RETROFIT OF LATTICED COMMUNICATION TOWERS

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RETROFIT OF LATTICED COMMUNICATION TOWERS

By

Yuan Xue

A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of Civil and Environmental Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science
at the University of Windsor

Windsor, Ontario, Canada

2015

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ABSTRACT

In this research, the effectiveness of channel section retrofit on angle section was investigated. Three unique angle section types (2∟25x19x3, 2∟51x32x4.8 and 2∟32x32x6.4) and totally eighteen specimens were tested. The used retrofit channel sections were C64x16 and C100x7). The results indicated that the failure load increased 37.5% - 122% after retrofit. The retrofit method was conclusively effective and easy to be accessed in the field. In addition, finite element analysis was also used to simulate the models of the experimental tests and the parametric study.
DEDICATION

To my parents, who have shown tremendous support and understanding.
ACKNOWLEDGEMENTS

I would like to thank all those who have helped me in the completion of this thesis. I would like to thank my advisor Dr. S. Das, for his encouragement during the master’s program and his numerous hours of help throughout my graduate studies. I would also like to express my appreciation to my committee members, Dr. Madugula, Dr. Kar for their time and assistance in the completion of this thesis. Special thanks to Dr. Cheng, for her tremendous help on the completion of this thesis and her encouragement and suggestion on my future career.

I would also like to thank the technicians at the University of Windsor. Lucian Pop and Matt St. Louis were always available for any help in the lab, in spite of their busy schedule.

I also had many contribution from my friend especially Jamshid Zohreh Heydariha and Hossein Ghaednia, who gave me tremendous help and encouragement.

Lastly, I would like to express my gratitude towards my parents who have supported my study and given me a lot of encouragement along the way.
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CHAPTER 1

INTRODUCTION

1.1 GENERAL
The retrofit of latticed communication towers is becoming a critical issue in this world. Approximately 70% of the latticed communication towers in Canada are more than 20 years old. During this period of time, latticed communication towers were endured outside damages and latticed communication towers with higher load capacity were highly required.

In terms of tower member retrofit, steel section members were commonly used. In this project, the effectiveness of the retrofit on angle members using channel sections was determined based on experimental tests.

1.2 PROBLEM STATEMENT
This project was developed to investigate the effectiveness of steel channel section retrofitting on angle section. The major problems of lattice tower retrofit, is optimizing the retrofit methods. It is required to determine the most effective retrofit section type, and the most reasonable method to access the rehabilitation.

1.3 OBJECTIVES
- Determine the effectiveness of the retrofit of latticed communication tower members using channel section.
- Simulate finite element models by ABAQUS for the specimens as built and retrofitted specimens. Model validation is required.
- Comparing the maximum load capacity while the slenderness ratio is controlled, based on finite element models.
1.4 SCOPE OF WORK

The scope of this research includes the following.

1. Undertaking detailed literature review

2. Preparation of specimens

3. Preparing the test setup, including the setup of loading jack, loadcell, top and bottom plates, strain gauge for the longitudinal strain and five linear variable displacement transducers (LVDT)

4. Testing the specimens with required instrumentation and data acquisition system

All the data (Load, displacement and strain) was monitored and recorded on the computer every second.

5. Preparation of standard coupons of specimens for material tests

6. Testing the coupons of specimens

7. Analyzing the test results

The result of the tests were used to determine the failure load of the specimens as built and retrofitted specimens and thus, to evaluate the effectiveness of the retrofit method of each specimen type.

8. Finite element simulation on ABAQUS

9. Undertaking numerical analysis and parametric study

10. Writing thesis

1.5 METHODOLOGY

The research methodology of this project includes two parts, experimental study and numerical study.
Totally 18 specimens were tested including six unique section types, which were designed as 74-VU, 74-RU, 76-VU, 76-RU, 76-VE and 76-RE. The tests were prepared in the Structure Laboratory at University of Windsor.

Finite element models were used to simulate the specimens. And the parametric study was conducted based on the finite element models.

**1.6 ORGANIZATION OF THESIS**

This thesis is organized as follows:

Chapter 1 – Introduction

Chapter 2 – Literature review: This chapter contains a detailed review of previous works which relate to the current research

Chapter 3 – Experimental Program

Chapter 4 – Experimental Results

Chapter 5 – Numerical Method

Chapter 6 – Numerical Results and Parametric Study

Chapter 7 – Summary and Conclusion
CHAPTER 2
LITERATURE REVIEW

2.1 GENERAL INTRODUCTION

A transmission tower is a high height structure, commonly a steel latticed tower, used to support power line. Latticed communication towers are used in high-voltage systems, and come in a wide variety of shapes and sizes. Typical height ranges from 15 to 55 meters. Generally, transmission towers are made of steel, but other materials may be used such as concrete and wood.

The purpose of this literature review is to review previous researches completed in this area.

2.2 THE REASONS FOR STRENGTHENING TOWERS

2.2.1 WIND FORCE

With the expanding of the telecommunication systems, the usage of freestanding latticed steel towers to support antennas has been intensive in the last few year. Due to the lightweight of these structures, wind forces are the primary concern in the design (Carril et al., 2003).

In many cases the main reason of transmission tower failure was due to the actions of high intensity winds and 80–100% of all weather-related failures were the result of high intensity winds (Savory et al., 2001). These meteorological phenomena are localized and unpredictable. Savory et al. (2001) researched on latticed tower by ABAQUS modeling. High intensity winds may resulted in tower member buckling and the buckling produces large horizontal deformation. The wind loading models for the tower presented in this
paper contained many simplifications. Nevertheless, wind load failure appears to concur with evidence from rehabilitating of the tower members.

2.2.2 ICE LOAD

Generally, atmospheric icing is a design consideration for communication towers, especially at cold areas. Ice storms are a natural hazard that cause towers to collapse. Atmospheric icing frequently causes tower failures in cold regions. Sundin and Makkonen (1998) reported 13 TV towers that collapsed due to ice loads in the US alone during the last 20 years. Ice can build up on towers from liquid precipitation. Further, the build-up of ice can increase the section area of the structure which will increase the wind loads. Ice load also cause signal interference, structural fatigue, wire stretch, ice load damage when the ice sheds, or complete tower failure (N.D. Mulherin, 1998). Figure 2.1 shows the typical icing situation of the tower.
2.2.3 SEISMIC

Latticed communication tower design usually considered wind effects as the sole source of lateral loads but rarely the influence of earthquake (Khedr and McClure, 2000). Khedr and McClure (2000) studied a simplified static method for estimating the member forces in self-supporting lattice telecommunication towers due to both horizontal and vertical earthquake excitations. The used method was modal superposition analysis. These results completely shows that for high risk seismic areas, earthquake effects on towers may not be negligible compared to wind effects and it should be considered as a design check. Two years later, Fatma and Jasbir (2002) studied the optimal design of latticed tower subjected to earthquake loading. This research provided the continuous and discrete variable optimization methods to predict earthquake influence when design lattice tower.
2.2.4 BOLT SLIP

Latticed communication towers consist of legs, bracings, and secondary bracings and cross members. A small rotation owing to bolt slip in the joint may cause additional deformation in the tower, which is difficult to predict and cannot be accounted for in the analysis (Rao et al., 2012). The slippage of bolts may have some effects on deflection, but it does not significantly influence the ultimate strength of lattice structures. In the analysis and design of towers, effects of deflections are generally ignored. However, if the tower is sufficiently tall and flexible, then deflections will be considerable and cannot be ignored, because they can cause secondary stresses (Rao et al., 2012).

2.2.5 CORROSION

Corrosion is a common damage on lattice tower, which may result from several reasons including temperature fluctuations, extensive use of deicing salts and improper coating (Chen et al., 2010). The load capacity of latticed tower reduced significantly when this tower corroded. In addition, it was found that, coating on the latticed tower gave a relation with the tower corrosion. Improper painting system and maintenance may also cause corrosion of lattice tower (Chen et al., 2010).

