_nF_u/A_gF_y provided can be checked using the mill certificate of the strap.

From the material tests in the experimental study, the yield strength of five flat bars at the strain rate $0.5s^{-1}$ was found to exceed the expected yield strength of 385 MPa prescribed in CSA-S16-01 (CSA 2005) for the design. There was only one flat bar that has a yield strength close to 385 MPa at the $0.5s^{-1}$ strain rate. Thus, a higher expected yield strength may have to be used in the design if a strain rate of close to or greater than $0.5s^{-1}$ can be expected during an earthquake.

Table 4.1 Test results.

Specimen no.	Max. tension load, $T_{\max}$, (kN)	Max. extension, $\Delta_{\max}$, (mm)	Hysteretic energy, E_h , (kJ)	Last loading cycle		Fracture location	Direction of buckling ¹
				Half cycle no.	$\frac{\delta}{\delta_y}$		
A8075a	120	11.31	2.36	47	5	Top ²	+
A8075b	114	9.36	1.79	43	4	Top ²	+
A6075a	118	7.52	1.31	43	4	Top ²	+
A6075b	116	8.30	1.63	47	5	Top ²	+
A4075a	116	9.14	2.21	55	7	Top ²	+
A4075b	117	6.74	1.50	51	6	Top ²	+
A4075c	117	10.60	2.65	57	7	Top ²	+/- ³
A4078a	247	37.83	23.5	91	16	Top ²	+
A4078b	240	34.09	20.4	87	15	Top ²	+
A2078a	231	23.95	26.1	107	20	Top ²	+
A2078b	231	26.48	30.1	115	22	Top ²	+
A2078c	240	28.96	41.9	117	22	Top ²	+
A2078d	246	29.47	5.66	NA	NA	Top ²	NA
A2078e	245	20.32	4.46	NA	NA	Top ²	NA
A4108a	350	42.48	34.4	99	18	Top ²	+
A4108b	357	46.84	41.2	107	20	Top ²	+
A2108a	331	28.00	45.2	125	24	Top ²	+
A2108b	337	29.13	47.7	127	25	Top ²	+
A4128a	372	54.87	54.1	119	23	Top ²	- ⁴
A4128b	376	53.19	53.7	119	23	Top ²	+
A2128a	358	32.82	65.3	139	28	Top ²	+
A2128b	355	34.62	67.9	143	29	Top ²	+
A2128c	359	48.90	151.4	195	42	Top ⁵	+/- ³
A2128d	349	32.17	59.5	137	27	Top ²	+
A2128e	402	42.26	14.6	NA	NA	Bottom ²	NA
A2128f	394	43.26	14.3	NA	NA	Top ²	NA

Table 4.1 Continue.

Specimen no.	Max. tension load, $T_{\max}$, (kN)	Max. extension, $\Delta_{\max}$, (mm)	Hysteretic energy, E_h , (kJ)	Last loading cycle		Fracture location	Direction of buckling ¹
				Half cycle no.	$\frac{\delta}{\delta_y}$		
B8075a	127	20.11	4.50	55	7	Top ²	+
B8075b	127	36.45	10.3	75	12	Top ²	+
B2078a	264	32.77	52.4	139	28	Top ²	+
B2078b	256	31.20	47.1	133	26	Top ²	+
B2128a	382	55.65	178.4	215	47	Middle	+
B2128b	391	55.44	180.5	213	46	Middle	+
B2128c	385	58.48	187.4	223	49	Top ²	- ⁶
B2128d	375	49.59	160.5	199	43	Middle	- ⁷
C8075a	157	219.13	304.9	299	65	NA	+ ⁸
C8075b	152	219.64	309.1	299	65	NA	+ ⁸
C6075a	163	228.90	191.4	262	90	NA	+/- ⁹
C6075b	159	228.63	303.6	318	90 ¹⁰	NA	+/- ⁹
C4075a	158	145.09	165.5	262	90 ¹¹	NA	+/- ¹²
C4075b	160	166.68	145.6	271	105	Middle	+/- ¹³
C4078a	333	203.01	416.1	307	75	NA	+/- ¹⁴
C4078b	332	199.60	418.2	307	75	NA	+/- ¹⁴
C4108a	444	192.22	501.6	307	75	NA	+/- ¹⁵
C4108b	446	197.12	473.9	307	75	NA	+/- ¹⁴
C2078a	284	48.23	111.0	191	41	Top ¹⁶	+
C2078b	285	54.32	131.0	209	45	Bottom ¹⁶	+
C2108a	385	55.00	166.0	209	45	Middle	+/- ¹⁷
C2108b	380	44.98	121.9	181	38	Top ¹⁸	+
C2108c	381	45.43	121.0	181	38	Top ¹⁸	+

Notes:

- ¹ The following sign convention on the buckling direction is adopted; (+) sign means buckling towards cable transducers, (-) sign means buckling away from cable transducers and (+/-) sign represents back and forth buckling.
- ² Fractured at the third bolt hole from the end.
- ³ Forced to buckle away from cable transducers by using a rod. Despite using the regular rod as shown in Fig. 4.1, the specimen continued with back and forth buckling.

