Compressive strength of solid round steel leg and bracing members of lattice communication towers reinforced with rods or angles.

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COMPRESSIVE STRENGTH OF SOLID ROUND STEEL LEG AND BRACING MEMBERS OF LATTICE COMMUNICATION TOWERS REINFORCED WITH RODS OR ANGLES

by

Cindy Kumalasari

A Thesis
Submitted to the Faculty of Graduate Studies and Research 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
2004
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ABSTRACT

Due to the increase in voice and data communication and the advent of digital television, there is a need to reinforce the solid round steel leg and bracing members of existing guyed lattice communication towers to carry additional antenna loads. Reinforcement is generally in the form of rods or angles connected to the leg and bracing members either by U-bolts only or by means of U-bolts and end welding. The sizes of reinforcing members were in accordance with industry practice. Finite element models were built to compute the compressive strength of such members using modified static Riks method.

Tests were carried out on 45 leg members and seven bracing members. Of the 45 leg member specimens, 15 were unreinforced and the remaining 30 test specimens were reinforced with angles. Of the seven bracing member specimens, two were unreinforced, three were rod-reinforced, and two were angle-reinforced. During experimental investigation, the effect of the failure of one leg member on the compressive strength of the remaining leg members was studied. In addition, the effect of (i) end welding, (ii) compressive pre-loading of leg members, (iii) number of U-bolts used to attach the reinforcing angle, and (iv) torque applied to U-bolts was investigated. The effectiveness of rod reinforcement and angle reinforcement to the compressive strength of bracing members were also compared by testing the bracing member specimens.

From experimental results, it was concluded that (i) the failure of one leg member has no effect on the strength of the remaining leg members, (ii) end welding provides additional reserve strength to the leg members, (iii) compressive pre-loading has no effect on the strength, (iv) the number of U-bolts has an effect on the strength, but the location of bolts is more important than the number, and (v) increased bolt torque results in an increase in the strength. It was also found that angle reinforcement is more effective than the rod reinforcement.

The finite element analysis results agree well with the experimental failure loads, thus the models can be used to determine the compressive strength of leg and bracing members reinforced with any size round bar or any size angle. Based on the finite element analysis and test results, a simplified and conservative design procedure is proposed to determine the compressive strength of solid round steel leg and bracing members reinforced with rods or angles.
For My Dearest Parents, Brother, and Sisters
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NOMENCLATURE

A  Gross area of cross-section
E  Young's modulus of elasticity
\( \dot{E} \)  Variable modulus lying between Young's modulus and tangent modulus
\( F_{cr} \)  Critical stress
\( F_u \)  Tensile strength
\( F_y \)  Specified minimum yield stress
I  Minimum moment of inertia
K  Effective length factor
L  Unbraced length of the member
n  Parameter for compressive resistance (1.34 for angles and hot-rolled solid rounds up to 51 mm in diameter)
P  Column load
\( P_E \)  Euler column load
r  Minimum radius of gyration
\( \phi \)  Resistance factor
\( \lambda \)  Non-dimensional slenderness parameter
1.1 GENERAL

Solid round steel members are widely used as leg and bracing members in lattice guyed communication towers because they are subjected to less wind load than angle members and have the same compressive strength about all axes (all axes are principal axes having the same moment of inertia) leading to economy in design. Typical lattice tower section is shown in Figure 1.1. Since the forces in the leg and bracing members are mainly axial, the strength of members under axial tension and compression is an important consideration in tower design. The determination of strength of members in tension is relatively simple compared to that of members in compression; so this research deals only with members in compression.

1.2 NEED FOR INVESTIGATION

The increase in instant voice and data communication by telephone and the advent of new technology such as digital television make it necessary for owners to re-evaluate the existing capacity of antenna towers. Where existing towers have insufficient capacity to support the new equipment, new towers will be required or existing towers have to be reinforced. Because of public opposition, it is becoming more difficult to place new towers in urbanized areas where the demand is greatest. This forces even competing providers of communication services to share the existing towers by adding new equipment.

If there are additional loads (e.g., antennas) added to an antenna tower and/or if there is an increase in the strength requirements, the existing antenna tower has to be reinforced to bring it in compliance with the latest antenna tower standard [CSA 2001]. There are two methods generally in use to increase the compressive strength of the members. The first method is to reduce the effective length of the members by adding redundant bracings. The compressive strength determination according to this method is straightforward. The second method consists of attaching an angle section to the leg members and either a rod or an angle section to the bracing members. These reinforcing angle members are connected to the main members at intervals by means of U-bolts, sometimes with welding at the ends, whereas the rod reinforcements are connected to the bracing members by means of U-bolts only.
Figure 1.1. Details of Tower Section with Three Unreinforced Leg Members
The current industry practice is to make the size of the rod reinforcement the same as the main bracing member. As far as the reinforcing angle member is concerned, the area of the angle is at least equal to the area of the main solid round leg or bracing member to which it is attached. In addition, the leg width of angle reinforcement is sufficient to accommodate the slotted holes for the U-bolt connections (as shown in Figures 1.2 to 1.5) and the width-to-thickness ratio of the legs of angle satisfies the requirements of a "compact" section.

To the best of authors' knowledge, there is no published research about the increase in the strength of the member according to the second method, i.e., when reinforcing rods or angles are attached to the solid round steel leg and bracing members. Review of Canadian Standards [CSA 2001], AISC-LRFD Specification [AISC 1999], American Specification ANSI/TIA/EIA-222-G.5 (Draft) [TIA 2004], and Eurocode prEN 1993-7-1 [CEN 2003] showed that no guidance is provided by any of these standards on the above topic. There is no uniformity in design practices in the telecommunications tower industry for the design of such members. Some designers assume that the reinforcement acts together with the main leg and bracing member as a composite cross-section, while others assume that the only benefit of strengthening is a reduction in the effective length of the main member.

There is no unanimity in the communication tower industry about the effect of the following:
(i) Failure of one leg member with consequent deformation of bracing members on the compressive strength of the remaining leg members.
(ii) Welding at the ends of the reinforcement.
(iii) Compressive pre-loading of the leg members.
   (Many engineers believe that when a member is already loaded before it is reinforced, the increase in strength of the member will be less than the increase in strength if the member is not pre-loaded. In the field, the need for strengthening occurs when the legs have no reserve capacity and have forces in them under service loads equal to nearly 60% of their compressive strength.)
(iv) Number of U-bolts used to attach the reinforcement.
   (The increase in the number of U-bolts significantly adds to the cost of fabrication in the shop and erection at site. Therefore, it is important to determine the optimum number of bolts to get the maximum benefit of strengthening.)
(v) Increase in the bolt torque.
   (Some engineers believe that higher bolt torque results in higher strength.)
(vi) Type of reinforcing member (rod and angle).
Figure 1.2. Details of Tower Section with Three Leg Members Reinforced with Angles using 11 U-bolts
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1.3 OBJECTIVES OF PRESENT RESEARCH

The objectives of this research include:

- Development of a reliable finite element model of leg and bracing members to estimate the compressive strength of the members reinforced with rods/angles.
- To carry out experimental investigation to validate the results of the finite element model.
- Study the effect of the failure of one leg member (with consequent deformation of bracing members) on the compressive strength of the remaining leg members.
- Study the effect of end welding of reinforcement to the main members on the compressive strength of leg members.
- Study the effect of compressive pre-loading of the leg members on the compressive strength of leg members.
- Study the effect of number of U-bolts used to attach the reinforcement on the compressive strength of leg members.
- Study the effect of increase in the bolt torque on the compressive strength of leg members.
- Comparison of the effectiveness of rod reinforcement and angle reinforcement.
- Establishment of a proposed design method to determine the compressive strength of solid round steel leg and bracing members reinforced with rods or angles.

1.4 ORGANIZATION OF THE THESIS

This thesis consists of seven chapters. In Chapter 1, the need for the study and the objectives of the research are presented. In Chapter 2, the literature on this research topic is reviewed for a better understanding of the problem. Chapter 3 presents the finite element analysis to determine the compressive strength of the members, and Chapter 4 presents the experimental investigation to validate the results of finite element analysis. In Chapter 5, comparison of the results from finite element analysis and experimental investigation are compared and discussed. A simplified conservative design method to calculate the compressive strength of solid round steel leg and bracing members reinforced with rods/angles is presented in Chapter 6. Finally, conclusions and recommendations are given in Chapter 7.
2.1 COMPRESSIVE STRENGTH OF COLUMNS

The strength of a column is defined as the maximum compressive force that the column can resist without excessive lateral deformation or plastic deformation. For cold-formed steel columns which are perfectly straight with concentric loading, the strength of the column is given by the critical-load theory. For hot-rolled steel columns which are geometrically imperfect and/or slightly eccentrically loaded, the strength of the column is given by the theory of imperfect column. In general, the column strength must be determined by including imperfections, material non-linearity, and residual stress effects. There is no published literature on the compressive strength of solid round bars (either unreinforced or reinforced). Therefore the following literature review deals with the general theory of buckling.

2.1.1 Critical-load Theory

The strength of a perfectly straight, linearly elastic homogenous column with concentric loading was first given by Euler in 1744 [Bleich 1952]. The Euler load, \( P_E \), is given by:

\[
P_E = \frac{\pi^2 EI}{(KL)^2}
\]  \hspace{1cm} (2.1)

where \( E \) is the modulus of elasticity, \( I \) is the moment of inertia of the column, and \( KL \) is the effective length of the column. Lamarle in 1845 had established the elastic limit as the limit of validity of Euler's formula.

Engesser presented the tangent-modulus theory in 1889 for inelastic buckling. In 1891, Considère predicted that the column strength in the case of inelastic buckling may be determined by a generalized Euler formula,

\[
P = \frac{\pi^2 \bar{E} I}{(KL)^2}
\]  \hspace{1cm} (2.2)

where \( \bar{E} \) is a variable modulus varying between Young's modulus and tangent modulus. Engesser in 1895 acknowledged Considère's concept and gave an improved solution of the column problem by presenting his "double-modulus" theory also called "reduced-modulus" theory. Engesser's theoretical studies were shown to be correct by a series of very careful tests performed by Kármán in 1908. Engesser's "double-modulus" theory was accepted as a true theory of column action in the inelastic buckling range till 1947 when Shanley showed that the tangent modulus load is the lower limit of the buckling load.
2.1.2 Imperfect Column Theory

Out-of-straightness of the column and/or eccentricity of the load which are unavoidable in practice, introduce bending from the start of the loading. Therefore, for real columns, there is no bifurcation of equilibrium, i.e., no critical load, but only buckling load.