The most common and conventional method to repair corrosion was to add plates. Recently, CFRP and other fiber material was applied in corrosion repair, the material which had lighter weight than conventional material.

2.3 METHODS OF RETROFIT

As soon as a new antenna is mounted, the tower has to satisfy current standards which are more stringent than the standards which were used while constructing the tower.

The common method of strengthening bracing member is to attach a reinforcing member to the main bracing member at intervals by clamps or bolts. The area of the rehabilitating angle was at least equal to the area of the main bracing member. C. Kumalasari (2004)
studied the effectiveness of the angle and rod reinforced bracing members at University of Windsor. Figure 2.2 provides the tested specimens with no rehabilitation, rod section rehabilitation and angle section rehabilitation.

![Figure 2.2 Reinforced and Non-Reinforced Bracing Members](image)

**Figure 2.2 Reinforced and Non-Reinforced Bracing Members**

(C. Kumalasari, 2004)

Based on this research, the number of U-bolts was also important when rehabilitating bracing members. It was found that, reducing the number of bolts resulted in reduction of the compressive strength of the members (C. Kumalasari, 2004).

Interconnectors of latticed tower member rehabilitation were also important to increase the rehabilitation effect. Yan et al., (2012) studied the rehabilitation of the angle legs of latticed
tower. Based on this research, three different interconnector types were provided, which were aligned plates, alternating plates and cruciform angle interconnectors (Figure 2.3).

![Figure 2.3 Type of Interconnectors](Yan et al., 2012)

The aim of the tests was to investigate the effect of interconnectors on the effectiveness of load capacity increment between the core and reinforcing members. It was found that, the cruciform angle interconnector had the highest average strength increment (above 30%), but with a large standard deviation (Yan et al., 2012).

However, for a real tower, where both compression and tension legs were reinforced, the effectiveness of the method may be reduced.

### 2.4 COMPARISON OF ROD AND ANGLE REHABILITATION

C. Kumalasari (2004) studied the compressive strength of bracing members reinforced with rods and angles. U bolts were used to rehabilitate the rod bracing members and the
reinforcing members. Tests were aim to determine the difference on failure load of rod and angle reinforcing members. Figures 2.2 provides the dimension of the specimens and the rehabilitation methods. Table 2.1 provides the results of the experimental test, which can be found that the failure load was increased from 30.4 kN to 44.9 kN and 53.9 kN respectively with the rehabilitation of rod and angle reinforcing members. Based on this research, rehabilitating rod bracing members using angle sections was 29.6% more effectiveness than rod section.

**Table 2.1 Failure Load of Specimens**

(C. Kumalasari, 2004)

<table>
<thead>
<tr>
<th>Brace #</th>
<th>Type</th>
<th>Experimental Failure Load</th>
<th>Average Experimental Failure Load</th>
<th>Relative Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kN (kips)</td>
<td>kN (kips)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Unreinforced</td>
<td>29.4 (6.61)</td>
<td>30.4 (6.63)</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>BU-1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BU-2</td>
<td>31.4 (7.06)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Rod-reinforced</td>
<td>44.0 (9.89)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BR-1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BR-2</td>
<td>42.7 (9.60)</td>
<td>44.9 (10.1)</td>
<td>1.48</td>
</tr>
<tr>
<td></td>
<td>BR-3</td>
<td>48.0 (10.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Angle-reinforced</td>
<td>56.2 (12.6)</td>
<td>53.9 (12.1)</td>
<td>1.77</td>
</tr>
<tr>
<td></td>
<td>BA-1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BA-2</td>
<td>51.6 (11.6)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.5 REHABILITATION WITH FRP

The carbon fiber reinforced polymer (CFRP) was firstly used in the military during 1950s (Hollaway, 1993). Due to its high strength-to-weight ratio, CFRP was used for products needs to achieve lightweight and durable products. The CFRP had been introduced to civil engineering infrastructure at the recent years and widely used in corrosion and fatigue repair and structure strengthening.
Corrosion repair with steel plate was the most common and conventional method. Although this method was effective, other serious problems could be introduced to the steel structure, such as fatigue problem, future galvanic corrosion, and additional dead load to the structure.

Chen (2008) studied the repairing of corroded steel beam by FRP material. The rehabilitation method included three steps, which were surface preparation, saturating resin preparation and application of FRP. Surface preparation was always important in a successful rehabilitation of a structural member. This step critically affected the stability of the connection between the surface of the specimen and the FRP material. In addition, correct proportioning and proper mixing were important when using epoxy resin systems. Improper preparation of resin can lead to de-bonding of CFRP laminate. Lastly, the CFRP sheet was cut into the required size. Once the epoxy was mixed, it was applied to both surfaces of the CFRP sheets using a paint roller to ensure the CFRP was saturated properly with epoxy.

In addition, FRP is an advanced material which was increasingly being used for strengthening and repair of existing metal structures. Islam and Young (2012) studied a series of tests on FRP strengthening of cold-formed stainless steel members. Externally bonded FRP can be used to strengthen the web crippling capacity of stainless steel tubular structural members (Islam and Young, 2012). Totally 10 rehabilitated specimens were tested and the rehabilitation design provided (Figure 2.4).
FRP plates presented effectiveness on steel beam rehabilitation. However, the increase of FRP width did not provide much improvement on the rehabilitation (Islam and Young, 2012).

Besides tubular steel sections, many researches in CFRP strengthening studied other different section types such as I-sections (Chalakani and Fernando, 2012), T sections (Harries et al., 2009), and angle sections (Eltawil and Ekiz, 2009) and lipped channels (Silvestre, 2008).
Chalakani and Fernando (2012) presented experiments and theoretical analysis of sixteen steel I-section beams strengthened using externally bonded CFRP under quasi-static large deformation three point bending. The steel beams were made of mild steel plates grade S275 and welded to BS 5950. The test matrix included six bare steel beams, four steel beams with CFRP strengthening on the bottom flange, four steel beams with CFRP strengthening on top and bottom flange and two steel beams with CFRP strengthening on top and bottom flanges as well as on steel web (Figure 2.5). CFRP plates were 100 mm wide and 1.2 mm thick resulted in a nominal cross sectional area of 120 millimeter square.

Figure 2.5 Rehabilitation Design

(Chalakani and Fernando, 2012)

According to the test result presented by Chalakani and Fernando (2012), the effectiveness of strengthening was found to be different for different section classes. CFRP strengthening
had lower effect which is only 7 – 15% to slender sections. For semi-compact specimens, only 7% increment when CFRP strengthening only on the tension flange, while it had a significant effect which was 32% load increase when CFRP strengthening on top and bottom flange. However, more tests were needed to confirm this conclusion.

2.6 STRENGTHENING WITH SPLIT PIPE

Dostatni (2011) studied on communication tower rehabilitation with split pipes. A split pipe was made by dividing one single pipe into two sections of equal cross-sectional area (Figure 2.6). Those split pipes were attached longitudinally to the main member using bolts, tabs, or welds. Strengthening with split pipes can reduce the possible intersection with outstanding angle antenna mounts, compared with angle or channel splints.

![Figure 2.6 Rehabilitation of Split Pipe](image-url)

(Dostatni, 2011)
The increment of compressive strength with split pipe rehabilitated was around 15%-30%. Different length of spilt pipe provided different rehabilitation effect. It was recommended to use strengthening members along the entire leg member (Dostatni, 2011).

2.7 CONCLUSIONS

Literature review shows that there are three main retrofit methods on steel structure members.

1. Reinforcing steel sections
2. FRP material
3. Split pipes

The test results from the research conduct by C. Kumulasari (2004) using rod and angle reinforcing members shows that, the average percentages of improvement on load capacity are 47.6% and 79.6%, respectively.