A wide rod as shown in Fig. 4.2 subsequently was used to force buckling away from cable transducers.

- ⁴ Buckled away from cable transducers in the first few cycles at the beginning, but it was later forced to buckle towards cable transducers by using a rod as shown in Fig. 4.1.
- ⁵ Fractured at a section close to the end of top gusset plate.
- ⁶ Buckled towards cable transducers at the beginning. However, it switched to buckling away from the cable transducers after that up to the end of the test.
- ⁷ Forced to buckle away from cable transducers by using a rod.
- ⁸ Forced to buckle towards cable transducers by using a very wide rod as shown in Figure 4.3.
- ⁹ Buckled towards cable transducers for most part of the test, but the buckling switched back and forth at the late stages even with using a wide rod.
- ¹⁰ Only two cycles were carried out at $\delta=90\delta_y$. It was subsequently reprogrammed to 30 cycles at $\delta=90\delta_y$ for C6075b.
- ¹¹ There was a problem with the control during the test. The actuator could not extent beyond around 140 mm.
- ¹² Buckled towards cable transducers at the beginning, but switched away from the cable transducers as the test progressed. Subsequently, a wide rod was used to force buckling to occur towards the cable transducers. Despite using the rod, the specimen still buckled back and forth at the late stages of the test.
- ¹³ Buckled towards cable transducers for most part of the test, but buckled away at late stages even by using a wide rod.
- ¹⁴ Forced to buckle towards cable transducers by using a very wide rod. Despite using the rod, the specimen buckled back and forth at late stages of the test.
- ¹⁵ Forced to buckle towards cable transducers by using a wide rod. Despite using the rod, the specimen buckled back and forth at late stages of the test.
- ¹⁶ Fractured at 5 mm away from the end of the reinforcement plate.
- ¹⁷ Forced to buckle away from cable transducers by using a wide rod. Despite using the rod, the specimen buckled back and forth at late stages of the test even by changing

the position of the rod.

- ¹⁸ Fractured at 10 mm away from the end of the reinforcement plate.

Table 4.2 Normalized test results.

Specimen no.	Max. tension load, $T_{\max}$, (kN)	Max. extension, $\Delta_{\max}$, (mm)	Normalized max. tension load, $T_{n\max}$	Normalized max. extension, $\Delta_{n\max}$	Normalized hysteretic energy, E_n
A8075a	120	11.31	1.10	3.35	6.51
A8075b	114	9.36	1.05	2.77	4.91
A6075a	118	7.52	1.08	2.97	4.71
A6075b	116	8.30	1.07	3.28	5.81
A4075a	116	9.14	1.06	5.40	11.8
A4075b	117	6.74	1.07	3.98	8.07
A4075c	117	10.60	1.07	6.25	14.6
A4078a	247	37.83	1.29	13.18	42.7
A4078b	240	34.09	1.25	11.88	37.1
A2078a	231	23.95	1.21	16.79	95.9
A2078b	231	26.48	1.21	18.57	110
A2078c	240	28.96	1.26	20.30	154
A2078d	246	29.47	1.28	20.62	20.8
A2078e	245	20.32	1.28	14.24	16.5
A4108a	350	42.48	1.25	13.47	39.0
A4108b	357	46.84	1.28	14.85	46.7
A2108a	331	28.00	1.19	17.85	103
A2108b	337	29.13	1.20	18.58	109
A4128a	372	54.87	1.14	18.82	57.1
A4128b	376	53.19	1.15	18.24	56.5
A2128a	358	32.82	1.11	22.67	140
A2128b	355	34.62	1.11	23.90	146
A2128c	359	48.90	1.11	33.78	324
A2128d	349	32.17	1.09	22.20	128
A2128e	402	42.26	1.23	29.19	30.9
A2128f	394	43.26	1.23	29.82	30.8

Table 4.2 Continue.

Specimen no.	Max. tension load, $T_{\max}$, (kN)	Max. extension, $\Delta_{\max}$, (mm)	Normalized max. tension load, $T_{n\max}$	Normalized max. extension, $\Delta_{n\max}$	Normalized hysteretic energy, E_n
B8075a	127	20.11	1.17	5.96	12.3
B8075b	127	36.45	1.17	10.79	28.0
B2078a	264	32.77	1.38	22.96	192
B2078b	256	31.20	1.34	21.88	173
B2128a	382	55.65	1.18	38.40	380
B2128b	391	55.44	1.21	38.32	387
B2128c	385	58.48	1.20	40.31	403
B2128d	375	49.59	1.16	34.18	342
C8075a	157	219.13	1.44	64.92	830
C8075b	152	219.64	1.40	65.07	846
C6075a	163	228.90	1.47	90.62	685
C6075b	159	228.63	1.45	90.51	1097
C4075a	158	145.09	1.45	85.71	894
C4075b	160	166.68	1.46	98.47	785
C4078a	333	203.01	1.74	70.77	758
C4078b	332	199.60	1.73	69.62	762
C4108a	444	192.22	1.59	60.98	570
C4108b	446	197.12	1.60	62.50	539
C2078a	284	48.23	1.47	33.94	404
C2078b	285	54.32	1.48	38.14	477
C2108a	385	55.00	1.38	35.11	380
C2108b	380	44.98	1.36	28.68	279
C2108c	381	45.43	1.37	29.00	277

Table 4.3 Ratios of average cross-section area and tension capacity for Type A and B specimens.