2.2 COLUMN DESIGN BASED ON STRENGTH THEORY

The present state of research is such that if the following information is known, accurate calculation of the maximum strength is possible [Galambos 1998]:

1. Material properties (yield stress $F_y$ and modulus of elasticity $E$).
2. Cross-sectional dimensions.
3. Distribution of the residual stresses.
4. The shape and the magnitude of the initial out-of-straightness.
5. The moment-rotation relationship of the end restraint.

2.2.1 Compressive Resistance of Solid Round Steel Members as per Canadian Standard [CSA 2001]

The Canadian Standard, CSA S37-01, specifies the compressive resistance as follows:

$$C_r = \phi \times A \times F_y \times \left(1 + \lambda^{2n}\right)^{1/n}$$

(2.3)

where the resistance factor $\phi = 0.9$.

The non-dimensional slenderness parameter $\lambda$ is given by:

$$\lambda = \frac{KL}{r} \sqrt{\frac{F_y}{\pi^2 E}}$$

(2.4)

2.2.2 Compressive Resistance of Solid Round Steel Members as per American Specification [AISC 1999]

Compressive resistance according to AISC-LRFD Specification is as follows:

$$C_r = \phi \times A \times F_{cr}$$

(2.5)

where the resistance factor $\phi = 0.85$. 

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For $\lambda \leq 1.5$, $F_{cr} = \left(0.658^2\right) \times F_y$  \hspace{1cm} (2.6)

For $\lambda > 1.5$, $F_{cr} = \left[\frac{0.877}{\lambda^2}\right] \times F_y$  \hspace{1cm} (2.7)

$\lambda$ is as defined in Equation 2.4.

Where:

- $A$ = gross area of cross-section
- $E$ = Young's modulus of elasticity
- $F_{cr}$ = critical stress
- $F_y$ = specified minimum yield stress
- $K$ = effective length factor
- $L$ = unbraced length of the member
- $n$ = parameter for compressive resistance (1.34 for angles and hot-rolled solid rounds up to 51 mm in diameter)
- $r$ = minimum radius of gyration
- $\phi$ = resistance factor
- $\lambda$ = non-dimensional slenderness parameter
CHAPTER 3
FINITE ELEMENT ANALYSIS TO DETERMINE THE COMPRESSION
STRENGTH OF SOLID ROUND STEEL MEMBERS

3.1 GENERAL

In order to evaluate the compressive strength of solid round steel leg and bracing members, post-
buckling analysis using modified static Riks method was carried out using ABAQUS, a
commercial finite element package developed by Hibbitt, Karlsson & Sorensen, Inc [HKS 2004].
The effect of four parameters was studied. The effects of end welding, compressive pre-loading,
and number of U-bolts were studied in the finite element analysis for leg members. The effect of
the type of the reinforcement was studied in the finite element analysis for bracing members.

3.2 DETERMINATION OF THE COMPRESSION STRENGTH OF SOLID ROUND STEEL LEG MEMBERS

3.2.1 Details of Finite Element Models

The finite element models consisted of five types of leg members. The leg members were 25.4
mm (1 in.) in diameter and 1750 mm long (69 in.) as shown in Figures 1.1 to 1.4. The first model
is unreinforced as shown in Figure 1.1. The second model is a leg member reinforced with L 51 x
51 x 4.8 mm (L 2 x 2 x 3/16 in.) section 1700 mm (67 in.) long and with 11 U-bolts of 9.53 mm (3/8
in.) diameter as shown in Figure 1.2. The third and fourth models are the same as the second
model, but having only eight U-bolts and five U-bolts respectively as shown in Figures 1.3 and
1.4. The last (fifth) model is a leg member reinforced with the same size of angle using both 11
U-bolts and end welding (Figure 1.2).

The unreinforced leg member was modelled as Euler-Bernoulli (slender) beam elements using
element type B23 (which is a two-node cubic element in plane). This type of element does not
allow transverse shear deformation and plane sections initially normal to the beam's axis remain
plane and normal to the beam axis (no warping) after deformation. This element was chosen
because the cross-sectional dimensions of the members were small compared to the distance
between support points, i.e. joints and end supports. The end conditions are assumed as fixed to
simulate the conditions to be used during experimental verification. At intermediate and end
panel points, translation in x-direction (for definition of x directions, refer to Figure 1.1) is
restrained to account for the finite length of the joints.
For reinforced members, the leg members and angle reinforcements were modelled as Euler-Bernoulli (slender) beam elements using element type B33 (a two-node cubic element in space which has more integration points for angle section than B23) with translation in y-direction, rotation with respect to x-axis, and rotation with respect to vertical axis restrained (for definition of x and y directions, refer to Figures 1.2 to 1.4). At intermediate and end panel points, translation in x-direction is restrained to account for the finite length of the joints.

The leg members and angle reinforcements were modelled as two beams connected together using multi-point constraint, which allows constraints to be imposed between different degrees of freedom of the member at the location of the joint, i.e. location of the U-bolts and end welding. “Pin” multi-point constraint was used at the location of U-bolts since this type of multi-point constraint makes the displacements equal but leaves the rotations independent of each other. To model the end welding, “tie” multi-point constraint was used. This type of multi-point constraint makes all degrees of freedom equal between the two nodes.

The material properties used are 200 GPa for Young’s modulus of elasticity and 0.3 for Poisson’s ratio (Appendix A). From laboratory tensile coupon tests using standard ASTM procedures, the yield stress of the 25.4 mm (1 in.) diameter main leg member was 404 MPa (58.6 ksi) and the tensile strength is 548 MPa (79.5 ksi). For the L 51 x 51 x 4.8 mm (L 2 x 2 x 3/16 in.) used as the reinforcing member, the yield stress was 323 MPa (46.9 ksi). Although elastic-perfectly plastic behaviour is assumed in the majority of cases, strain hardening effects have to be included at the top and bottom of the models (there is a 25.4 mm (1 in.) gap and a 63.5 mm (2.5 in.) length of angle which has no load carrying capacity till the first U-bolt) to eliminate premature yielding of the leg member. Without the strain hardening of the main leg member, finite element analysis results in a maximum load of only 205 kN or 46.1 kips (yield stress times the area of the leg) irrespective of the size of the reinforcement. To account for strain hardening effect for models 2 to 5, the tensile strength is included in the plastic material properties for the 88.9 mm (3.5 in.) length of main leg member.

The solid round main leg member was divided into 276 elements and angle reinforcement was divided into 268 elements. From preliminary analysis using different numbers of elements for leg member reinforced with angle using 11 U-bolts (Figure 3.1), it is determined that the number of elements chosen will give results with sufficient accuracy and without excessive computational effort.
Figure 3.1. Number of Element vs. Maximum Load for Leg Member Reinforced with Angles using 11 U-bolts
3.2.2 Analysis Procedures

3.2.2.1 Eigenvalue buckling prediction [HKS 2004]

Eigenvalue buckling analysis is generally used to estimate the critical (bifurcation) load of "stiff" structures. ABAQUS contains a capability for estimating elastic buckling by eigenvalue extraction. This estimation is typically useful for "stiff" structures, where the pre-buckling response is almost linear. The buckling load estimation is obtained as a multiplier of the pattern of perturbation loads, which are added to a set of base state loads. The base state of the structure may have resulted from any type of response history, including non-linear effects. It represents the initial state to which the perturbation loads are added. The response to the perturbation loads must be elastic up to the estimated buckling load values for the eigenvalue estimates to be reasonable.

In simple cases, linear eigenvalue analysis may be sufficient for design evaluation. But if there is concern about material non-linearity, geometric non-linearity prior to buckling, or unstable post-buckling response, a load-deflection analysis (e.g., modified static Riks method) must be performed to investigate the problem further.

3.2.2.2 Modified Riks algorithm [HKS 2004]

It is necessary to obtain non-linear static equilibrium solutions for unstable problems, where the load-displacement response can exhibit the type of behaviour sketched in Figure 3.2(a), i.e., during periods of response, the load and/or the displacement may decrease as the solution evolves. The modified Riks method is an algorithm that allows effective solution of such cases. It is assumed that the loading is proportional (Figure 3.2(b)), i.e., all load magnitudes vary with a single scalar parameter. It is also assumed that the response is reasonably smooth. (Sudden bifurcations do not occur.)

The essence of the method is that the solution is viewed as the discovery of a single equilibrium path in a space defined by the nodal variables and the loading parameter. Development of the solution requires that the path is traversed as far as required. The basic algorithm remains the Newton method. Therefore, there will be a finite radius of convergence at any time. Further, many of the materials (and possibly loadings) of interest will have path-dependent response. For these reasons, it is essential to limit the increment size.
Figure 3.2. Load-Displacement Curves of Unstable Response [HKS 2004]

(a) Typical Unstable Static Response

(b) Proportional Loading with Unstable Response

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In the modified Riks algorithm, the increment size is limited by moving a given distance (determined by the standard, convergence rate-dependent, automatic increment algorithm for static case) along the tangent line to the current solution point and then searching for equilibrium in the plane that passes through the point thus obtained and that is orthogonal to the same tangent line. Here the geometry referred to is the space of displacements, rotations, and the load parameter mentioned above.

The Riks method uses the load magnitude as an additional unknown, it solves simultaneously for loads and displacements. Another quantity, i.e., "arc length", is used to measure the progress of the solution along the static equilibrium path in load-displacement space. This approach provides solutions regardless of whether the response is stable or unstable. This method, which is available in ABAQUS, is generally used to predict unstable, geometrically non-linear collapse of a structure. This method can also include non-linear materials and boundary conditions and often follows an eigenvalue buckling analysis to provide complete information about a structure's collapse. It can be used to solve post-buckling problems, both with stable and unstable post-buckling behaviour.