The test results from the research conduct by Chalakani and Fernando (2012) using FRP material retrofitting H steel sections shows an average 20% effectiveness on that FRP retrofit.

The test results from the research conduct by Dostatni (2011) using split pipes retrofit shows 15% - 30% increment on compression strength after retrofit.

Literature review found how various methods used on latticed tower member retrofit and the advantages and disadvantages of the rehabilitation methods. However, the literature review showed that no research has been conducted in the past using channel sections retrofitting two angles.
The current research aims to find the effectiveness of retrofit method for angle members used in latticed communication towers using channel sections. The research also compares the different performance of this retrofit method on different slenderness ratios.
CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 INTRODUCTION

This project investigated a retrofit method for communication tower members. The objective of this project is to determine the effectiveness of this retrofit method for the steel angle members used in communication towers using steel channel section.

A total of 18 bracing member specimens in three different types were tested at the Structural Laboratory of the University of Windsor, Windsor, Ontario, Canada. The objective of these tests was to determine the load carrying capacity and failure mode of each specimen. Each of three types of specimens includes three identical specimens as built and three identical retrofitted specimens (Table 3.1).

During the test, longitudinal and lateral displacement were measured by linear variable displacement transducers (LVDT) at different locations of the specimen. One strain gauge was installed and used to determine the maximum longitudinal strain during the loading process. All the data were acquired using a computerized data acquisition system (DAS).

The arrangement of the tests is:

- Two specimens of each section type (first two groups) were tested aim to determine the failure load capacity and the corresponded longitudinal displacement.
- Besides failure load and longitudinal displacement, longitudinal strain and lateral displacement were also tested when testing the third specimen of each section type (last group).
Table 3.1 Test Matrix

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Specimen Name</th>
<th>Number of Specimens Tested</th>
<th>L (mm)</th>
<th>Gap (mm)</th>
<th>Angle Size</th>
<th>Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>74-VU</td>
<td>3</td>
<td>1880</td>
<td>0</td>
<td>2(\angle 25\times19\times3)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>74-RU</td>
<td>3</td>
<td>1880</td>
<td>10</td>
<td>2(\angle 25\times19\times3)</td>
<td>C64x16</td>
</tr>
<tr>
<td>2</td>
<td>76-VU</td>
<td>3</td>
<td>1930</td>
<td>0</td>
<td>2(\angle 51\times32\times4.8)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>76-RU</td>
<td>3</td>
<td>1930</td>
<td>10</td>
<td>2(\angle 51\times32\times4.8)</td>
<td>C100x7</td>
</tr>
<tr>
<td>3</td>
<td>76-VE</td>
<td>3</td>
<td>1930</td>
<td>0</td>
<td>2(\angle 32\times32\times6.4)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>76-RE</td>
<td>3</td>
<td>1930</td>
<td>10</td>
<td>2(\angle 32\times32\times6.4)</td>
<td>C100x7</td>
</tr>
</tbody>
</table>

3.2 REHABILITATION METHOD

Figure 3.1 shows the retrofit method applied on a 74 inches (1880 mm) specimen as built (74-VU). The detail of the retrofit of each type of specimen is shown in section 3.3.

According to the Canadian standard CAN/CSA-S16, Section 22.3 (Canadian Standards Association (CSA), 2001, “Limit States Design of Steel Structures.” Canadian Standard Association, Mississauga, Ontario, Canada. – for standards and codes.), the minimum space between centers of bolt holes shall be 2.7 times the bolt diameter. Hence, the minimum space was 17.1 mm which was calculated as 2.7 times 1/4 inches (6.35 mm), was less than the designed distance (230mm). Further, according to the same standard, the minimum space from the edge of the specimen to the first bolt hole should be 28 mm when the bolt diameter is less than 5/8 inches (15.8 mm). The design space was 2 inches (50 mm), which was larger than 28 mm.
Three unique types of specimens as built tested in this project were designated as 74-VU, 76-VU, and 76-VE (Table 3.1). These specimens were retrofitted using channel sections (Figure 3.1 and Table 3.1). These retrofitted specimens corresponded to the specimens as built are designated as 74-RU, 76-RU, and 76-RE (Table 3.1). The numbers 74 or 76 refer to the length of the specimens, which mean that, the length of the shorter specimen was 74 inches (1880 mm) and the length of the longer one was 76 inches (1930 mm). The letter V or R indicates that, the specimen was either the specimen as built or retrofitted. The last letter U or E indicates the specimen was made of equal angles or unequal angles, respectively.

### 3.3.1 UNEQUAL ANGLE SPECIMEN

There were two types of specimens as built belong to the unequal angle sections, which are specimens 74-VU and 76-VU.
Specimen 74-VU was the specimen built with the smallest angle section among the six specimens (Figure 3.2). Six stitch bolts of 1/4 inches (6.35 mm) diameter were used to connect the angle sections at 14 inches (355 mm) spacing (Figure 3.1). The space between the first bolt hole and the edge of the specimen was 2 inches (50 mm).

![Figure 3.2 Specimen 74-VU](image)

Specimen 74-RU was the retrofitted specimen of 74-VU (Figure 3.3). The angle section and channel section were connected by eight vertical bolts of 9.5 mm diameter at 9 inches (230 mm) spacing.

![Figure 3.3 Specimen 74-RU](image)

Specimen 76-VU was the second unequal angle section specimen as built (Figure 3.4). Five stitch bolts were used for rehabilitation at 18 inches (457 mm) spacing.
Specimen 76-RU was the retrofitted specimen of 76-VU (Figure 3.5). Seven stitch bolts were used for rehabilitation at 11 inches (280 mm) spacing.

3.3.2 *EQUAL ANGLE SPECIMEN*

Specimen 76-VE was the only specimen as built with equal double angle section among the six specimens (Figure 3.6). Bolts retrofit design was the same with specimen 76-VU.
Specimen 76-RE was the retrofitted specimen of specimen 76-VE (Figure 3.7). Bolts rehabilitation design was the same with specimen 76-RU.

### 3.4 TEST SETUP

A schematic of the test setup is shown in Figure 3.8. A horizontal beam was set at the top of the frame, which was enough for adjusting the location of the specimen (Figure 3.9).
Figure 3.8 Sketch of Test Setup

Figure 3.9 Test Frame
A 20kN capacity universal loading jack was used to apply compression load and the magnitude of the load was measured though the loadcell. The loading jack was mounted on the top beam of the load frame (Figure 3.9).

![Figure 3.10 Test Setup of Load Cell and Loading Jack](image)

The top plate (Figure 3.11a) was clamped under the loadcell via the adapter. And the bottom plate (Figure 3.11b) was clamped to the strong floor. The plates were made with cross gaps to ensure that, the specimen was not able to move during the test but it could rotate, which means the boundary condition of the specimen for both ends were pinned.
A digital level was used to ensure the specimen was vertical and leveled (Figure 3.12).

Two LVDTs were used to determine the longitudinal deformation of the specimen at the top end and the maximum stroke of these LVDTs was 25 mm. These two LVDTs were installed at 180° on the loading jack (Figures 3.13).
Three LVDTs were mounted along the length of the specimen to determine lateral displacement (Figure 3.14) when testing the last group of specimens. These LVDTs were placed at every one-fourth length of the specimen. The LVDT mounted at mid-length of the specimen was expected to experience the largest lateral deformation. The other two LVDTs were installed to determine the lateral displacement of the one-fourth length of the specimen. The upper and lower two LVDTs were expected to experience similar displacement to check if the buckling happens at the mid-length of specimen.
A strain gauge (Figures 3.16 and 3.17) was installed at the mid-length to determine the longitudinal strain during the test.
3.5 TEST PROCEDURE

Each section type had three specimens. The test procedure of different angle sections was similar (Figures 3.18 and 3.19). Test started after test completely setup.