Strap	A_g	A_n	$\frac{A_n}{A_g}$	$\frac{A_n F_u}{A_g F_y}$			
				Strain rate (s^{-1})			
				Static	Dynamic		
				0.0001	0.0001	0.01	0.5
76 mm x 4.8 mm	354.4	250.5	0.71	1.01	1.02	0.94	0.89
76 mm x 7.9 mm	602.0	425.5	0.71	1.23	1.20	1.14	1.12
102 mm x 7.9 mm	802.3	628.3	0.78	1.26	1.22	1.18	1.16
127 mm x 7.9 mm	983.0	810.6	0.83	1.24	1.25	1.12	1.12

Table 4.4 Horizontal deflection.

Specimen	Cycle range, $\frac{\delta}{\delta_y}$	Maximum lateral deflection				Ratio		
		Deflection, a (mm)				Eq.(4.6)	Eq.(4.7)	Eq.(4.8)
		Actual	Eq.(4.6)	Eq.(4.7)	Eq.(4.8)	Actual	Actual	Actual
A2078a	4	47.27	41.47	52.15	47.96	0.88	1.10	1.01
	11	90.91	70.28	95.00	92.20	0.77	1.05	1.01
	18	122.13	89.78	124.91	122.65	0.74	1.02	1.00
C2078a	4	45.45	38.13	50.26	47.68	0.84	1.11	1.05
	22	125.76	94.13	132.43	130.37	0.75	1.05	1.04
	38	173.35	125.21	180.13	178.37	0.72	1.04	1.03
A8075a	1	45.16	49.38	65.05	46.48	1.09	1.44	1.03
	2	80.29	72.67	98.71	81.10	0.91	1.23	1.01
	4	132.91	106.13	146.95	134.93	0.80	1.11	1.02
C8075a	4	124.00	104.73	145.15	132.96	0.84	1.17	1.07
	12	240.19	186.45	263.50	256.80	0.78	1.10	1.07
	20	332.33	240.44	342.71	337.23	0.72	1.03	1.01
A6075a	1	34.79	37.02	48.89	37.94	1.06	1.41	1.09
	2	59.58	56.23	74.45	62.61	0.94	1.25	1.05
	3	80.97	69.50	94.20	84.79	0.86	1.16	1.05
A4075a	1	21.53	24.67	31.98	25.14	1.15	1.49	1.17
	3	52.03	45.89	60.82	54.86	0.88	1.17	1.05
	6	88.18	65.88	90.89	87.79	0.75	1.03	1.00
A4128b	4	94.75	86.99	108.47	99.31	0.92	1.14	1.05
	12	198.51	151.38	207.01	201.29	0.76	1.04	1.01
	21	271.17	200.80	280.60	275.94	0.74	1.03	1.02

Table 4.5 Monotonic tests.

Specimen	Maximum dynamic load, kN	Maximum static load, kN	$A_n F_u$, kN			
			Strain rate (s^{-1})			
			Static	Dynamic		
			0.0001	0.0001	0.01	0.5
A2078d	246	240	235	244	249	262
A2078e	245	238	237	246	251	264
A2128e	402	392	406	425	430	454
A2128f	394	382	398	416	421	445

Table 4.6 Comparison of monotonic and cyclic tests.

Specimen	Average maximum tension load (non-static), $T_{\max}$			Average maximum extension, $\Delta_{\max}$		
	Cyclic (kN)	Monotonic (kN)	Cyclic/Monotonic ratio	Cyclic (mm)	Monotonic (mm)	Cyclic/Monotonic ratio
A2078	234	245	0.95	26.46	24.89	1.06
A2128 (exclude A2128c)	354	398	0.89	33.20	42.76	0.78

Table 4.7 Average normalized maximum extension and hysteretic energy for Type A specimens.

Specimen	$\frac{A_n}{A_g}$	$\frac{A_n F_u}{A_g F_y}$		Average Δ_{nmax}	Average E_n
		Strain rate (s ⁻¹)			
		Static	0.0001		
A2078	0.71	1.23	1.20	18.55	119.97
A2108	0.78	1.26	1.22	18.22	106.00
A2128	0.83	1.24	1.25	22.92	138.00
A4075	0.71	1.01	1.02	4.69	9.94
A4078	0.71	1.23	1.20	12.53	39.90
A4108	0.78	1.26	1.22	14.16	42.85
A4128	0.83	1.24	1.25	18.24	56.50

Table 4.8 Comparison of average normalized maximum extension for various connection details.

Specimen	Average normalized maximum extension , Δ_{nmax}				
	Connection Type				
	A	B		C	
	Δ_{nmax} (a)	Δ_{nmax} (b)	Ratio (b)/(a)	Δ_{nmax} (c)	Ratio (c)/(a)
x8075	3.06	8.38	2.74	65.00	21.24
x4075	4.69	-	-	98.47	21.00
x4078	12.53	-	-	70.19	5.60
x2078	18.55	22.42	1.21	36.04	1.94
x2108	18.22	-	-	30.93	1.70
x2128	22.92	38.36	1.67	-	-

Table 4.9 Comparison of average normalized hysteretic energy for various connection details.