However, the exact post-buckling response cannot be analyzed directly due to the discontinuous response at the point of buckling. To analyze a post-buckling problem, it must be turned into a problem with continuous response instead of bifurcation. This effect can be accomplished by introducing an initial imperfection into a "perfect" geometry so that there is some response in the buckling mode before the critical load is reached. The imperfections are usually introduced by perturbations in the geometry, although perturbations in loads or boundary conditions can also be used to introduce initial imperfections.

Unless the precise shape of an imperfection is known, an imperfection consisting of multiple superimposed buckling modes must be introduced. In this way, the Riks method can be used to perform post-buckling analyses of structures that show linear behaviour prior to (bifurcation) buckling. Imperfections based on linear buckling modes can also be useful for the analysis of structures that behave inelastically prior to reaching peak load.

3.2.2.3 Analysis steps

For each model, there were two analyses, one step in each analysis. The first analysis performed an eigenvalue buckling analysis on the member. This facilitated the introduction of geometric imperfection, i.e., initial out-of-straightness, to the member. The fundamental buckling
modes of the five types of specimens are given in Figures 3.3 to 3.4. The photographs of the actual specimens can be seen in Figures 4.1 to 4.5.

In the second analysis, an imperfection in the geometry was added to the straight member using results of the first analysis. For main leg members, L/750 was used as initial out-of-straightness since the ends are not free to rotate [Timoshenko and Gere, 1961]. Using modified static Riks method, a geometrically non-linear load-displacement analysis of the models containing the imperfection was performed. The result of this second analysis was the load magnitude parameter, which results in the actual load if multiplied by the applied load during analysis.

For leg members with compressive pre-loading, the models were given a compressive load up to desired percentage of pre-loading, i.e. 50% (90 kN or 20.2 kips) and 70% (125 kN or 28.1 kips) of the maximum load carrying capacity of the unreinforced leg member. Using model change – remove option, the reinforcing angle was removed during the pre-loading. After loading, the reinforcing angle was added using model change – add option in ABAQUS. This option allows the stress-free element reactivation, with the activated element, i.e., reinforcing angle, following the displacement of the deformed leg member.

3.2.3 Finite Element Analysis Results

3.2.3.1 Effect of end welding

The failure loads according to finite element analysis are presented in column 5 of Table 3.1. Model number 5 (with end welding) has 6% (16 kN or 3.5 kips) more strength than model 2 (without end welding). However, the buckling modes of the model 2 and 5 (Figures 3.4(a) and (d)) are not much different. It can be concluded that end welding provides additional reserve strength to the reinforced member with 11 U-bolts.

3.2.3.2 Effect of compressive pre-loading

A close examination of column 5 of Table 3.1 shows that the compressive pre-loading has no effect on the strength of the reinforced leg member.
Figure 3.3. Fundamental Buckling Mode for Unreinforced Leg Member (Model 1)
(a) Reinforced using 11 U-bolts (Model 2)
(b) Reinforced using Eight U-bolts (Model 3)
(c) Reinforced using Five U-bolts (Model 4)
(d) Reinforced using 11 U-bolts and End Welding (Model 5)

Figure 3.4. Fundamental Buckling Modes of Reinforced Leg Members
Table 3.1. Failure Loads of Leg Members

<table>
<thead>
<tr>
<th>Type of Leg Member</th>
<th>Finite Element Model #</th>
<th>Number of U-bolts</th>
<th>Pre-load kN (kips)</th>
<th>Failure Load kN (kips)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unreinforced</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>166 (37.3)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>90 (20.2)</td>
<td>262 (58.9)</td>
<td></td>
</tr>
<tr>
<td>Reinforced with angle without end welding</td>
<td>3</td>
<td>8</td>
<td>125 (28.1)</td>
<td>260 (58.4)</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>90 (20.2)</td>
<td>245 (55.1)</td>
<td></td>
</tr>
<tr>
<td>Reinforced with angle with end welding</td>
<td>5</td>
<td>11</td>
<td>-</td>
<td>278 (62.5)</td>
</tr>
</tbody>
</table>

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3.2.3.3 Effect of number of U-bolts

The load-displacement curves at the maximum displaced node of the models are shown in Figure 3.5 for all five finite element models. It can be readily seen that by using a reinforcing angle, the displacement of the models is reduced. Also, using 11 U-bolts resulted in maximum reduction in the displacement (models 2 and 5). It is clear that the displacement of the leg members reinforced with an angle with eight U-bolts (model 3) is not much different from that with five U-bolts (model 4).

Even though 60% more U-bolts are used in model 3 compared to model 4, there is only a slight increase in the strength of the member (compare columns 5 of Table 3.1). It can be seen that the eight-bolt arrangement (Figure 1.3) results in the maximum U-bolt distance of 254 mm (10 in.), whereas the five-bolt arrangement (Figure 1.4) reduces the maximum distance between U-bolts to 216 mm (8.5 in.). Thus, the arrangement of U-bolts in leg members with five U-bolts is more effective than that of tower with eight U-bolts in each leg, thus partially offsetting the beneficial effect of increased number of U-bolts. It can be concluded that the arrangement of U-bolts is more important than the number of U-bolts.

3.3 DETERMINATION OF THE COMPRESSIVE STRENGTH OF SOLID ROUND STEEL BRACING MEMBERS

3.3.1 Details of Finite Element Models

The finite element models consisted of three types of bracing members. The bracing members were 15.9 mm (5/8 in.) diameter, 737 mm long (29 in.), with a 152 x 152 x 12.7 mm (6 x 6 x 1/2 in.) plate welded at top and bottom of the members as shown in Figures 1.5, 3.6, and 3.7. The first model is unreinforced as shown in Figure 3.6. The second model is a bracing member reinforced with 15.9 mm (5/8 in.) diameter 711 mm (28 in.) long rods with three 9.53 mm (3/8 in.) diameter U-bolts as shown in Figure 3.7. The last (third) model is a bracing member reinforced with L 44 x 44 x 3.2 mm (L 1 3/4 x 1 3/4 x 1/8 in.) 711 mm (28 in.) long with three 9.53 mm (3/8 in.) diameter U-bolts as shown in Figure 1.5.

From mill test certificates, the yield stress of the 15.9 mm (5/8 in.) diameter main bracing member was 343 MPa (49.8 ksi). For the 15.9 mm (5/8 in.) diameter rod used as the reinforcing member, the yield stress was 405 MPa (58.8 ksi). For the angle member, the yield stress was 330 MPa (47.9 ksi).
Figure 3.5. Load-displacement Curves for Leg Members
Figure 3.6. Details of Unreinforced Bracing Member
Figure 3.7. Details of Bracing Member Reinforced with Rod
The unreinforced and rod-reinforced bracing members (bracing member and the reinforcing rod) were modelled as Euler-Bernoulli (slender) beam elements using element type B23, which is a two-node cubic element in plane. For angle-reinforced bracing members, the bracing member and the reinforcing angle were modelled as Euler-Bernoulli (slender) beam using element type B33 (a two-node cubic element in space) to get more integration points for the reinforcing members with translation in y-direction, rotation with respect to x-axis, and rotation with respect to vertical axis restrained (for definition of x and y directions, refer to Figure 1.5). This element does not allow transverse shear deformation and plane sections initially normal to the beam's axis remain plane and normal to the beam axis (no warping). This element was chosen because the cross-sectional dimensions of the members were small compared to the distance between support points.

For reinforced members, the test specimens were modelled as two beams connected using multi-point constraint option, which allows constraints to be imposed between different degrees of freedom of the member at the location of the joint, i.e. location of the U-bolts. Pin multi-point constraint was used since this type of multi-point constraint makes the displacements equal but leaves the rotations independent of each other.

The solid round main bracing member was divided into 116 elements and the rod reinforcement and angle reinforcement were divided into 112 elements each. From preliminary analysis using different numbers of elements, it is determined that the number of elements chosen will give results with sufficient accuracy without excessive computational effort.

3.3.2 Analysis Procedures

For each type of specimen, there were two analyses, one step for each analysis. The first analysis performed an eigenvalue buckling analysis. This facilitated the introduction of geometric imperfection, i.e., initial out-of-straightness, to the member. The fundamental buckling modes of the three types of specimens are given in Figures 3.8 and 3.9.

In the second analysis, an imperfection in the geometry was added to the straight member using results of the first analysis. For the main bracing members, L/400 was used as initial out-of-straightness. This is slightly less than the maximum permissible L/250 out-of-straightness stipulated in CSA S37-01. Using modified static Riks method, a geometrically non-linear load-displacement analysis of the specimens containing the imperfection was performed. The result of this second analysis was the load magnitude parameter, which results in the actual load if multiplied by the applied load during analysis.
Figure 3.8. Fundamental Buckling Mode for Unreinforced Bracing Member (Model 1)

Figure 3.9. Fundamental Buckling Modes for Reinforced Bracing Members

(a) Reinforced with Rod (Model 2)  (b) Reinforced with Angle (Model 3)

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3.3.3 Finite Element Analysis Results

The failure loads according to finite element analysis results are tabulated in column 3 of Table 3.2. The load-displacement curves at the middle node of the test specimens are shown in Figure 3.10 for unreinforced, rod-reinforced, and angle-reinforced specimens. An examination of Figure 3.10 clearly shows that the maximum deflection is reduced from 19 mm for the case of unreinforced specimens to 12 mm for rod-reinforced case and 3.5 mm for angle-reinforced specimens.