Axial load was gradually applied at the top of the specimen by the loading jack and measured by loadcell. The displacement and stain were determined by LVDTs and strain gauge. All the test data was monitored and recorded every second on the computer. Specimens unloaded when the monitored load capacity had dropped which means the specimen had been failed.
Figure 3.18 Test Procedure (Before Buckling)

Figure 3.19 Test Procedure (After Buckling)
3.6 SUMMARY

This experimental test of the project was completed to determine the effectiveness of channel section retrofit. However, two imperfection points which might influence the test results. Firstly, the specimens themselves were not exactly straight and may even have initial bending. Secondly, the failure load of specimen 74-VU and 74-RU was less than 2 kN which was too small to control the pump when loading.
CHAPTER 4

EXPERIMENTAL RESULTS

This chapter provides a detailed discussion on data reduction, organization and analysis of test data. Discussion and conclusion are included. The test results include the deformed shapes of the specimens, the longitudinal strain determined by the strain gauge, load-deformation behavior determined by the load cell and the LVDTs, and the comparison of the failure load between specimens as built and retrofitted specimens.

4.1 MATERIAL PROPERTY

This section provides the stress-strain plots of the materials based on the coupon tests. Standard coupon of each specimen was tested. The test results of each specimen are shown in Table 4.1 and the stress-strain plot of angle specimen 74-VU is shown in Figure 4.1. In addition, the stress-strain plots of other specimens are shown in Appendix A.1.

![Figure 4.1 Material Property of 74-VU](image)
The value of $\sigma_y$, $\sigma_u$, and $E$ are shown in Table 4.1.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Young’s module (GPa)</th>
<th>$\sigma_y$ (MPa)</th>
<th>$\sigma_u$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>74-VU-Angle</td>
<td>202</td>
<td>301</td>
<td>468</td>
</tr>
<tr>
<td>74-RU-Channel</td>
<td>228</td>
<td>275</td>
<td>448</td>
</tr>
<tr>
<td>76-VU-Angle</td>
<td>182</td>
<td>269</td>
<td>470</td>
</tr>
<tr>
<td>76-VE-Angle</td>
<td>199</td>
<td>306</td>
<td>487</td>
</tr>
<tr>
<td>76-RU-Channel</td>
<td>181</td>
<td>302</td>
<td>476</td>
</tr>
<tr>
<td>76-RE-Channel</td>
<td>204</td>
<td>302</td>
<td>476</td>
</tr>
</tbody>
</table>

### 4.2 BUCKLING MODE

According to the Euler buckling formula (Equation 4.1), $P_{\text{crit}}$ of the specimens can be calculated.

$$
\sigma = \frac{F}{A} = \frac{\pi^2E}{(\ell/r)^2}
$$

(4.1)

In addition, according to the result of material coupon test (Table 4.1). The value of $P_{\text{crit}}$ and $P_{\text{yield}}$ of each specimen was calculated and shown in Table 4.2.
Table 4.2 Specimen Properties

<table>
<thead>
<tr>
<th>Specimen</th>
<th>L (mm)</th>
<th>r</th>
<th>Area (mm²)</th>
<th>Yield Stress (MPa)</th>
<th>P_{crit} (N)</th>
<th>P_{yield} (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>74-VU</td>
<td>1880</td>
<td>7</td>
<td>246</td>
<td>301</td>
<td>6725</td>
<td>76752</td>
</tr>
<tr>
<td>74-RU</td>
<td>1880</td>
<td>7.5</td>
<td>904</td>
<td>275</td>
<td>24713</td>
<td>280240</td>
</tr>
<tr>
<td>76-VU</td>
<td>1930</td>
<td>12</td>
<td>751</td>
<td>269</td>
<td>57250</td>
<td>231308</td>
</tr>
<tr>
<td>76-RU</td>
<td>1930</td>
<td>15</td>
<td>1629</td>
<td>306</td>
<td>194034</td>
<td>496845</td>
</tr>
<tr>
<td>76-VE</td>
<td>1930</td>
<td>9</td>
<td>737</td>
<td>302</td>
<td>31602</td>
<td>211519</td>
</tr>
<tr>
<td>76-RE</td>
<td>1930</td>
<td>11</td>
<td>1615</td>
<td>302</td>
<td>103450</td>
<td>478040</td>
</tr>
</tbody>
</table>

Since the calculated structure buckling loads (P_{crit}) are much smaller than the material yielding load (P_{yield}), it can be said that all the specimens experienced pre-yielding buckling or elastic buckling.

4.3 BUCKLING PLANE

This section provides the buckling plane of the specimens in the tests. Generally, buckling plane is related to the smallest radius of gyration of the sections.

4.3.1 INTRODUCTION

The smallest radius of gyration controls the buckling plane. Radius of gyration is critical and can predict the buckling behavior of the specimen. Hence, buckling plane can be predicted and controlled. This is an important consideration in the structural design of communication tower members.

4.3.2 BUCKLING PLANE OF SPECIMENS

Table 4.3 provides the calculated radius of gyration about both x-axis and y-axis of each specimen.
According to the deformed shapes (Section 4.4) of all the specimens, buckling planes of the specimens are shown in Tables 4.4. The definition of x-x and y-y axes are shown in Figure 4.2. All the specimen of y-axis buckling plane, changed to x-axis after retrofit.

### Table 4.3 Section Properties

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Radius of Gyration Axis x-x</th>
<th>Radius of Gyration Axis y-y</th>
</tr>
</thead>
<tbody>
<tr>
<td>74-VU</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>74-RU</td>
<td>7.5</td>
<td>19</td>
</tr>
<tr>
<td>76-VU</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>76-RU</td>
<td>15</td>
<td>32</td>
</tr>
<tr>
<td>76-VE</td>
<td>9</td>
<td>14</td>
</tr>
<tr>
<td>76-RE</td>
<td>11</td>
<td>33</td>
</tr>
</tbody>
</table>

### Table 4.4 Buckling Plane of Specimens

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Tests</th>
<th>Buckling Axis</th>
<th>Maximum Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimens as built</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>74-VU</td>
<td>74-VU-1</td>
<td>y-y</td>
<td>1255</td>
</tr>
<tr>
<td></td>
<td>74-VU-2</td>
<td>y-y</td>
<td>1384</td>
</tr>
<tr>
<td></td>
<td>74-VU-3</td>
<td>y-y</td>
<td>1266</td>
</tr>
<tr>
<td>76-VU</td>
<td>76-VU-1</td>
<td>y-y</td>
<td>7969</td>
</tr>
<tr>
<td></td>
<td>76-VU-2</td>
<td>y-y</td>
<td>7503</td>
</tr>
<tr>
<td></td>
<td>76-VU-3</td>
<td>y-y</td>
<td>7504</td>
</tr>
<tr>
<td>76-VE</td>
<td>76-VE-1</td>
<td>x-x</td>
<td>5040</td>
</tr>
<tr>
<td></td>
<td>76-VE-2</td>
<td>x-x</td>
<td>4897</td>
</tr>
<tr>
<td></td>
<td>76-VE-3</td>
<td>x-x</td>
<td>5968</td>
</tr>
<tr>
<td>Retrofitted Specimens</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>74-RU</td>
<td>74-RU-1</td>
<td>x-x</td>
<td>1960</td>
</tr>
<tr>
<td></td>
<td>74-RU-2</td>
<td>x-x</td>
<td>1904</td>
</tr>
<tr>
<td></td>
<td>74-RU-3</td>
<td>x-x</td>
<td>1971</td>
</tr>
<tr>
<td>76-RU</td>
<td>76-RU-1</td>
<td>x-x</td>
<td>14115</td>
</tr>
<tr>
<td></td>
<td>76-RU-2</td>
<td>x-x</td>
<td>14674</td>
</tr>
<tr>
<td></td>
<td>76-RU-3</td>
<td>x-x</td>
<td>14204</td>
</tr>
<tr>
<td>76-RE</td>
<td>76-RE-1</td>
<td>x-x</td>
<td>11170</td>
</tr>
<tr>
<td></td>
<td>76-RE-2</td>
<td>x-x</td>
<td>10771</td>
</tr>
<tr>
<td></td>
<td>76-RE-3</td>
<td>x-x</td>
<td>11154</td>
</tr>
</tbody>
</table>
4.4 TEST RESULTS

This section provides the test results including the deformed shapes and failure load of the specimens.