Specimen	Average normalized hysteretic energy , E_n				
	Connection Type				
	A	B		C	
	E_n (a)	E_n (b)	Ratio (b)/(a)	E_n (c)	Ratio (c)/(a)
x8075	5.71	20.15	3.53	838.00	146.76
x4075	9.94	-	-	785.00	78.97
x4078	39.90	-	-	760.00	19.05
x2078	119.97	182.50	1.52	440.50	3.67
x2108	106.00	-	-	312.00	2.94
x2128	138.00	383.50	2.78	-	-

Figure 4.1 Test with a regular rod.

Figure 4.2 Test with a wide rod.

Figure 4.3 Test with a very wide rod.

Innermost bolt hole, A2128a.

Close to the end of gusset plate, A2128c.

Figure 4.4 Fracture for Type A specimens.

C2078a

C2108a

Figure 4.5 Fracture of C2078a and C2108a.

Figure 4.6 Out-of-plane deformation for fixed end elastic buckling.

Figure 4.7 Out-of-plane deformation for pinned end elastic buckling.

Figure 4.8 Comparison of A2078c (cyclic) and A2078e (monotonic).

Figure 4.9 Comparison of A2128b (cyclic) and A2128e (monotonic).

Figure 4.10 Normalized maximum tension load versus slenderness ratio for Type A specimens.

Figure 4.11 Normalized maximum extension versus slenderness ratio for Type A specimens.

Figure 4.12 Normalized maximum tension load versus slenderness ratio for Type C specimens.

Figure 4.13 Normalized maximum extension versus slenderness ratio for Type C specimens.

CHAPTER 5 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary

A brief review on bracing research and seismic design requirements was presented in Chapter 2. Some previous experimental and numerical studies were discussed. In these studies, slenderness ratio has been found to be one of the main factors that greatly affect the hysteretic behaviour of the bracing member. Most cyclic tests carried out have focused mainly on structural shapes with the slenderness ratio less than 200. Tests on specimens with the slenderness ratio greater than 200 have mostly been limited to tie-rods and thin cold-formed steel straps. Thus, this experimental study was carried out to study the performance of slender flat bar braces at the slenderness ratio between 200 and 800.

Forty nine hot-rolled flat bar specimens were tested in this experimental study. All specimens were tested under cyclic loading except for four, which were tested under monotonic tension loading. Four cross-section sizes of flat bar were used. Three connection types, four slenderness and three net to gross section area ratios were considered for the tests. Tension coupon tests have been carried out to obtain material properties of the flat bars. Yield and ultimate strengths at static and three strain rates were obtained.

Test results were analyzed and discussed. Effects of connection detail, slenderness

ratio, net to gross section area ratio, net section fracture to the gross section yielding strength ratio, dissipated energy, load-deformation relationship, location of fracture, and ductility were discussed. Comparisons of results from monotonic and cyclic tests were made. In order to have a better comparison on test results of specimens with different material and length, the normalized energy, maximum tension force and maximum extension were also calculated. Equations were developed to predict the out-of-plane deflection and validated with the measured test data. Based on the test results, some preliminary recommendations and guidelines were proposed on using a strap tension-only bracing system in a seismic design with flat bars.

5.2 Conclusions

A number of conclusions can be drawn from the results of the experiment.

- 1) In the test, every specimen achieved a higher tension load with increasing range of deformation until the last leg of the loading cycle before fracture occurred. This means that the largest extension attained in the test can be considered as the useful ductility of the brace.
- 2) All except one specimens with no reinforcement fractured at the innermost bolt hole. By clamping a reinforcement plate at the connection, the ductility of the brace improved over the one without any reinforcement by shifting the location of the largest bending strain away from the innermost bolt hole to the end of the

reinforcement plate. A larger ductility improvement proportionally was observed for the specimen without any reinforcement that has a low ductility.

- 3) The net section fracture to gross section yielding strength (A_nF_u/A_gF_y) ratio is a good indicator of the ductility of the brace with no reinforcement, but not a definitive one. The net to gross section area ratio and the shape of the material stress-strain curve may also have some influence on the ductility. In general, the higher the (A_nF_u/A_gF_y) ratio is above 1, the greater will the ductility be.
- 4) All specimens welded with the reinforcement plate achieved a very high ductility. Braces with the welded reinforcement plate and slenderness ratio $KL/r \geq 200$ can meet the ductility demand required for NBCC 2005 draft limit.
- 5) Equations have been developed to predict the out-of-plane deflection of the brace. In most cases, the predicted deflection is within 10% of the measured deflection. The accuracy of the prediction generally improves at a larger plastic deformation.
- 6) When changing the slenderness ratio by changing the length, the ductility of the brace with welded reinforcement plate increases with the slenderness ratio while the reverse holds for the brace without reinforcement. Both the length and slenderness ratio are important factors on the ductility of the brace with no reinforcement.
- 7) A brace with no reinforcement can meet the ductility demand, if a certain A_nF_u/A_gF_y ratio is maintained. In the test, specimens sized with the expected A_nF_u/A_gF_y ratio greater than 1 or specimens with the actual static A_nF_u/A_gF_y ratio

greater than 1.2 managed to achieve the required ductility. However, the performance of these specimens still needs to be investigated for a longer length. There is insufficient test data to make any definitive recommendation in the design of a brace with no reinforcement.