From column 4 of Table 3.2, it is seen that the increase in strength due to the angle reinforcement is 67% while it is 29% for rod reinforcement. However, it should be noted that angle reinforcement is 38% heavier and also results in higher wind load on the tower because of larger exposed area and flat shape.
Table 3.2. Failure Loads of Bracing Members

<table>
<thead>
<tr>
<th>Type of Bracing Member</th>
<th>Finite Element Model #</th>
<th>Failure Load kN (kips)</th>
<th>Relative Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unreinforced</td>
<td>1</td>
<td>32.9 (7.40)</td>
<td>1.00</td>
</tr>
<tr>
<td>Rod-reinforced</td>
<td>2</td>
<td>42.4 (9.53)</td>
<td>1.29</td>
</tr>
<tr>
<td>Angle-reinforced</td>
<td>3</td>
<td>55.0 (12.4)</td>
<td>1.67</td>
</tr>
</tbody>
</table>
Figure 3.10. Load-displacement Curves for Bracing Members
CHAPTER 4
EXPERIMENTAL INVESTIGATION

4.1 GENERAL

The results of finite element analysis have to be validated by experimental investigations. Fifteen tower sections (45 leg member specimens) and seven bracing member specimens were included in this investigation.

4.2 EXPERIMENTAL INVESTIGATION ON THE COMPRESSION STRENGTH OF LEG MEMBERS

The effects of (i) failure of one leg members to the strength of the remaining leg members, (ii) end welding, (iii) compressive pre-loading, (iv) number of U-bolts, and (v) bolt torque on the compressive strength of leg members were studied during this experimental investigation.

4.2.1 Design of Experiments

Since it is difficult, expensive, and time-consuming to fabricate the antenna tower sections, it is desirable to get the maximum information by testing as few specimens as possible. Since each tower has three legs, it would be advantageous if each leg is tested separately. This of course assumes that the failure of one leg (with consequent deformation of cross bracings) has no effect on the strength of the remaining legs. To verify this assumption, preliminary tests (Series I) on three tower sections were conducted.

4.2.2 Preliminary Tests (Series I)

The purpose of these tests was to determine whether the failure of one or two leg member(s) with consequent deformation of bracing members has an effect on the strength of the remaining leg member(s). This series consisted of three triangular antenna tower sections as shown in Figure 1.1. These tower sections were fabricated by Electronics Research Inc., Chandler, Indiana, using normal shop practice without taking any special precautions. This was necessary to get representative samples for testing.

Since only one leg was tested at a time, the top and bottom of the one of the legs were fixed to the test structure while the other two legs were free. Load was applied concentrically in small increments at the top of the leg through a hydraulic jack, and the load applied was measured with
a load cell. Figure 4.1 shows the test setup. After the first leg failed, the process was repeated with the second and third legs.

The failure loads for the three legs of each of the three tower sections are given in Table 4.1. An examination of Table 4.1 clearly shows that the compressive strength of the leg member(s) was not affected by the failure of other leg member(s) in the tower.

4.2.3 Description of Test Specimens (Series II)

Having confirmed that failure of one leg member has no effect on the strength of the remaining leg members, additional twelve tower sections were fabricated by Electronics Research Inc., Chandler, Indiana, and tests were carried out on individual leg members to study the effect of the various parameters discussed above.

4.2.3.1 The effect of end welding

To study the effect of end welding to the compressive strength of leg members, six tower sections (# 4 to # 9) were included in this investigation. Tower sections # 4 to # 6 were reinforced with angles using 11 U-bolts. Tower sections # 7 to # 9 were reinforced with angles using 11 U-bolts and end welding. Both details of tower sections can be seen in Figure 1.2. Figure 4.2 shows the tower sections reinforced with angles using 11 U-bolts after failure. The results are tabulated in Table 4.2. It can be seen that end welding increase the strength by 12% from reinforced specimens without end welding.

4.2.3.2 The effect of compressive pre-loading

Six tower sections (# 10 to # 15) identical to the ones used in preliminary tests were included in this investigation. One leg of each test specimen was tested without any reinforcement while the second leg was reinforced (before applying any load) with an angle. The third leg of each test specimens was also reinforced with the same stock of angle, but the reinforcement was attached to the leg member after the leg member was pre-loaded. The pre-load was 50% (90 kN or 20.2 kips) of the strength of unreinforced leg member, i.e., leg # 1, for towers # 10, 11, and 12, and 70% (125 kN or 28.1 kips) for towers # 13, 14, and 15.

Comparing the failure loads for leg # 3 with those of leg # 2 for each of the six test specimens (shown in column 6 of Table 4.3), it is obvious that pre-load has no effect on the strengthening of the member.
Figure 4.1. Test Setup for Preliminary Tests (Series I)
Table 4.1. Results of Preliminary Tests (Series I)

<table>
<thead>
<tr>
<th>Tower Section #</th>
<th>Leg #</th>
<th>Maximum Load kN (kips)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>164 (36.9)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>169 (38.0)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>174 (39.1)</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>169 (38.0)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>164 (36.9)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>164 (36.9)</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>169 (38.0)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>164 (36.9)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>164 (36.9)</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>167 (37.5)</td>
</tr>
<tr>
<td>Standard deviation</td>
<td></td>
<td>3.32 (0.75)</td>
</tr>
<tr>
<td>Coefficient of variation</td>
<td></td>
<td>2%</td>
</tr>
</tbody>
</table>
Figure 4.2. Leg Member Reinforced with Angle using 11 U-bolts after Failure (Series II)
### Table 4.2. Results of Tower Tests # 4 to # 9 (Series II)

<table>
<thead>
<tr>
<th>Tower Section #</th>
<th>Leg #</th>
<th>Maximum Load</th>
<th>Tower Section #</th>
<th>Leg #</th>
<th>Maximum Load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>283 (63.7)</td>
<td>4</td>
<td>1</td>
<td>283 (63.7)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>242 (54.4)</td>
<td>7</td>
<td>2</td>
<td>288 (64.7)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>251 (56.5)</td>
<td></td>
<td>3</td>
<td>292 (65.7)</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>251 (56.5)</td>
<td>8</td>
<td>1</td>
<td>274 (61.6)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>251 (56.5)</td>
<td></td>
<td>2</td>
<td>279 (62.7)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>256 (57.5)</td>
<td></td>
<td>3</td>
<td>279 (62.7)</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>256 (57.5)</td>
<td>9</td>
<td>1</td>
<td>288 (64.7)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>247 (55.5)</td>
<td></td>
<td>2</td>
<td>288 (64.7)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>274 (61.6)</td>
<td></td>
<td>3</td>
<td>283 (63.7)</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>254 (57.2)</td>
<td>Average</td>
<td></td>
<td>284 (63.8)</td>
</tr>
</tbody>
</table>

### Table 4.3. Results of Tower Tests # 10 to # 15 (Series II)

<table>
<thead>
<tr>
<th>Tower Section #</th>
<th>Leg #</th>
<th>Number of Bolts</th>
<th>Pre-load Bolt Torque</th>
<th>Bolt Torque N.m (lb-ft)</th>
<th>Maximum Load</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>170 (38.2)</td>
<td>No separation</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>11</td>
<td>-</td>
<td>27 (20)</td>
<td>266 (59.8)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>90 (20.2)</td>
<td>271 (60.9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>178 (40.0)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8</td>
<td>-</td>
<td>239 (53.7)</td>
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<td>Separated</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>90 (20.2)</td>
<td>236 (53.1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>175 (39.3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5</td>
<td>-</td>
<td>242 (54.4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>90 (20.2)</td>
<td>242 (54.4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>186 (41.8)</td>
<td>No separation</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>11</td>
<td>-</td>
<td>41 (30)</td>
<td>278 (62.5)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>125 (28.1)</td>
<td>278 (62.1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>175 (39.3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8</td>
<td>-</td>
<td>41 (30)</td>
<td>253 (56.9)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>125 (28.1)</td>
<td>254 (57.1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>177 (39.8)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5</td>
<td>-</td>
<td>41 (30)</td>
<td>244 (54.9)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>125 (28.1)</td>
<td>239 (63.7)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.2.3.3 The effect of number of U-bolts

Failure loads for leg # 2 of specimens # 10 and # 13 with 11 bolts were 266 and 278 kN (59.8 and 62.5 kips) respectively, with an average value of 272 kN (61.2 kips). The failure loads for leg # 2 of specimens # 11 and # 14 with eight bolts were 239 and 253 kN (53.7 and 56.9 kips), with an average value of 246 kN (55.3 kips). For specimens # 12 and # 15 with five bolts, the corresponding failure loads were 242 and 244 kN (54.4 and 54.9 kips) with an average value of 243 kN (54.6 kips).

It is obvious that reducing the number of bolts from 11 to eight and five bolts resulted in reduction of the compressive strength of the members. From Figure 4.3, it can be seen that there was no separation between the leg members and reinforcing members at failure when the angle was attached by 11 bolts (three bolts in one panel). However, when eight and five bolts were used for each leg, there was separation at failure as can be seen in Figures 4.4 and 4.5.

It is clear that the strength of the leg members reinforced with an angle with eight bolts is not much greater than that with five bolts. Effective arrangement of bolts can reduce the number of bolts, resulting in a reduction of the fabrication cost in the shop and the labour cost at the field.

To prevent separation of the reinforcing member and leg member at failure, it is recommended that the maximum distance between bolts be determined such that the non-dimensional slenderness parameter $\lambda$ for the leg member is less than 0.25, so that the reinforced member between the bolts can be treated as a stocky column. Any further increase in the number of bolts with consequent decrease in $\lambda$ does not result in any increase in the compressive strength.

4.2.3.4 The effect of torque applied to U-bolts

Two torques were applied: 27 N.m (20 lb-ft) was applied to leg # 2 of towers # 10, 11, and 12, while 41 N.m (30 lb-ft) was applied to leg # 2 of towers # 13, 14, and 15. If the bolt torque is higher, the connections of the leg member and reinforcing member at the bolt locations act more like rigid connections (where the rotation and translation of the joints are equal in those two members). If the bolt torque is lower, they act more like pinned connections, where only the translations between the members are equal. So higher bolt torque resulted in higher compressive strength.
Figure 4.3. Failure Mode of a Leg Member Reinforced using 11 U-Bolts
(Three U-Bolts in a Panel)
Figure 4.4. Failure Mode of a Leg Member Reinforced using Eight U-Bolts
(Two U-Bolts in a Panel)
Figure 4.5. Failure Mode of a Leg Member Reinforced using Five U-Bolts
(One U-Bolt in a Panel)
Comparing failure loads of leg # 2 of tower sections # 10 and # 13, the failure load increased from 266 to 278 kN (59.8 to 62.5 kips) for an increase in bolt torque from 27 N.m (20 lb-ft) to 41 N.m (30 lb-ft). Similarly, comparing the failure loads of tower sections # 11 and # 14, the increase was 239 to 253 kN (53.7 to 56.9 kips) for the same increase in bolt torque. Results for tower sections # 12 and # 15 show that failure load increased from 242 to 244 kN (54.4 to 54.9 kips) for the same increase in bolt torque. Therefore, it can be concluded that increase in bolt torque results in an increase in the failure load, even though the increase is not commensurate with the increase in the torque.