According to the deformed shape of specimen 74-VU (Figure 4.3), buckling happened at the mid-length of the specimen and buckling occurred about axis y-y. Figures 4.8 and 4.9 provide load-deformation plot and load-strain plot of specimen 74-VU. Maximum load capacity was found to be 1255 N, 1384 N and 1266 N result from the tests of three specimens, respectively (Table 4.4 and Figure 4.4). Determined longitudinal strain at maximum load was 0.031%, which was much smaller than 0.2% (Figure 4.5). It can be said that this specimen 74-VU experienced elastic buckling.
After the retrofit of 74-VU, test results of specimen 74-RU were shown in Figures 4.6, 4.7 and 4.8). Buckling happened at the mid-length of the specimen and buckling occurred about axis x-x (Figure 4.6). Maximum load capacity was found to be 1960 N, 1904 N and 1971 N result from the tests of three specimens, respectively (Table 4.4 and Figure 4.7). Determined longitudinal strain at maximum load was 0.06%, which was much smaller than 0.2% (Figure 4.8). It can be said that this specimen 74-RU experienced elastic buckling.
According to the deformed shape of specimen 74-VU and 74-RU (Figures 4.3 and 4.6), buckling plane changed after the retrofit from y-axis to x-axis.

According to the comparison of the test results of specimens as built and retrofitted specimens, the failure load increment of this three retrofitted specimens was about 56.2%, 37.5% and 55.7%.

In addition, determined by three side LVDTs (Figure 3.14), lateral displacement at $P_{max}$ decreased after retrofitted.
The test results of other specimens (76-VU, 76-RU, 76-VE and 76-RE) are shown in Appendix A.2. The test results are summarized at Table 4.5.
### Table 4.5 Test Results

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Maximum Load (N)</th>
<th>Increment of Load Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>74-VU-1</td>
<td>1255</td>
<td>56.2%</td>
</tr>
<tr>
<td>74-RU-1</td>
<td>1960</td>
<td></td>
</tr>
<tr>
<td>74-VU-2</td>
<td>1384</td>
<td>37.5%</td>
</tr>
<tr>
<td>74-RU-2</td>
<td>1904</td>
<td></td>
</tr>
<tr>
<td>74-VU-3</td>
<td>1266</td>
<td>55.7%</td>
</tr>
<tr>
<td>74-RU-3</td>
<td>1971</td>
<td></td>
</tr>
<tr>
<td>76-VU-1</td>
<td>7969</td>
<td>77.1%</td>
</tr>
<tr>
<td>76-RU-1</td>
<td>14115</td>
<td></td>
</tr>
<tr>
<td>76-VU-2</td>
<td>7503</td>
<td>95.6%</td>
</tr>
<tr>
<td>76-RU-2</td>
<td>14674</td>
<td></td>
</tr>
<tr>
<td>76-VU-3</td>
<td>7504</td>
<td>89.3%</td>
</tr>
<tr>
<td>76-RU-3</td>
<td>14204</td>
<td></td>
</tr>
<tr>
<td>76-VE-1</td>
<td>5040</td>
<td>120%</td>
</tr>
<tr>
<td>76-RE-1</td>
<td>11170</td>
<td></td>
</tr>
<tr>
<td>76-VE-2</td>
<td>4897</td>
<td>122%</td>
</tr>
<tr>
<td>76-RE-2</td>
<td>10771</td>
<td></td>
</tr>
<tr>
<td>76-VE-3</td>
<td>5968</td>
<td>86.9%</td>
</tr>
<tr>
<td>76-RE-3</td>
<td>11154</td>
<td></td>
</tr>
</tbody>
</table>

#### 4.5 SUMMARY

First, bolts connection was easy to be achieved when retrofit on angle section using channel section in site. Second, according to the test results, the average percentages of the increment ($\Delta P_{\text{max}}$) were 49.4%, 87.6% and 102% for the three unique angle section types, respectively, which was conclusively effective.
CHAPTER 5

NUMERICAL METHOD

5.1 GENERAL INTRODUCTION

This chapter provides finite element modelling of the experimental tests using ABAQUS. The objective of finite element modelling is to simulate the specimens of the experimental test and model. In addition, the validated finite element models were used to the parametric study.

5.2 FINITE ELEMENT MODELLING

5.2.1 ELEMENT TYPE

Generally, compared to solid element, shell element was preferred when modeling the structural elements in which two dimensions are much greater than the third one. In addition, shell element was preferred when loading in normal to the shell surface, result may be better than solid element. Since this tests were about slender column buckling analysis, solid element was preferred to shell element. And the geometry of the column specimen was relatively simple, which means meshing and time consuming were not problems when modeling in solid element. Further, according to the geometry of specimen and the loading condition, solid element was determined to be used. The type of the solid element was the general 8-node linear brick.

5.2.2 GEOMETRY MODELING

The geometry of models was simulated from the test specimens (Section 3.3). There was no gap between angle sections of the specimens as built (Figure 3.1) and there was 10 mm gap between the angle sections of retrofitted specimens. Figures 5.1 and 5.2 shows the geometry modeling of the retrofitted specimens and the specimens as built.
5.2.3 MATERIAL PROPERTY

According to the result from material test (Section 4.1). Engineering stress-strain plot was converted to true stress-strain plot (Figure 5.3). Young’s module, $\sigma_y$ and $\sigma_u$ were calculated and shown in Table 4.1. Further, ten points were selected from the true stress-strain plot as the material property of the FE models.
5.2.4 MESH STUDY

This section provides mesh independence study of the model 74-VU (Figure 5.4). Mesh sizes were controlled as 6392, 3196, 2131, 1598, 1279 and 1066. The maximum load of specimen 74-VU was compared between different mesh sizes.
According to Figure 5.4, the results of the FE models get closer with the decreasing of mesh size. The maximum load of the model with mesh size (1598, 1279 and 1066) were similar. Hence, mesh size 1279 was determined to be used in modeling.

5.2.5 BOUNDARY CONDITION

Boundary condition is critical on ABAQUS modeling. According to the boundary condition of the experimental test, the boundary condition of both ends of the model was pinned (Figures 5.5 and 5.6). In addition, since displacement control was used in this model, x, y and z directions were all fixed at the bottom end of the models, and x and y directions were fixed while z direction was free to apply displacement at the top edge of the models (z direction is axial along the models).
5.2.6 TEST SIMULATION

Displacement control and load control were both available to simulate the specimens. Displacement control greatly improves the stability of the analysis. Hence, in this FE model, displacement control was determined to be used.

Take specimens 76-VE and 76-RE as an example, 12 mm displacement was applied at the top edge of model 76-VE using boundary condition, and 20 mm displacement for model 76-RE. Displacement was gradually applied with the running of the model. Specific node
at the top edge, where displacement applied, was selected. Reaction force of the selected node and its corresponded displacement were calculated and output by the software.

5.3 MODELS

Final models and deformed shapes of 74-VU are shown in Figures 5.7 and 5.8. The finite element models of other specimens are shown in Appendix A.3.

Figure 5.7 FE Model of 74-VU
5.4 MODEL VALIDATION

Since the displacement and reaction force of the node on the top edge were output by the software, the load-deformation plot of the FE models can be calculated and compared to the results of experimental test.