5.3 Recommendations

- 1) The testing program was designed to investigate effects of the net section fracture to gross section yielding strength ratio ($A_n F_u / A_g F_y$) through changing the net to gross section area ratio. Due to the difference in the material properties, the $A_n F_u / A_g F_y$ ratio turned out to be almost the same for three of the flat bar cross-section sizes. A proper variation of $A_n F_u / A_g F_y$ ratio can be achieved if the straps are cut from a single plate.
- 2) From the material tests, the ultimate to yield strength ratio was found to decrease with the increase in the strain (loading) rate. Current tests did not consider effects of loading rate on the performance. Tests should be carried out at various constant strain rates to study effects of the loading rate.
- 3) The ductility of the brace without reinforcement is greatly affected by the $A_n F_u / A_g F_y$ ratio and to some extent its length. A finite element analysis parametric study should be carried out to supplement any additional test in establishing the ductility of the brace without reinforcement for various

combinations of member length, slenderness ratio, A_n/A_g ratio, and A_nF_u/A_gF_y ratio.

- 4) Current tests considered only fixed end condition. In an actual structure, the end may not be completely fixed. Other end conditions between pinned and fixed should be investigated.
- 5) Results of current tests are appropriate for a diagonal bracing system. In a structure, a cross bracing system may be employed. The performance of the flat bar brace in a cross bracing configuration should be investigated.
- 6) The brace was tested individually in this study. Additional experimental and numerical studies should be carried out to investigate the performance of the brace in a frame under cyclic loading including shaketable tests.

REFERENCES

1. AISC. 1997. Seismic Provisions for Structural Steel Buildings. American Institute of Steel Construction, (AISC), Chicago, Illinois.
2. AISC. 2005. ANSI /AISC 341-05, Seismic Provisions for Structural Steel Buildings. American Institute of Steel Construction, (AISC), Chicago, Illinois.
3. Al-Kharat, M., and Rogers, C.A. 2007. Inelastic Performance of Cold-Formed Steel Strap Braced Walls. *Journal of Construction Steel Research*, 63(4): 460-474.
4. Al-Kharat, M., and Rogers, C.A. 2008. Inelastic Performance of Screw Connected Cold-Formed Steel Strap Braced Walls. *Canadian Journal of Civil Engineering*, 35(1): 11-26.
5. Astaneh-Asl, A., A.M., Goel, S.C. and Hanson, R.D. 1985. Cyclic Out-of-Plane Buckling of Double-Angle Bracing. *Journal of the Structural Engineering, ASCE*, 111(5): 1135-1153.
6. ATC. 1992. ATC-24, Guidelines for Cyclic Seismic Testing of Components of Steel Structures. Applied Technology Council (ATC), California.
7. CSA. 2005. Limit States Design of Steel Structures, CAN/CSA-S16-01. Including Supplement S16-05. Canadian Standards Association, Toronto, On, Canada.
8. Davaran, A. 2001. Effective Length Factor for Discontinuous X-Bracing Systems. *Journal of Engineering Mechanics*, 127(2): 106-112.

9. DeWolf J.T. and Pelliccione, J.F. 1979. Cross-bracing Design. *Journal of the Structural Division, ASCE*, 105(7): 1379-1391.
10. El-Tayem, A.A. and Geol, S.C. 1986. Effective Length Factor for the Design of X-bracing Systems. *Engineering Journal, AISC*, 23(1): 41-45.
11. Filiatrault, A. and Tremblay, R. 1996. Behavior of Tension-only Concentrically Braced Steel Frames under Simulated Earthquake Loads. *Proceedings of International Conference on Advances in Steel Structures*, Vol. II: 1047-1052.
12. Filiatrault, A. and Tremblay, R. 1998. Design of Tension-only Concentrically Braced Steel Frames for Seismic Induced Impact Loading. *Engineering Structures*, 20(12): 1087-1096.
13. Goggings, J.M., Broderick, B.M., Elghazouli, A.Y. and Lucas, A.S. 2005. Experimental Cyclic Response of Cold-formed Hollow Steel Bracing Members. *Engineering Structures*, 27(6): 977-989.
14. Higginbotham, A.B. and Hanson, R.D. 1976. Axial Hysteretic Behavior of Steel Members. *Journal of the Structural Division, ASCE*, 102(7): 1365-1381.
15. Jain, A.K., Geol, S.C. and Hanson, R.D. 1978. Inelastic Response of Restrained Steel Tubes. *Journal of the Structural Division, ASCE*, 104(6): 897-910.
16. Kahn, L.F. and Hanson, R.D. 1976. Inelastic Cycles of Axially Loaded Steel Members. *Journal of the Structural Division, ASCE*, 102(5): 947-959.