4.3 EXPERIMENTAL INVESTIGATION ON THE COMPRRESSIVE STRENGTH OF BRACING MEMBERS

Two unreinforced solid round bracing member specimens, three bracing member specimens reinforced with rods, and two bracing member specimens reinforced with angles were included in the investigation. The dimensions of the specimens are given in Figures 1.5, 3.6, and 3.7. The number of U-bolts was chosen to reduce the slenderness ratio of the bracing members to approximately 60 ($\lambda = 0.8$), which is the current industry practice. The effectiveness of the two types of reinforcing members, i.e. rod and angles, was also studied.

4.3.1 Test Setup and Testing of Specimens

The test setup is shown in Figure 4.6. The plates at the top and bottom of the specimens were fixed to the test structure to prevent lateral displacement of the specimens during testing. Load was applied concentrically in small increments from the top of the specimen through a hydraulic jack until the test specimen failed. The applied load was measured by means of a 111 kN (25 kips) load cell.

4.3.2 Test Results

The maximum applied load was recorded and presented in column 4 of Table 4.4. Figures 4.7 to 4.10 show the test specimens after failure. It can be seen from these figures that the displacement in the middle of the specimens was reduced because of the strengthening, especially for the specimen reinforced with angle. From column 5 of Table 4.4, it is seen that increase in strength due to the angle reinforcement is 77% while it is 48% for rod reinforcement.
Figure 4.6. Test Setup for Bracing Member Specimen
Table 4.4. Experimental Failure Loads of Bracing Members

<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></td>
<td>kN (kips)</td>
<td>kN (kips)</td>
<td></td>
</tr>
<tr>
<td>BU-1</td>
<td>Unreinforced</td>
<td>29.4 (6.61)</td>
<td>30.4 (6.83)</td>
<td>1.00</td>
</tr>
<tr>
<td>BU-2</td>
<td></td>
<td>31.4 (7.06)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BR-1</td>
<td>Rod-reinforced</td>
<td>44.0 (9.89)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BR-2</td>
<td></td>
<td>42.7 (9.60)</td>
<td>44.9 (10.1)</td>
<td>1.48</td>
</tr>
<tr>
<td>BR-3</td>
<td></td>
<td>48.0 (10.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BA-1</td>
<td>Angle-reinforced</td>
<td>56.2 (12.6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BA-2</td>
<td></td>
<td>51.6 (11.6)</td>
<td>53.9 (12.1)</td>
<td>1.77</td>
</tr>
</tbody>
</table>
Figure 4.7. Photograph of Unreinforced Specimen after Failure
Figure 4.8. Photograph of Rod-reinforced Specimen after Failure - 1
Figure 4.9. Photograph of Rod-reinforced Specimen after Failure - 2
Figure 4.10. Photograph of Angle-reinforced Specimen after Failure
CHAPTER 5
COMPARISON OF RESULTS FROM FINITE ELEMENT ANALYSIS AND EXPERIMENTAL INVESTIGATION

5.1 GENERAL

In this chapter, the results from finite element analysis of the compressive strength of solid round steel leg and bracing members are compared with the results from experimental investigation, in order to validate the finite element models built.

5.2 COMPARISON OF FINITE ELEMENT ANALYSIS AND EXPERIMENTAL INVESTIGATION ON COMPRESSION STRENGTH OF LEG MEMBERS

The results from finite element analysis given in Chapter 3 and the averaged results of experimental failure load given in Chapter 4 on the compressive strength of leg members are compared together in Table 5.1.

Comparing values in columns 4 and 6, it can be readily concluded that the experimental results validated the finite element analysis. Thus, the finite element analysis can be used to determine the compressive strength of any size of leg members reinforced with proper size angles.

Although actual displacements during experimental investigation was not measured, by comparing the fundamental buckled shapes in Figures 3.3 and 3.4 with Figures 4.1 to 4.5, it can be seen that except for the specimen with 11 U-bolts, the deflected shapes of the leg members are the same as the corresponding buckled shapes. It can also be seen that the separation between the leg member and the reinforcing angle is increasing during buckling when the number of bolts is reduced, which is also confirmed during experimental investigation.
Table 5.1. Failure Load of Leg Members According to Finite Element Analysis (FEA) and Experimental Investigation

<table>
<thead>
<tr>
<th>Type of Leg Member</th>
<th>Number of U-bolts</th>
<th>Pre-load</th>
<th>FEA</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Failure Load</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Number of Specimens</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Average Failure Load</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Unreinforced</td>
<td>-</td>
<td>-</td>
<td>166</td>
<td>(37.3)</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>262</td>
<td>(59.0)</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>262</td>
<td>1</td>
<td>271</td>
</tr>
<tr>
<td></td>
<td>(20.2)</td>
<td>(58.9)</td>
<td></td>
<td>(60.9)</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>260</td>
<td>1</td>
<td>276</td>
</tr>
<tr>
<td></td>
<td>(28.1)</td>
<td>(58.4)</td>
<td></td>
<td>(62.1)</td>
</tr>
<tr>
<td>Reinforced with angle without end welding</td>
<td>8</td>
<td>90</td>
<td>245</td>
<td>(20.2)</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>254</td>
<td>1</td>
<td>254</td>
</tr>
<tr>
<td></td>
<td>(28.1)</td>
<td>(57.0)</td>
<td></td>
<td>(57.2)</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>240</td>
<td>(53.9)</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>243</td>
<td>1</td>
<td>242</td>
</tr>
<tr>
<td></td>
<td>(20.2)</td>
<td>(54.6)</td>
<td></td>
<td>(54.4)</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>242</td>
<td>1</td>
<td>239</td>
</tr>
<tr>
<td></td>
<td>(28.1)</td>
<td>(54.5)</td>
<td></td>
<td>(53.7)</td>
</tr>
<tr>
<td>Reinforced with angle with end welding</td>
<td>11</td>
<td>-</td>
<td>278</td>
<td>(62.5)</td>
</tr>
</tbody>
</table>

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Comparing Figures 3.4 and 4.2 (leg member reinforced with 11 U-bolts, with and without end welding), it should be noted that the buckled shapes from finite element analysis (Figures 3.4(a) and (d)) are different from the deflected shape observed during experimental investigation (Figure 4.2). In the finite element analysis, the maximum displacement of the angle member is not in the middle of the specimens. This can be readily explained as follows. In the finite element models, there were no horizontal and diagonal bracing members modelled. The panel points were modelled as simple unyielding supports, with no translation in x-direction. During the experimental testing, due to the horizontal and diagonal bracing members (which were connected to other legs), the deflected shapes of the angles were reversed and the maximum displacement of the angle occurred at the mid-height of the specimens.

5.3 COMPARISON OF FINITE ELEMENT ANALYSIS AND EXPERIMENTAL INVESTIGATION ON COMpressive STRENGTH OF BRACING MEMBERS

In a similar way, the results from finite element analysis in Chapter 3 and the averaged results of experimental investigation in Chapter 4 on the compressive strength of bracing members are presented together in Table 5.2.

Comparing values in columns 2 and 4, it can be readily concluded that the experimental results validated the finite element analysis. Thus, the finite element analysis can be used to determine the compressive strength of any size of bracing members reinforced with proper size rods or angles.

The buckled shape in Figures 3.8 and 3.9 and the deflected shape of the bracing members after failure in the test showed in Figures 4.7 to 4.10 agree closely, although the actual displacement during testing is not measured. There is a similar reduction in the displacement of the middle node because of the reinforcement in both finite element analysis and experimental investigation.
Table 5.2. Failure Load of Bracing Members According to Finite Element Analysis (FEA) and Experimental Investigation

<table>
<thead>
<tr>
<th>Type</th>
<th>FEA Failure Load</th>
<th>Experiment Number of Specimens</th>
<th>Average Failure Load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kN (kips)</td>
<td></td>
<td>kN (kips)</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Unreinforced</td>
<td>32.9 (7.40)</td>
<td>2</td>
<td>30.4 (6.83)</td>
</tr>
<tr>
<td>Rod-reinforced</td>
<td>42.4 (9.53)</td>
<td>3</td>
<td>44.9 (10.1)</td>
</tr>
<tr>
<td>Angle-reinforced</td>
<td>55.0 (12.4)</td>
<td>2</td>
<td>53.9 (12.1)</td>
</tr>
</tbody>
</table>

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CHAPTER 6
PROPOSED DESIGN METHOD TO CALCULATE THE COMPRESSION STRENGTH OF SOLID ROUND STEEL LEG AND BRACING MEMBERS

6.1 GENERAL

After the validation of the finite element results and experimental investigation, simplified conservative design methods to calculate the compressive strength of solid round steel leg and bracing members reinforced with rods/angles are proposed. The results from the proposed method were also validated with the finite element analysis results.

6.2 PROPOSED DESIGN METHOD TO CALCULATE THE COMPRESSION STRENGTH OF LEG MEMBERS REINFORCED WITH ANGLES

Based on the finite element analysis and experimental validation, the following method is proposed to determine the compressive resistance of solid round steel leg members reinforced with angles. It is assumed that the area of angle is at least equal to the area of the main leg member. The angle leg is also assumed to be wide enough to accommodate the slotted holes for U-bolt connection, as shown in Figures 1.2 to 1.4, and the width-to-thickness ratio of the angle leg does not exceed the limit for a "compact" section.