The maximum buckling capacity of model 74-VU was 1190 N, which was similar to the experimental test (Figure 5.9).
The models validation of other models (74-RU, 76-VU, 76-RU, 76-VE, and 76-RE) were shown in Appendix B.1. In addition, the results were summarized in Table 5.1.

Figure 5.9 Model Validation of 74-VU
Table 5.1 Model Validation

<table>
<thead>
<tr>
<th>Test</th>
<th>Failure Load (N)</th>
<th>Average (N)</th>
<th>Failure Load of FEA (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>74-VU-1</td>
<td>1255</td>
<td>1302</td>
<td>1190</td>
</tr>
<tr>
<td>74-VU-2</td>
<td>1384</td>
<td></td>
<td></td>
</tr>
<tr>
<td>74-VU-3</td>
<td>1266</td>
<td></td>
<td></td>
</tr>
<tr>
<td>74-RU-1</td>
<td>1960</td>
<td>1945</td>
<td>2105</td>
</tr>
<tr>
<td>74-RU-2</td>
<td>1904</td>
<td></td>
<td></td>
</tr>
<tr>
<td>74-RU-3</td>
<td>1971</td>
<td></td>
<td></td>
</tr>
<tr>
<td>76-VU-1</td>
<td>7969</td>
<td>7659</td>
<td>7113</td>
</tr>
<tr>
<td>76-VU-2</td>
<td>7503</td>
<td></td>
<td></td>
</tr>
<tr>
<td>76-VU-3</td>
<td>7504</td>
<td></td>
<td></td>
</tr>
<tr>
<td>76-RU-1</td>
<td>14115</td>
<td>14331</td>
<td>13700</td>
</tr>
<tr>
<td>76-RU-2</td>
<td>14674</td>
<td></td>
<td></td>
</tr>
<tr>
<td>76-RU-3</td>
<td>14204</td>
<td></td>
<td></td>
</tr>
<tr>
<td>76-VE-1</td>
<td>5040</td>
<td>5301</td>
<td>4600</td>
</tr>
<tr>
<td>76-VE-2</td>
<td>4897</td>
<td></td>
<td></td>
</tr>
<tr>
<td>76-VE-3</td>
<td>5968</td>
<td></td>
<td></td>
</tr>
<tr>
<td>76-RE-1</td>
<td>11170</td>
<td>11032</td>
<td>11000</td>
</tr>
<tr>
<td>76-RE-2</td>
<td>10771</td>
<td></td>
<td></td>
</tr>
<tr>
<td>76-RE-3</td>
<td>11157</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.5 SUMMARY

Compared to the experimental test results, finite element models closely simulated the specimens of the experimental tests, though the results were not exactly the same. Hence, these validated FE models were determined to be used to the parametric study.
CHAPTER 6

NUMERICAL PARAMETRIC STUDY

6.1 INTRODUCTION

This chapter provides parametric study based on the finite element models. Six identical types of specimen were selected related to construction report of WITI 988’ self-support tower (Table 6.1). Based on the section types of these selected specimens, slenderness ratios were controlled. The objective of this parametric study is to determine the difference of failure load after retrofitted with controlled slenderness ratios. The constant slenderness ratios were controlled as 75, 125, 175 and 225.

According to CAN/CSA-S16-01, Section 10.4.2.1 (Canadian Standards Association (CSA), 2001, “Limit States Design of Steel Structures.” Canadian Standard Association, Mississauga, Ontario, Canada. – for standards and codes.), the maximum slenderness ratio in design should not exceed 200. While in US design code, the maximum slenderness ratio should not exceed 225.

6.2 PROPERTY OF SPECIMENS

The identical specimens of parametric study were selected from the construction report of WII self-support tower (Table 6.1).
Table 6.1 Tower Member Properties

<table>
<thead>
<tr>
<th>Part</th>
<th>Section No.</th>
<th>Reinforcement Details</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Double Angle Size</td>
<td>Channel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(mm)</td>
<td>Size</td>
</tr>
<tr>
<td>Top Part 1</td>
<td>T23</td>
<td>H</td>
<td>50x30x6.4</td>
</tr>
<tr>
<td>Top Part 2</td>
<td>T30</td>
<td>H</td>
<td>64x64x6.4</td>
</tr>
<tr>
<td></td>
<td>T31</td>
<td>H</td>
<td>50x50x6.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50x50x6.4</td>
</tr>
<tr>
<td>Mid Part</td>
<td>T32</td>
<td>H</td>
<td>64x64x8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D</td>
<td>50x50x4.8</td>
</tr>
<tr>
<td></td>
<td>T33</td>
<td>H</td>
<td>76x64x8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D</td>
<td>50x50x4.8</td>
</tr>
<tr>
<td></td>
<td>T35</td>
<td>H</td>
<td>76x64x8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D</td>
<td>64x50x4.8 (MD)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50x50x4.8 (SH)</td>
</tr>
<tr>
<td></td>
<td>T36</td>
<td>H</td>
<td>76x64x4.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50x50x4.8</td>
</tr>
<tr>
<td>Bot Part 1</td>
<td>T37</td>
<td>D</td>
<td>50x50x4.8</td>
</tr>
<tr>
<td></td>
<td>T39</td>
<td>D</td>
<td>76x50x6.4 (MD)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>64x50x6.4 (SD)</td>
</tr>
<tr>
<td></td>
<td>T40</td>
<td>D</td>
<td>76x50x6.4 (MD)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>64x50x6.4 (SD)</td>
</tr>
<tr>
<td>Bot Part 2</td>
<td>T42</td>
<td>D</td>
<td>76x64x6.4</td>
</tr>
</tbody>
</table>

Where:

H: Horizontal members of the section

D: Diagonal members of the section

VA: Virgin angle

RA: Repaired angle

GAP: Gap between two angles (back to back)

MD: Main diagonal member

SD: Secondary diagonal member
MH: Main horizontal member

SH: Secondary horizontal member

The six unique angle sections are $2\angle 64\times 50\times 4.8$, $2\angle 76\times 76\times 8$, $2\angle 76\times 50\times 6.4$, $2\angle 64\times 64\times 6.4$, $2\angle 76\times 64\times 8$ and $2\angle 50\times 50\times 4.8$, which include three equal angle sections and three unequal angle sections. In addition, totally four different channel sections were used to retrofit the angle sections, which were C6x8.2, C6x10.5, C6x13 and C7x9.8.

6.3 METHODOLOGY

Finite element models were simulated to determine the failure load of the models of the selected sections.

6.4 FINITE ELEMENT MODEL

Totally, 48 models (24 specimens as built and 24 retrofitted specimens) were simulated. The slenderness ratio were controlled from 75 to 225. Tables 6.2 and 6.3 shows the properties of specimens. Finite simulation method is same with the FE simulation of the experimental tests (Section 5.2).
Table 6.2 Effective Length of Specimens

<table>
<thead>
<tr>
<th>Section</th>
<th>Effective length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L/\tau = 75</td>
</tr>
<tr>
<td>2\L 64x50x4.8</td>
<td>1470</td>
</tr>
<tr>
<td>2\L 76x76x8</td>
<td>1747</td>
</tr>
<tr>
<td>2\L 76x50x6.4</td>
<td>1410</td>
</tr>
<tr>
<td>2\L 64x64x6.4</td>
<td>1477</td>
</tr>
<tr>
<td>2\L 76x64x8</td>
<td>1777</td>
</tr>
<tr>
<td>2\L 50x50x4.8</td>
<td>1162</td>
</tr>
</tbody>
</table>

Table 6.3 Radius of Gyration of Specimens

<table>
<thead>
<tr>
<th>Section</th>
<th>Smaller radius of gyration</th>
</tr>
</thead>
<tbody>
<tr>
<td>2\L 64x50x4.8</td>
<td>19.6</td>
</tr>
<tr>
<td>2\L 76x76x8</td>
<td>23.3</td>
</tr>
<tr>
<td>2\L 76x50x6.4</td>
<td>18.8</td>
</tr>
<tr>
<td>2\L 64x64x6.4</td>
<td>19.7</td>
</tr>
<tr>
<td>2\L 76x64x8</td>
<td>23.7</td>
</tr>
<tr>
<td>2\L 50x50x4.8</td>
<td>15.5</td>
</tr>
</tbody>
</table>

Models were simulated on ABAQUS. Solid element was used and the meshing size was 40 which were similar with the FE modeling of experimental tests (Section 5.2). The boundary condition of both ends was pinned and axial displacement was controlled at the top edge of the models using boundary condition. The buckling capacity was indicated from the calculated reaction force. Figures 6.2 and 6.3 shows the load-deformation plot model 2\L 50x50x4.8 (Slenderness ratio = 75). Finite element model and deformed are
shown in Figure 6.1. The test results are summarized in Table 6.4. The load-deformation plots of all the models are shown in Appendix B.2.