17. Kim, T.W., Wilcoski, J., Foutch, D.A. and Lee, M.S. 2006. Shakedown Tests of a Cold-formed Steel Shear Panel. *Journal of the Structural Engineering, ASCE*, 28(10): 1462-1470.
18. NRCC. 2005. National Building Code of Canada 2005. National Research Council of Canada, Ottawa, Ontario.
19. Picard, A. and Beaulieu, D. 1987. Design of Diagonal Cross Bracings. Part1: Theoretical Study. *Engineering Journal, AISC*, 24(3): 122–126.
20. Popov, E.P. and Black, R.G. 1981. Steel Struts Under Severe Cyclic Loadings. *Journal of the Structural Division, ASCE*, 107(9): 1857-1881.
21. Prathuangsit, D., Geol, S.C. and Hanson, R.D. 1978. Axial Hysteresis Behavior with End Restraints. *Journal of the Structural Division, ASCE*, 104(6): 883-896.
22. Sabelli, R. and Hohbach, D. 1999. Design of Cross-braced Frames for Predictable Buckling Behavior. *Journal of the Structural Engineering, ASCE*, 125(2): 163-168.
23. Shaback, B. and Brown, T. 2003. Behavior of Square Hollow Structural Steel Braces with End Connections Under Reversed Cyclic Axial Loading. *Canadian Journal of Civil Engineering*, 30(4): 745-753.
24. SSPC (2004). Surface Preparation Specifications No. 1, 2, and 3. Steel Structures Painting Council (SSPC), the Society for Protective Coatings, Pittsburgh, PA, U.S.A.

25. Tremblay, R. 2000. Influence of Brace Slenderness on the Seismic Response of Concentrically Braced Steel Frames. Behavior of Steel Structures in Seismic Areas. Proceedings of the Third STESSA Conference 2000, Montreal: 527-534.
26. Tremblay, R. 2001. Seismic Behavior and Design of Concentrically Braced Steel Frames. Engineering Journal. AISC, 38(3): 148-166.
27. Tremblay, R. 2002. Inelastic Seismic Response of Steel Bracing Members. Journal of Construction Steel Research, 58(5-8): 665-701.
28. Tremblay, R., Archambault, M.H., and Filiatrault, A. 2003. Seismic Response of Concentrically Braced Steel Frames Made with Rectangular Hollow Bracing Members. Journal of the Structural Engineering, ASCE, 129(12): 1626-1636.
29. Tremblay, R., Robert, N., and Filiatrault A. 1997. Tension-only Bracing: A Viable Earthquake Resistant System for Low-rise Steel Buildings. SDSS'97, Proceedings of 5th International Colloquium on Stability and Ductility of Steel Structures, Vol.II: 1163-1170.

APPENDIX A: MATERIAL PROPERTIES

Table A.1 Material ductility and elastic modulus.

Coupon	Strain rate (s ⁻¹)	Elongation (%)		$\frac{A_o}{A_f}$		Elastic modulus, E (MPa)	
			Avg.		Avg.		Avg.
76 mm x 4.8 mm (3" x 3/16")							
A1	0.0001	34.4	34.7	2.68	2.71	208419	210700
A2		35.0		2.74		205296	
A3	0.01	31.3	31.9	2.47	2.52	216061	
A4		32.5		2.56		215558	
A5	0.5	37.0	38.1	2.53	2.55	210745	
A6		39.2		2.57		208094	
76 mm x 7.9 mm (3" x 5/16")							
B1	0.0001	29.5	28.5	2.37	2.33	195251	205100
B2		27.4		2.28		198837	
B3	0.01	28.7	29.2	2.45	2.46	204741	
B4		29.7		2.46		204491	
B5	0.5	27.4	28.1	2.43	2.41	217878	
B6		28.7		2.38		209507	
102 mm x 7.9 mm (4" x 5/16")							
C1	0.0001	32.5	31.9	2.28	2.44	200978	204200
C2		31.3		2.60		197924	
C3	0.01	30.1	30.7	2.57	2.54	210597	
C4		31.3		2.51		209591	
C5	0.5	30.5	30.7	2.44	2.44	214087	
C6		30.9		2.43		192092	
127 mm x 7.9 mm (5" x 5/16")							
D1	0.0001	34.1	33.5	2.66	2.59	194090	208300
D2		32.9		2.52		200428	
D3	0.01	31.5	31.2	2.54	2.50	218418	
D4		30.9		2.46		215221	
D5	0.5	33.7	34.1	2.55	2.54	215030	
D6		34.4		2.52		206519	

Table A.1 Continue.

Coupon	Strain rate (s ⁻¹)	Elongation (%)		$\frac{A_o}{A_f}$		Elastic modulus, E (MPa)	
			Avg.		Avg.		Avg.
64 mm x 4.8 mm (2-1/2 " x 3/16")							
E1	0.0001	29.1	28.6	2.25	2.23	217161	212700
E2		28.1		2.21		227968	
E3	0.01	30.9	30.9	2.43	2.43	206694	
E4		30.9		2.43		203004	
E5	0.5	32.9	32.3	2.42	2.41	212600	
E6		31.7		2.40		208579	
64 mm x 7.9 mm (2-1/2 " x 5/16")							
F1	0.0001	33.7	33.5	2.37	2.36	212320	213400
F2		33.3		2.35		212786	
F3	0.01	33.5	33.0	2.42	2.38	216834	
F4		32.5		2.34		215605	
F5	0.5	35.4	34.5	2.34	2.35	212677	
F6		33.5		2.36		210189	

Table A.2 Material yield and ultimate strengths at various loading rates.