6.2.1 Design Procedure

a) For main leg member, use effective length factor \( K = 1.0 \) and length as the maximum distance between the U-bolts. For finite element model 2, \( L \) is equal to 127 mm (5 in.). For finite element model 3, \( L \) is equal to 254 mm (10 in.), and for finite element model 4, \( L \) is equal to 216 mm (8.5 in.). Calculate the compressive resistance as per Canadian Standard and American Specification given in Chapter 2, which is repeated below:

Compressive resistance according to CSA S37-01:

\[
C_r = \phi \times A \times F_y \times \left(1 + \frac{\lambda^2}{n}\right)\frac{1}{n}
\]

\[
\lambda = \frac{KL}{r} \frac{F_y}{\sqrt{\pi^2E}}
\]
Compressive resistance according to AISC-LRFD Specification:

\[ C_r = \phi \times A \times F_{cr} \]  \hspace{1cm} (2.5)

For \( \lambda \leq 1.5 \), \( F_{cr} = \left( 0.658 \lambda^2 \right) \times F_y \) \hspace{1cm} (2.6)

For \( \lambda > 1.5 \), \( F_{cr} = \left[ \frac{0.877}{\lambda^2} \right] \times F_y \) \hspace{1cm} (2.7)

\( \lambda \) is as defined in Equation 2.4.

b) For the reinforcing angle, use effective length factor \( K = 1.0 \) and length as the panel length, i.e. 432 mm (17 in.) for all models. Calculate the compressive resistance using the formulas above and take 50% of the calculated value to account for eccentricity effects (the load is concentric to the main leg member).

c) Add the above two resistances to get the resistance of the reinforced member.

Resistance factor \( \phi \) is taken as 0.9 for CSA S37-01 Standard, and 0.85 for AISC-LRFD Specification.

The results calculated as above are tabulated in the last two column of Table 6.1. It can be readily seen that this method is a simple and conservative approach to determine the resistance of reinforced member. Welding adds additional strength which is considered as reserve capacity and is not accounted for in the simplified design method proposed.

6.2.2 Design Examples

The proposed method was used to determine the compressive resistance of 102 mm (4 in.) diameter leg member reinforced with L 203 x 203 x 22 (L 8 x 8 x \( \frac{7}{8} \)) and 127 mm (5 in.) diameter leg member reinforced with L 203 x 203 x 29 (L 8 x 8 x \( \frac{11}{8} \)).

The results of finite element analysis and the proposed method based on Canadian Standard and American Specification are presented in Table 6.2.

It can be seen that the proposed design method is satisfactory. Thus, this proposed design method could be used to calculate the compressive resistance of any size leg members reinforced with any size angles.
Table 6.1. Failure Loads and Compressive Resistances of Reinforced Leg Members

<table>
<thead>
<tr>
<th>Type of Leg Member</th>
<th>Number of U-bolts</th>
<th>Failure Load</th>
<th>Average Failure Load</th>
<th>Proposed Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>FEA</td>
<td>Experiment</td>
<td>CSA S37-01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>kN</td>
<td>kN</td>
<td>kN</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(kips)</td>
<td>(kips)</td>
<td>(kips)</td>
</tr>
<tr>
<td>Reinforced with angle without end welding</td>
<td>11</td>
<td>262</td>
<td>258</td>
<td>238</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(59.0)</td>
<td>(57.9)</td>
<td>(53.5)</td>
</tr>
<tr>
<td>Reinforced with angle with end welding</td>
<td>8</td>
<td>253</td>
<td>246</td>
<td>217</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(56.9)</td>
<td>(55.3)</td>
<td>(48.7)</td>
</tr>
<tr>
<td>Reinforced with angle with end welding</td>
<td>5</td>
<td>240</td>
<td>243</td>
<td>225</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(53.9)</td>
<td>(54.6)</td>
<td>(50.6)</td>
</tr>
</tbody>
</table>

Table 6.2. Design Examples of Reinforced Leg Members using Proposed Method

<table>
<thead>
<tr>
<th>Leg Member</th>
<th>Reinforcing Angle</th>
<th>Failure Load based on FEA</th>
<th>Proposed Compressive Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>CSA S37-01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>kN</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(kips)</td>
</tr>
<tr>
<td>102 mm diameter</td>
<td>L 203 x 203 x 22 mm</td>
<td>4197</td>
<td>3950</td>
</tr>
<tr>
<td>(4 in.) diameter</td>
<td>(L 8 x 8 x 7/8 in.)</td>
<td>(944)</td>
<td>(888)</td>
</tr>
<tr>
<td>127 mm diameter</td>
<td>L 203 x 203 x 29 mm</td>
<td>6570</td>
<td>5723</td>
</tr>
<tr>
<td>(5 in.) diameter</td>
<td>(L 8 x 8 x 1 1/8 in.)</td>
<td>(1477)</td>
<td>(1287)</td>
</tr>
</tbody>
</table>
6.3 PROPOSED DESIGN METHOD TO CALCULATE THE COMPRESSIVE STRENGTH OF BRACING MEMBERS REINFORCED WITH RODS OR ANGLES

Based on the finite element analysis and experimental investigation, the following method is proposed to determine the compressive resistance of solid round steel bracing members reinforced with rods/angles as below. It is assumed that the area of the reinforcement is at least equal to the area of the main bracing member. In addition, the angle leg is assumed to be wide enough to accommodate the slotted holes for U-bolt connection, as shown in Figure 1.5, and the width-to-thickness ratio of the angle leg does not exceed the limit for a “compact” section.

6.3.1 Design Procedure

(a) For a bracing member reinforced with rod, take the effective length factor \( K = 1.0 \) and the unbraced length of the bracing member as the distance between U-bolts.

(b) For bracing member reinforced with angle, take the effective length factor \( K = 0.75 \) and the effective length as the distance between the U-bolts. Examination of Figure 3.9(b) shows that the angle reinforcement not only reduces the unbraced length to the distance between the U-bolts, but also provides rotational restraint to the bracing member at the connection points. Therefore a \( K \) factor of 0.75 (average of pinned-end and fixed-end condition) is proposed to calculate the compressive resistance of the angle-reinforced member.

Resistance factor \( \phi \) is taken as 0.9 for CSA S37-01 Standard, and 0.85 for AISC-LRFD Specification.

The results based on the proposed method are given in the last two columns of Table 6.3. It can be readily seen that this method is a simple and conservative approach to determine the resistance of reinforced bracing member.

6.3.2 Design Examples

The proposed method was used to calculate the compressive strength of 31.8 mm (1\(\frac{1}{4}\) in.) diameter bracing member reinforced with the same size of rod and 47.6 mm (1\(\frac{7}{8}\) in.) diameter leg member reinforced with the same size of rod. The results of finite element analysis and the proposed method based on Canadian Standard and American Specification are presented in Table 6.4.
Table 6.3. Failure Loads and Compressive Resistances of Reinforced Bracing Members

<table>
<thead>
<tr>
<th>Type</th>
<th>Failure Load</th>
<th>Average Failure Load</th>
<th>Proposed Method</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>FEA</td>
<td>Experimental</td>
<td>CSA S37-01</td>
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<tr>
<td></td>
<td>kN</td>
<td>kN</td>
<td>kN</td>
</tr>
<tr>
<td></td>
<td>(kips)</td>
<td>(kips)</td>
<td>(kips)</td>
</tr>
<tr>
<td>Rod-reinforced</td>
<td>42.4</td>
<td>44.9</td>
<td>42.4</td>
</tr>
<tr>
<td></td>
<td>(9.53)</td>
<td>(10.1)</td>
<td>(9.53)</td>
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<tr>
<td>Angle-reinforced</td>
<td>55.0</td>
<td>53.9</td>
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</tr>
<tr>
<td></td>
<td>(12.4)</td>
<td>(12.1)</td>
<td>(11.3)</td>
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Table 6.4. Design Examples of Rod-reinforced Bracing Members using Proposed Method

<table>
<thead>
<tr>
<th>Bracing Member</th>
<th>Reinforcing Rod</th>
<th>Failure Load based on FEA</th>
<th>Proposed Compressive Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>31.8 mm diameter</td>
<td>31.8 mm diameter</td>
<td>170</td>
<td>CSA S37-01</td>
</tr>
<tr>
<td>(1/4 in.) diameter</td>
<td>(1/4 in.) diameter</td>
<td>(38.2)</td>
<td>kN</td>
</tr>
<tr>
<td>47.6 mm diameter</td>
<td>47.6 mm diameter</td>
<td>382</td>
<td>AISC-LRFD</td>
</tr>
<tr>
<td>(1/4 in.) diameter</td>
<td>(1/4 in.) diameter</td>
<td>(85.9)</td>
<td>kN</td>
</tr>
</tbody>
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Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
The proposed method was also used to calculate the compressive strength of 31.8 mm (1\text{\textfrac{1}{4}}\text{ in.}) diameter bracing member reinforced with L 64 x 64 x 7.9 (L 2\text{\textfrac{1}{2}} x 2\text{\textfrac{1}{2}} x 5_{16}) and 47.6 mm (1\text{\textfrac{7}{8}}\text{ in.}) diameter leg member reinforced with L 89 x 89 x 11 (L 3\text{\textfrac{1}{2}} x 3\text{\textfrac{1}{2}} x 7_{16}) as reinforcing angle. The results of finite element analysis and the proposed method based on Canadian Standard and American Specification are presented in Table 6.5.