Figure 6.1 FE Model and Deformed Shape

Figure 6.2 Plot of 2L 50x50x4.8 as Built (Slenderness ratio = 75)
Figure 6.3 Plot of retrofitted 2\(\triangle 50\times50\times4\). 8 (Slenderness ratio = 75)
Table 6.4 Results of the Parametric Study

<table>
<thead>
<tr>
<th>Sections</th>
<th>Slenderness ratio</th>
<th>Failure Load (N)</th>
<th>Retrofit Channel Section</th>
<th>Failure Load (Retrofitted) (N)</th>
<th>Increment of Load Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 □ 50x50x4.8</td>
<td>75</td>
<td>45324</td>
<td>C6x10.5</td>
<td>79652</td>
<td>76%</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>19254</td>
<td></td>
<td>33200</td>
<td>72%</td>
</tr>
<tr>
<td></td>
<td>175</td>
<td>15200</td>
<td></td>
<td>19865</td>
<td>31%</td>
</tr>
<tr>
<td></td>
<td>225</td>
<td>4625</td>
<td></td>
<td>9025</td>
<td>95%</td>
</tr>
<tr>
<td>2 □ 64x50x4.8</td>
<td>75</td>
<td>52300</td>
<td>C6x10.5</td>
<td>101200</td>
<td>93%</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>20250</td>
<td></td>
<td>39850</td>
<td>97%</td>
</tr>
<tr>
<td></td>
<td>175</td>
<td>9800</td>
<td></td>
<td>18356</td>
<td>87%</td>
</tr>
<tr>
<td></td>
<td>225</td>
<td>7230</td>
<td></td>
<td>12980</td>
<td>80%</td>
</tr>
<tr>
<td>2 □ 64x64x6.4</td>
<td>75</td>
<td>56500</td>
<td>C7x9.8</td>
<td>116500</td>
<td>106%</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>21200</td>
<td></td>
<td>40523</td>
<td>91%</td>
</tr>
<tr>
<td></td>
<td>175</td>
<td>12056</td>
<td></td>
<td>22356</td>
<td>85%</td>
</tr>
<tr>
<td></td>
<td>225</td>
<td>6200</td>
<td></td>
<td>12021</td>
<td>94%</td>
</tr>
<tr>
<td>2 □ 76x50x6.4</td>
<td>75</td>
<td>71200</td>
<td>C6x10.5</td>
<td>125060</td>
<td>76%</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>22070</td>
<td></td>
<td>38500</td>
<td>74%</td>
</tr>
<tr>
<td></td>
<td>175</td>
<td>13500</td>
<td></td>
<td>23650</td>
<td>75%</td>
</tr>
<tr>
<td></td>
<td>225</td>
<td>7120</td>
<td></td>
<td>13200</td>
<td>85%</td>
</tr>
<tr>
<td>2 □ 76x64x8</td>
<td>75</td>
<td>72300</td>
<td>C7x9.8</td>
<td>151020</td>
<td>109%</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>25100</td>
<td></td>
<td>48500</td>
<td>93%</td>
</tr>
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<td></td>
<td>175</td>
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<td></td>
<td>23650</td>
<td>94%</td>
</tr>
<tr>
<td></td>
<td>225</td>
<td>6800</td>
<td></td>
<td>15200</td>
<td>124%</td>
</tr>
<tr>
<td>2 □ 76x76x8</td>
<td>75</td>
<td>78650</td>
<td>C7x9.8</td>
<td>139680</td>
<td>103%</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>26500</td>
<td></td>
<td>58200</td>
<td>120%</td>
</tr>
<tr>
<td></td>
<td>175</td>
<td>13980</td>
<td></td>
<td>23540</td>
<td>68%</td>
</tr>
<tr>
<td></td>
<td>225</td>
<td>7600</td>
<td></td>
<td>16050</td>
<td>111%</td>
</tr>
</tbody>
</table>

6.5 SUMMARY

This section provides the results of the parametric study. The slenderness ratios were controlled as 75, 125, 175 and 225. The figures shows the effectiveness of the retrofit method of angle sections. Since the retrofit channel sections were required to follow the real tower (Table 6.1), the models of retrofitted specimens were not controlled.

According to the test results of specimen 2 □ 50x50x4.8 (Table 6.4), the average increment of the failure load is 68.5%, which can be said that this retrofit method is conclusively
effective. Load capacity dropped rapidly while the slenderness ratio increased. In addition, the failure load of retrofitted specimens also dropped though the slenderness ratio was not controlled. However, the increment of failure load maintains similar level when slenderness ratio changed (Table 6.4), which can be found that the effectiveness of this retrofit method was not influenced by slenderness ratio. Figure 6.4 provides the comparison of failure load with different slenderness ratios of model 2∟ 50x50x4.8.

![Graph showing the comparison of maximum capacity of 2∟ 50x50x4.8](image)

**Figure 6.4 Maximum capacity of 2∟ 50x50x4.8**

Test results of sections 2∟ 64x64x6.4, 2∟ 76x76x8, 2∟ 64x50x4.8, 2∟ 76x50x6.4 and 2∟ 76x64x8 are provided in Figures 6.5 – 6.9.
Figure 6.5 Maximum capacity of $2 \perp 64x64x6.4$

Figure 6.6 Maximum capacity of $2 \perp 76x76x8$
Figure 6.7 Maximum capacity of $2\times 64\times 50\times 4.8$

Figure 6.8 Maximum capacity of $2\times 76\times 50\times 6.4$
Figure 6.9 Maximum capacity of $2\left(\overline{76}\times64\times8\right)$
CHAPTER 7

SUMMARY AND CONCLUSION

7.1 SUMMARY

The objectives of this research were the following.

1. Determine the effectiveness of the retrofit of angle sections used in communication tower members using channel section.

2. Simulate finite element model by ABAQUS. Model validation is required.

3. Compare the difference of failure load before and after retrofit when slenderness ratios are controlled.

To accomplish these objectives, a total of eighteen specimens were tested. These specimens includes three different specimens as built and three different retrofitted specimens. In research, channel sections were used to retrofit the angle sections. Retrofit design was conducted according to Canadian standard CAN/CSA-S16, Section 22.3 (Canadian Standards Association (CSA), 2001.

Numerical study was performed based on the experimental tests. Results of the FE model were compared with the results of the real tests for validation. In addition, FE models were used to parametric study. In this study, six unique angle sections were selected from the construction report of WITI 988’ Self Support Tower, and the retrofit design followed the real tower. Slenderness ratios were controlled as 75, 125, 175 and 225. Difference of failure load of each section was compared before and after retrofit with controlled slenderness ratios.
7.2 CONCLUSION

The conclusions presented here are based on the results obtained from this research. Hence, the results might not be applicable for different retrofit methods or tower members with different slenderness ratios.