Coupon	Strain rate (s ⁻¹)	Yield strength, F _y (MPa)		Ultimate strength, F _u (MPa)		$\frac{F_u}{F_y}$	$\frac{F_Y}{F_y(\text{static})}$
			Avg.		Avg.	Avg.	Avg.
76 mm x 4.8 mm (3" x 3/16")							
A1	Static (0.0001)	308.4	308.0	437.9	440.9	1.43	1
A2		307.6		443.8			
A1	0.0001	326.5	326.1	464.4	466.6	1.43	1.06
A2		325.6		468.7			
A3	0.01	359.9	356.8	473.1	472.3	1.32	1.16
A4		353.6		471.5			
A5	0.5	385.7	387.2	486.8	489.1	1.26	1.26
A6		388.7		491.3			
76 mm x 7.9 mm (3" x 5/16")							
B1	Static (0.0001)	316.8	318.2	551.8	553.8	1.74	1
B2		319.6		555.7			
B1	0.0001	342.5	342.6	576.0	577.6	1.69	1.08
B2		342.7		579.1			
B3	0.01	372.8	369.3	590.7	589.7	1.60	1.16
B4		365.7		588.7			
B5	0.5	401.2	394.3	619.6	619.7	1.57	1.24
B6		387.3		619.7			
102 mm x 7.9 mm (4" x 5/16")							
C1	Static (0.0001)	353.1	348.1	567.8	562.1	1.61	1
C2		343.1		556.3			
C1	0.0001	379.8	375.1	590.3	586.3	1.56	1.08
C2		370.4		582.3			
C3	0.01	396.5	394.8	596.3	596.9	1.51	1.13
C4		393.0		597.4			
C5	0.5	431.1	422.6	629.0	628.0	1.49	1.21
C6		414.0		626.9			

Table A.2 Continue.

Coupon	Strain rate (s ⁻¹)	Yield strength, F _y (MPa)		Ultimate strength, F _u (MPa)		$\frac{F_u}{F_y}$	$\frac{F_y}{F_y(\text{static})}$
			Avg.		Avg.	Avg.	Avg.
127 mm x 7.9 mm (5" x 5/16")							
D1	Static (0.0001)	329.6	328.5	493.0	494.2	1.50	1
D2		327.4		495.4			
D1	0.0001	346.3	345.9	518.1	518.4	1.50	1.05
D2		345.4		518.6			
D3	0.01	358.7	361.7	522.7	524.2	1.45	1.10
D4		364.7		525.7			
D5	0.5	411.3	408.7	553.5	552.8	1.35	1.24
D6		406.1		552			
64 mm x 4.8 mm (2-1/2" x 3/16")							
E1	Static (0.0001)	339.4	337.6	492.4	490.7	1.45	1
E2		335.7		488.9			
E1	0.0001	351.3	351.5	514.4	515.8	1.47	1.04
E2		351.7		517.1			
E3	0.01	371.7	373.5	521.3	521.6	1.40	1.11
E4		375.2		521.8			
E5	0.5	417.8	418.2	546.9	547.9	1.31	1.24
E6		418.5		548.9			
64 mm x 7.9 mm (2-1/2" x 5/16")							
F1	Static (0.0001)	323.6	325.2	496.1	497.4	1.53	1
F2		326.8		498.6			
F1	0.0001	337.6	339.9	517.0	518.6	1.53	1.05
F2		342.2		520.2			
F3	0.01	364.6	363.2	527.2	527.8	1.45	1.12
F4		361.7		528.3			
F5	0.5	407.4	407.3	554.2	555.3	1.36	1.25
F6		407.2		556.4			

Table A.3 Average specimen strength for various loading rates.

Strap	Strain rate (s ⁻¹)	Average A _g F _y (kN)	Average A _g F _u (kN)	Average A _n F _u (kN)
76 mm x 4.8 mm	Static (0.0001)	109	156	110
	0.0001	115	165	117
	0.01	126	167	118
	0.5	137	173	122
76 mm x 7.9 mm	Static (0.0001)	192	333	235
	0.0001	206	348	245
	0.01	222	355	251
	0.5	237	373	263
102 mm x 7.9 mm	Static (0.0001)	279	451	353
	0.0001	301	470	368
	0.01	317	479	375
	0.5	339	504	394
127 mm x 7.9 mm	Static (0.0001)	323	486	401
	0.0001	340	510	420
	0.01	356	515	425
	0.5	402	543	448

APPENDIX B: LOAD VERSUS DEFORMATION CURVES

Figure B.1 Axial load versus axial deformation for A8075a specimen.

Figure B.2 Axial load versus axial deformation for A8075b specimen.

Figure B.3 Axial load versus axial deformation for A6075a specimen.

Figure B.4 Axial load versus axial deformation for A6075b specimen.