It can be seen from Tables 6.4 and 6.5 that the proposed design method is satisfactory.
Table 6.5. Design Examples of Angle-reinforced Bracing Members using Proposed Method

<table>
<thead>
<tr>
<th>Bracing Member</th>
<th>Reinforcing Angle</th>
<th>Failure Load based on FEA</th>
<th>Proposed Compressive Resistance</th>
<th>CSA S37-01</th>
<th>AISC-LRFD</th>
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<tr>
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<td>kN</td>
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<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
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<tr>
<td>31.8 mm diameter</td>
<td>L 64 x 64 x 7.9 mm</td>
<td>219</td>
<td>202</td>
<td>195</td>
<td></td>
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<tr>
<td>(1 1/4 in.) diameter</td>
<td>(L 2 1/2 x 2 1/2 x 5/16 in.)</td>
<td>(49.2)</td>
<td>(45.4)</td>
<td>(43.8)</td>
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<tr>
<td>47.6 mm diameter</td>
<td>L 89 x 89 x 11 mm</td>
<td>490</td>
<td>454</td>
<td>439</td>
<td></td>
</tr>
<tr>
<td>(1 7/8 in.) diameter</td>
<td>(L 3 1/2 x 3 1/2 x 7/16 in.)</td>
<td>(110)</td>
<td>(102)</td>
<td>(98.7)</td>
<td></td>
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</tbody>
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CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

Based on the finite element analysis and experimental investigation, the following conclusions can be drawn:

a. The experimental results validated the finite element models and thus the finite element models can be used to determine the compressive strength of any size solid round leg member reinforced with proper size angle and the compressive strength of any size solid round bracing member reinforced with proper size round bar or proper size angle.

b. The failure of one leg member has no effect on the strength of the remaining leg members.

c. End welding provides additional reserve strength to the leg members.

d. Compressive pre-loading has no effect on the strengthening.

e. The number of U-bolts has an effect on the strength, but the location of bolts is more important than the number. It is recommended that the number and arrangement of U-bolts is such that the non-dimensional slenderness parameter $\lambda$ for leg member is less than 0.25, so that the member can be treated as a stocky column. The number of U-bolts for bracing member should be sufficient to reduce the slenderness ratio into 60 ($\lambda = 0.8$).

f. Increased bolt torque results in an increase in the strength.

g. The angle reinforcement is more effective than rod reinforcement.

h. If the sizes of rods and angles follow the current industry practice (mentioned in the beginning of Chapter 6), the design method proposed is simple and conservative for determining the compressive resistance of leg members reinforced with angles and the compressive resistance of bracing members reinforced with rods/angles.

7.2 RECOMMENDATIONS

It is recommended that further finite element analysis be carried out using continuum elements in order to model the bolt torque applied to U-bolts. Further experimental investigation on solid round steel members with larger size than those used in the present investigation is also recommended.
REFERENCES


APPENDIX A – MATERIAL PROPERTIES

Young's modulus = 200 GPa
Poisson's ratio = 0.3

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<th>Type</th>
<th>Cross-section</th>
<th>$F_y$ MPa (ksi)</th>
<th>$F_u$ MPa (ksi)</th>
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<tr>
<td>Leg member</td>
<td>25.4 mm – $\phi$ round bar (1 in. – $\phi$ round bar)</td>
<td>404 (58.6)</td>
<td>548 (79.5)</td>
</tr>
<tr>
<td>Bracing member</td>
<td>15.9 mm – $\phi$ round bar ($\frac{5}{8}$ in. – $\phi$ round bar)</td>
<td>343 (49.8)</td>
<td>-</td>
</tr>
<tr>
<td>Reinforcing angle</td>
<td>L 51 x 51 x 4.8 mm (L 2 x 2 x $\frac{3}{16}$ in.)</td>
<td>323 (46.9)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>L 44 x 44 x 3.2 mm (L 1$\frac{3}{4}$ x 1$\frac{3}{4}$ x $\frac{1}{8}$ in.)</td>
<td>330 (47.9)</td>
<td>-</td>
</tr>
<tr>
<td>Reinforcing rod</td>
<td>15.9 mm – $\phi$ round bar ($\frac{3}{16}$ in. – $\phi$ round bar)</td>
<td>405 (58.8)</td>
<td>-</td>
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APPENDIX B – CALIBRATION OF LOAD CELLS

B1. Calibration of 890 kN (200 kips) Compression Flat Load Cell

Model: FL200C(C) 250K
S/N: 05320-3
Gauge factor: 2.062 (full bridge)
Date: 2003-05-20

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Figure B1. Load-Strain Curve for 890 kN (200 kips) Load Cell

$y = 0.2285x$
### Calibration of 445 kN (100 kips) Universal Flat Load Cell

**Model:** FL100U(C) 25GKT  
**S/N:** 05320-2  
**Gauge factor:** 2.061 (full bridge)  
**Date:** 2004-02-16

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Figure B2. Load-Strain Curve for 445 kN (100 kips) Load Cell

\[ y = 0.1139x \]
B3. Calibration of 111 kN (25 kips) Universal Flat Load Cell

Model: FL25U-ZSG
S/N: FL25U-0214EE
Gauge factor: 2.062 (full bridge)
Date: 2003-09-08

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<td>3627</td>
</tr>
<tr>
<td>106</td>
<td>3695</td>
</tr>
<tr>
<td>108</td>
<td>3767</td>
</tr>
<tr>
<td>110</td>
<td>3836</td>
</tr>
<tr>
<td>112</td>
<td>3905</td>
</tr>
<tr>
<td>114</td>
<td>3974</td>
</tr>
<tr>
<td>116</td>
<td>4040</td>
</tr>
</tbody>
</table>

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Figure B3. Load-Strain Curve for 111 kN (25 kips) Load Cell
APPENDIX C – ABAQUS INPUT FILES

C1. ABAQUS Input Files for Unreinforced Leg Member

*HEADING
Unreinforced Leg Member
International System Unit
Eigenvalue Buckling Analysis

*PARAMETER
L1 = 25.4 * 1.5
L2 = 25.4 * 6.25
L3 = 25.4 * 2.5
L4 = 25.4 * 15.5
L5 = 25.4 * 0.5
L6 = 25.4 * 16.5
R = 25.4 * 0.5 * 1
Y1 = L1
Y2 = Y1 + L2
Y3 = Y2 + L3
Y4 = Y3 + L4
Y5 = Y4 + L5
Y6 = Y5 + L6
Y7 = Y6 + L5
Y8 = Y7 + L4
Y9 = Y8 + L3
Y10 = Y9 + L2
Y11 = Y10 + L1

*NODE, NSET = BOT1-1
  1, 0, 0
*NODE, NSET = BOT1-2
  151.0, Y1, 0
*NODE, NSET = MID2-1
  776, 0, Y2, 0
*NODE, NSET = MID2-2
  1026.0, Y3, 0
*NODE, NSET = MID3-1
  2576, 0, Y4, 0
*NODE, NSET = MID3-2
  2626, 0, Y5, 0
*NODE, NSET = MID4-1
  4276, 0, Y6, 0
*NODE, NSET = MID4-2
  4326, 0, Y7, 0
*NODE, NSET = MID5-1
  5876, 0, Y8, 0
*NODE, NSET = MID5-2
  6126, 0, Y9, 0
*NODE, NSET = TOP6-1
  6751.0, Y10, 0
*NODE, NSET = TOP6-2
  6901.0, Y11, 0

*NFILL, NSET = NBC
  BOT1-1, BOT1-2, 6, 25
  MID2-1, MID2-2, 10, 25
  MID3-1, MID3-2, 2, 25
  MID4-1, MID4-2, 2, 25
  MID5-1, MID5-2, 10, 25
  TOP6-1, TOP6-2, 6, 25
*NFILL, NSET = NALL
BOT1-2, MID2-1, 25, 25
MID2-2, MID3-1, 62, 25
MID3-2, MID4-1, 66, 25
MID4-2, MID5-1, 62, 25
MID5-2, TOP6-1, 25, 25
*NSET, NSET = NALL
NBC
*ELEMENT, TYPE = B23
  1, 1, 26
*ELGEN, ELSET = EROUND
  1, 276, 25, 1
*BEAM SECTION, SECTION = CIRC, ELSET = EROUND, MATERIAL = ROUND
  <R>
  *MATERIAL, NAME = ROUND
  *ELASTIC
  200000, 0.3
  *PLASTIC
  404, 0
  *STEP
  *BUCKLE
  5
  *BOUNDARY
  NBC, 1
  BOT1-1, 2
*LOAD
  TOP6-2, 2, -150000
*NODE FILE
U
*OUTPUT, FIELD, VARIABLE = ALL, FREQUENCY = 1
*NODE OUTPUT
U
*END STEP
Unreinforced Leg Member
International System Unit
Post-buckling Analysis

**PARAMETER**

\[
\begin{align*}
L_1 &= 25.4 \times 1.5 \\
L_2 &= 25.4 \times 6.25 \\
L_3 &= 25.4 \times 2.5 \\
L_4 &= 25.4 \times 15.5 \\
L_5 &= 25.4 \times 0.5 \\
L_6 &= 25.4 \times 16.5 \\
R &= 25.4 \times 0.5 \times 1 \\
Y_1 &= L_1 \\
Y_2 &= Y_1 + L_2 \\
Y_3 &= Y_2 + L_3 \\
Y_4 &= Y_3 + L_4 \\
Y_5 &= Y_4 + L_5 \\
Y_6 &= Y_5 + L_6 \\
Y_7 &= Y_6 + L_5 \\
Y_8 &= Y_7 + L_4 \\
Y_9 &= Y_8 + L_3 \\
Y_{10} &= Y_9 + L_2 \\
Y_{11} &= Y_{10} + L_1 \\
L &= Y_{11}
\end{align*}
\]

**MODESCALE**

\[
\text{MODESCALE} = L / 750
\]