All specimens experienced elastic buckling and there was improvement in the failure load after retrofit for all specimens (37.5% - 122%). The deformation at $P_{\text{max}}$ of was increased after retrofit.

In addition, since stitch bolts were used for rehabilitation instead of welding, this method is fund saved and easy to be accessed in the field. Hence, it can be said that this retrofit method is conclusively effectiveness.
REFERENCES

- Celio F. Carril, N. Isyumov, and R. Brasil, 2003, “Experimental study of the wind


APPENDIX A

A.1 MATERIAL PROPERTIES

![Stress vs Strain Graph](image)

Figure A.1 Channel Specimen of 74-RU
Figure A.2 Channel Specimen of 76-RU and 76-RE

Figure A.3 Angle Specimen of 76-VU
Figure A.4 Angle Specimen of 76-VE
A.2 EXPERIMENTAL TEST RESULTS

Figure A.5 Deformed Shape of 76-VU

Figure A.6 Load-Deformation Plot of 76-VU
Figure A.7 Load-Strain Plot of 76-VU

Figure A.8 Deformed Shape of 76-RU
Figure A.9 Load-Deformation Plot of 76-RU

Figure A.10 Load-Strain plot of 76-RU
Figure A.11 Deformed Shape of 76-VE

Figure A.12 Load-Deformation Plot of 76-VE
Figure A.13 Load-Strain Plot of 76-VE

Figure A.14 Deformed Shape of 76-RE
Figure A.15 Load-Deformation Plot of 76-RE

Figure A.16 Load-Strain plot of 76-RE
A.3 ELEMENT MODELS OF SPECIMENS

Figure A.17 FE Model of 76-VU

Figure A.18 Deformed Shape of Model 76-VU
Figure A.19 FE Model of 76-RU

Figure A.20 Deformed Shape of Model 76-RU
Figure A.21 FE Model of 76-VE

Figure A.22 Deformed Shape of Model 76-VE
Figure A.23 FE Model of 76-RE

Figure A.24 Deformed Shape of Model 76-RE
APPENDIX B

B.1 MODEL VALIDATION

Figure B.1 Model Validation of 74-RU

Figure B.2 Model Validation of 76-VU
Figure B.3 Model Validation of 76-RU

Figure B.4 Model Validation of 76-VE
Figure B.5 Model Validation of 76-RE
B.2 LOAD-DEFORMATION PLOT OF PARAMETRIC STUDY

Figure B.6 Plot of retrofitted $2 \angle 50 \times 50 \times 4.8$ (Slenderness ratio = 75)

Figure B.7 Plot of $2 \angle 50 \times 50 \times 4.8$ (Slenderness ratio = 125)
Figure B.8 Plot of Retrofitted $2 \perp 50 \times 50 \times 4.8$ (Slenderness ratio = 125)

Figure B.9 Plot of $2 \perp 50 \times 50 \times 4.8$ (Slenderness ratio = 175)
Figure B.10 Plot of Retrofitted $2\perp 50\times 50\times 4.8$ (Slenderness ratio = 175)

Figure B.11 Plot of $2\perp 50\times 50\times 4.8$ (Slenderness ratio = 225)
Figure B.12 Plot of Retrofitted 2∟ 50x50x4.8 (Slenderness ratio = 225)

Figure B.13 Plot of 2∟ 64x64x6.4 (Slenderness ratio = 75)
Figure B.14 Plot of Retrofitted $2 \perp 64\times64\times6.4$ (Slenderness ratio = 75)

Figure B.15 Plot of $2 \perp 64\times64\times6.4$ (Slenderness ratio = 125)
Figure B.16 Plot of Retrofitted 2\(\square\) 64x64x6.4 (Slenderness ratio = 125)

Figure B.17 Plot of 2\(\square\) 64x64x6.4 (Slenderness ratio = 175)
Figure B.18 Plot of Retrofitted 2∟ 64x64x6.4 (Slenderness ratio = 175)

Figure B.19 Plot of 2∟ 64x64x6.4 (Slenderness ratio = 225)
Figure B.20 Plot of Retrofitted $2 \angle 64x64x6.4$ (Slenderness ratio = 225)

Figure B.21 Plot of $2 \angle 76x76x8$ (Slenderness ratio = 75)
Figure B.22 Plot of Retrofitted 2\(\perp\) 76x76x8 (Slenderness ratio = 75)

Figure B.23 Plot of 2\(\perp\) 76x76x8 (Slenderness ratio = 125)
Figure B.24 Plot of Retrofitted 2∟ 64x64x6.4 (Slenderness ratio = 125)

Figure B.25 Plot of 2∟ 76x76x8 (Slenderness ratio = 175)
Figure B.26 Plot of Retrofitted 2\(\perp 76\times 76\times 8\) (Slenderness ratio = 175)

Figure B.27 Plot of 2\(\perp 76\times 76\times 8\) (Slenderness ratio = 225)
Figure B.28 Plot of Retrofitted $2\perp 76\times 76\times 8$ (Slenderness ratio = 225)

Figure B.29 Plot of $2\perp 64\times 50\times 4.8$ (Slenderness ratio = 75)
Figure B.30 Plot of Retrofitted 2\( \angle 64\times 50\times 4.8 \) (Slenderness ratio = 75)

Figure B.31 Plot of 2\( \angle 64\times 50\times 4.8 \) (Slenderness ratio = 125)
Figure B.32 Plot of Retrofitted $2\perp 64\times 50\times 4.8$ (Slenderness ratio = 125)

Figure B.33 Plot of $2\perp 64\times 50\times 4.8$ (Slenderness ratio = 175)
Figure B.34 Plot of Retrofitted $2\perp 64\times50\times4.8$ (Slenderness ratio = 175)

Figure B.35 Plot of $2\perp 64\times50\times4.8$ (Slenderness ratio = 225)
Figure B.36 Plot of Retrofitted 2∟ 64x50x4.8 (Slenderness ratio = 225)

Figure B.37 Plot of 2∟ 76x50x6.4 (Slenderness ratio = 75)
Figure B.38 Plot of Retrofitted $2\perp 76\times50\times6.4$ (Slenderness ratio = 75)

Figure B.39 Plot of $2\perp 76\times50\times6.4$ (Slenderness ratio = 125)
Figure B.40 Plot of Retrofitted $2\perp 76\times 50\times 6.4$ (Slenderness ratio = 125)

Figure B.41 Plot of $2\perp 76\times 50\times 6.4$ (Slenderness ratio = 175)
Figure B.42 Plot of Retrofitted 2\(\square 76\times50\times6.4\) (Slenderness ratio = 175)

Figure B.43 Plot of 2\(\square 76\times50\times6.4\) (Slenderness ratio = 225)
Figure B.44 Plot of Retrofitted $2\sqrt{76} \times 50 \times 6.4$ (Slenderness ratio = 225)

Figure B.45 Plot of $2\sqrt{76} \times 64 \times 8$ (Slenderness ratio = 75)
Figure B.46 Plot of Retrofitted $2 \perp 76x64x8$ (Slenderness ratio = 75)

Figure B.47 Plot of $2 \perp 76x64x8$ (Slenderness ratio = 125)
Figure B.48 Plot of Retrofitted $2 \square 76x64x8$ (Slenderness ratio = 125)

Figure B.49 Plot of $2 \square 76x64x8$ (Slenderness ratio = 175)
Figure B.50 Plot of Retrofitted $2\perp$ 76x64x8 (Slenderness ratio = 175)

Figure B.51 Plot of $2\perp$ 76x64x8 (Slenderness ratio = 225)
Figure B.52 Plot of Retrofitted 2 ∟ 76x64x8 (Slenderness ratio = 225)
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