Figure B.5 Axial load versus axial deformation for A4075a specimen.

Figure B.6 Axial load versus axial deformation for A4075b specimen.

Figure B.7 Axial load versus axial deformation for A4075c specimen.

Figure B.8 Axial load versus axial deformation for A4078a specimen.

Figure B.9 Axial load versus axial deformation for A4078b specimen.

Figure B.10 Axial load versus axial deformation for A2078a specimen.

Figure B.11 Axial load versus axial deformation for A2078b specimen.

Figure B.12 Axial load versus axial deformation for A2078c specimen.

Figure B.13 Axial load versus axial deformation for A2078d specimen.

Figure B.14 Axial load versus axial deformation for A2078e specimen.

Figure B.15 Axial load versus axial deformation for A4108a specimen.

Figure B.16 Axial load versus axial deformation for A4108b specimen.

Figure B.17 Axial load versus axial deformation for A2108a specimen.

Figure B.18 Axial load versus axial deformation for A2108b specimen.

Figure B.19 Axial load versus axial deformation for A4128a specimen.

Figure B.20 Axial load versus axial deformation for A4128b specimen.

Figure B.21 Axial load versus axial deformation for A2128a specimen.

Figure B.22 Axial load versus axial deformation for A2128b specimen.

Figure B.23 Axial load versus axial deformation for A2128c specimen.

Figure B.24 Axial load versus axial deformation for A2128d specimen.

Figure B.25 Axial load versus axial deformation for A2128e specimen.

Figure B.26 Axial load versus axial deformation for A2128f specimen.

Figure B.27 Axial load versus axial deformation for B8075a specimen.

Figure B.28 Axial load versus axial deformation for B8075b specimen.

Figure B.29 Axial load versus axial deformation for B2078a specimen.

Figure B.30 Axial load versus axial deformation for B2078b specimen.

Figure B.31 Axial load versus axial deformation for B2128a specimen.

Figure B.32 Axial load versus axial deformation for B2128b specimen.

Figure B.33 Axial load versus axial deformation for B2128c specimen.

Figure B.34 Axial load versus axial deformation for B2128d specimen.

Figure B.35 Axial load versus axial deformation for C8075a specimen.

Figure B.36 Axial load versus axial deformation for C8075b specimen.

Figure B.37 Axial load versus axial deformation for C6075a specimen.

Figure B.38 Axial load versus axial deformation for C6075b specimen.

Figure B.39 Axial load versus axial deformation for C4075a specimen.

Figure B.40 Axial load versus axial deformation for C4075b specimen.

Figure B.41 Axial load versus axial deformation for C4078a specimen.

Figure B.42 Axial load versus axial deformation for C4078b specimen.

Figure B.43 Axial load versus axial deformation for C4108a specimen.

Figure B.44 Axial load versus axial deformation for C4108b specimen.

Figure B.45 Axial load versus axial deformation for C2078a specimen.

Figure B.46 Axial load versus axial deformation for C2078b specimen.

Figure B.47 Axial load versus axial deformation for C2108a specimen.

Figure B.48 Axial load versus axial deformation for C2108b specimen.

Figure B.49 Axial load versus axial deformation for C2108c specimen.

APPENDIX C: PICTURES OF SPECIMEN FRACTURE AND BUCKLING

A8075a

A8075b

Figure C.1 Failure of A8075a and A8075b.

A6075a

A6075b

Figure C.2 Failure of A6075a and A6075b.

A4075a

A4075b

Figure C.3 Failure of A4075a and A4075b.

A4075c

A4078a

Figure C.4 Failure of A4075c and A4078a.

A4078b

A2078a

Figure C.5 Failure of A4078b and A2078a.

A2078b

A2078d

Figure C.6 Failure of A2078b and A2078d.

A2078e

A4108a

Figure C.7 Failure of A2078e and A4108a.

A4108b

A2108a

Figure C.8 Failure of A4108b and A2108a.

A2108b

A4128a

Figure C.9 Failure of A2108b and A4128a.

A4128b

A2128a

Figure C.10 Failure of A4128b and A2128a.

A2128b

A2128c

A2128e

A2128f

Figure C.11 Failure of A2128b and A2128c.

Figure C.12 Failure of A42128e and A2128f.

B8075a

B8075b

Figure C.13 Failure of B8075a and B8075b.

B2078a

B2078b

Figure C.14 Failure of B2078a and B2078b.

B2128a

B2128b

Figure C.15 Failure of B2128a and B2128b.

B2128c

B2128d

Figure C.16 Failure of B2128c and B2128d.

C8075a

C8075b

Figure C.17 Buckling of C8075a and C8075b.

C6075a

C6075b

Figure C.18 Buckling of C6075a and C6075b.

C4075a

C4075b

Figure C.19 Buckling of C4075a and C4075b.

C4078a

C4078b

Figure C.20 Buckling of C4078a and C4078b.

C2078a

C2078b

Figure C.21 Failure of C2078a and C2078b.

C4108a

C4108b

Figure C.22 Buckling of C4108a and C4108b.

C2108a

C2108b

C2108c

Figure C.24 Failure of C2108c.

Figure C.23 Failure of C2108a and C2108b.