**NODE, NSET = BOT1-1**

1, 0, 0, 0

**NODE, NSET = BOT1-2**

151, 0, <Y1>, 0

**NODE, NSET = MID2-1**

776, 0, <Y2>, 0

**NODE, NSET = MID2-2**

1026, 0, <Y3>, 0

**NODE, NSET = MID3-1**

2576, 0, <Y4>, 0

**NODE, NSET = MID3-2**

2626, 0, <Y5>, 0

**NODE, NSET = MID4-1**

4276, 0, <Y6>, 0

**NODE, NSET = MID4-2**

4326, 0, <Y7>, 0

**NODE, NSET = MID5-1**

5876, 0, <Y8>, 0

**NODE, NSET = MID5-2**

6126, 0, <Y9>, 0

**NODE, NSET = TOP6-1**

6751, 0, <Y10>, 0

**NODE, NSET = TOP6-2**

6901, 0, <Y11>, 0

**NFILL, NSET = NBC**

BOT1-1, BOT1-2, 6, 25

MID2-1, MID2-2, 10, 25

MID3-1, MID3-2, 2, 25

MID4-1, MID4-2, 2, 25

MID5-1, MID5-2, 10, 25

TOP6-1, TOP6-2, 6, 25

**NFILL, NSET = NALL**

BOT1-2, MID2-1, 25, 25

MID2-2, MID3-1, 62, 25

MID3-2, MID4-1, 66, 25

MID4-2, MID5-1, 62, 25

MID5-2, TOP6-1, 25, 25
*NSET, NSET = NALL
NBC
*ELEMENT, TYPE = B23
  1, 1, 26
*ELGEN, ELSET = EROUND
  1, 276, 25, 1
*BEAM SECTION, SECTION = CIRC, ELSET = EROUND, MATERIAL = ROUND
  <R>
*MATERIAL, NAME = ROUND
*ELASTIC
  200000, 0.3
*PLASTIC
  404, 0
*IMPERFECTION, FILE = LU-b, STEP = 1
  1, <Modescale1>
*STEP, NAME = LOAD, NLGEOM, INC = 50
*STATIC, RIKS
  0.25, , 0.5
*BOUNDARY
  NBC, 1
  BOT1-1, 2
*CLOAD
  TOP6-2, 2, -150000
*OUTPUT, FIELD, VARIABLE = ALL, FREQUENCY = 1
*NODE PRINT, NSET = NALL
  U
*EL PRINT, ELSET = EROUND
  S11
*END STEP
C2. ABAQUS Input Files for Leg Member Reinforced with Angle using 11 U-bolts

*HEADING
Leg Member Reinforced with Angle without End Welding (3 bolts in middle panel)
International System Unit
Eigenvalue Buckling Analysis
*PARAMETER
R = 25.4 * 1 * 0.5
Z1 = 25.4 * 1
Z2 = 25.4 * 3.5
Z3 = 25.4 * 9
Z4 = 25.4 * 12.5
Z5 = 25.4 * 17.5
Z6 = 25.4 * 22.5
Z7 = 25.4 * 26
Z8 = 25.4 * 29.5
Z9 = 25.4 * 34.5
Z10 = 25.4 * 39.5
Z11 = 25.4 * 43
Z12 = 25.4 * 46.5
Z13 = 25.4 * 51.5
Z14 = 25.4 * 56.5
Z15 = 25.4 * 60
Z16 = 25.4 * 65.5
Z17 = 25.4 * 68
Z18 = 25.4 * 69
*NODE, NSET = BOT1
1, 0, 0, 0
*NODE, NSET = MMID2
351, 0, 0, <Z2>
*NODE, NSET = MID2
901, 0, 0, <Z3>
*NODE, NSET = MMID3
1251, 0, 0, <Z4>
*NODE, NSET = MMID4
1751, 0, 0, <Z5>
*NODE, NSET = MMID5
225, 0, 0, <Z6>
*NODE, NSET = MID3
2601, 0, 0, <Z7>
*NODE, NSET = MMID6
2951, 0, 0, <Z8>
*NODE, NSET = MMID7
3451, 0, 0, <Z9>
*NODE, NSET = MMID8
3951, 0, 0, <Z10>
*NODE, NSET = MID4
4301, 0, 0, <Z11>
*NODE, NSET = MMID9
4651, 0, 0, <Z12>
*NODE, NSET = MMID10
5151, 0, 0, <Z13>
*NODE, NSET = MMID11
5651, 0, 0, <Z14>
*NODE, NSET = MID5
6001, 0, 0, <Z15>
*NODE, NSET = MMID12
6551, 0, 0, <Z16>
*NODE, NSET = TOP6
6901, 0, 0, <Z18>
*NODE, NSET = LBOT1
102, 0, 0, <Z1>
*NODE, NSET = LMID2
352, 0, 0, <Z2>
*NODE, NSET = LMID3
1252, 0, 0, <Z4>
*NODE, NSET = LMID4
1752, 0, 0, <Z5>
*NODE, NSET = LMID5
2252, 0, 0, <Z6>
*NODE, NSET = LMID6
2952, 0, 0, <Z8>
*NODE, NSET = LMID7
3452, 0, 0, <Z9>
*NODE, NSET = LMID8
3952, 0, 0, <Z10>
*NODE, NSET = LMID9
4652, 0, 0, <Z12>
*NODE, NSET = LMID10
5152, 0, 0, <Z13>
*NODE, NSET = LMID11
5652, 0, 0, <Z14>
*NODE, NSET = LMID12
6552, 0, 0, <Z16>
*NODE, NSET = LTOP13
6802, 0, 0, <Z17>
*NFILL, NSET = NMAIN
BOT1, TOP6, 276, 25
*NSET, NSET = NBC, GENERATE
1, 151, 25
776, 1026, 25
2576, 2626, 25
4276, 4326, 25
5876, 6126, 25
6751, 6901, 25
*NFILL, NSET = NANGLE
LBOT1, LTOP13, 268, 25
*NSET, NSET = NALL
NMAIN, NANGLE
*ELEMENT, TYPE = B33
1, 1, 26
15, 351, 376
263, 6551, 6576
277, 102, 127
*ELGEN, ELSET = EROUNDSH
1, 14, 25, 1
263, 14, 25, 1
*ELGEN, ELSET = EROUND
15, 248, 25, 1
*ELGEN, ELSET = EANGLE
277, 268, 25, 1
*ELSET, ELSET = EALL
EROUNDSH, EROUND, EANGLE
*MPC
PIN, MMID2, LMID2
PIN, MMID3, LMID3
PIN, MMID4, LMID4
PIN, MMID5, LMID5
PIN, MMID6, LMID6
PIN, MMID7, LMID7
PIN, MMID8, LMID8
PIN, MMID9, LMID9
PIN, MMID10, LMID10

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PIN, MMID11, LMID11
PIN, MMID12, LMID12
*BEAM SECTION, SECTION = CIRC, ELSET = EROUNDSH, MATERIAL = ROUNDSH
  <R>
  0, 1, 0
*BEAM SECTION, SECTION = CIRC, ELSET = EROUND, MATERIAL = ROUND
  <R>
  0, 1, 0
*BEAM SECTION, SECTION = ARBITRARY, ELSET = EANGLE, MATERIAL = ANGLE
  2, 18.82, 35.92, -17.1, 0, 4.76
  18.82, -35.92, 4.76
  0, 1, 0
*MATERIAL, NAME = ROUNDSH
*ELASTIC
  200000, 0.3
*PLASTIC
  404, 0
  548, 0.045
*MATERIAL, NAME = ROUND
*ELASTIC
  200000, 0.3
*PLASTIC
  404, 0
*MATERIAL, NAME = ANGLE
*ELASTIC
  200000, 0.3
*PLASTIC
  323, 0
*STEP
*BUCKLE
  5
*BOUNDARY
  NBC, 1, 2
  BOT1, 3
  NALL, 2
  NALL, 4
  NALL, 6
*CLOAD
  TOP6, 3, -150000
*NODE FILE
  U
*OUTPUT, FIELD, VARIABLE = ALL, FREQUENCY = 1
*END STEP
**HEADING**
Leg Member Reinforced with Angle without End Welding (3 bolts in middle panel)
International System Unit
Post-buckling Analysis

**PARAMETER**
R = 25.4 * 1 * 0.5
Z1 = 25.4 * 1
Z2 = 25.4 * 3.5
Z3 = 25.4 * 9
Z4 = 25.4 * 12.5
Z5 = 25.4 * 17.5
Z6 = 25.4 * 22.5
Z7 = 25.4 * 26
Z8 = 25.4 * 29.5
Z9 = 25.4 * 34.5
Z10 = 25.4 * 39.5
Z11 = 25.4 * 43
Z12 = 25.4 * 46.5
Z13 = 25.4 * 51.5
Z14 = 25.4 * 56.5
Z15 = 25.4 * 60
Z16 = 25.4 * 65.5
Z17 = 25.4 * 68
Z18 = 25.4 * 69
L=Z18
Modescale1=L/750

*NODE, NSET = BOT1
1, 0, 0, 0
*NODE, NSET = MMID2
351, 0, 0, <Z2>
*NODE, NSET = MID2
901, 0, 0, <Z3>
*NODE, NSET = MMID3
1251, 0, 0, <Z4>
*NODE, NSET = MMID4
1751, 0, 0, <Z5>
*NODE, NSET = MMID5
2251, 0, 0, <Z6>
*NODE, NSET = MID3
2601, 0, 0, <Z7>
*NODE, NSET = MMID6
2951, 0, 0, <Z8>
*NODE, NSET = MMID7
3451, 0, 0, <Z9>
*NODE, NSET = MMID8
3951, 0, 0, <Z10>
*NODE, NSET = MID4
4301, 0, 0, <Z11>
*NODE, NSET = MMID9
4651, 0, 0, <Z12>
*NODE, NSET = MMID10
5151, 0, 0, <Z13>
*NODE, NSET = MMID11
5651, 0, 0, <Z14>
*NODE, NSET = MID5
6001, 0, 0, <Z15>
*NODE, NSET = MMID12
6551, 0, 0, <Z16>
*NODE, NSET = TOP6
6901, 0, 0, <Z18>
*NODE, NSET = LBOT1
102, 0, 0, <Z1>
*NODE, NSET = LMID2
  352, 0, 0, <Z2>
*NODE, NSET = LMID3
  1252, 0, 0, <Z4>
*NODE, NSET = LMID4
  1752, 0, 0, <Z5>
*NODE, NSET = LMID5
  2252, 0, 0, <Z6>
*NODE, NSET = LMID6
  2952, 0, 0, <Z8>
*NODE, NSET = LMID7
  3452, 0, 0, <Z9>
*NODE, NSET = LMID8
  3952, 0, 0, <Z10>
*NODE, NSET = LMID9
  4652, 0, 0, <Z12>
*NODE, NSET = LMID10
  5152, 0, 0, <Z13>
*NODE, NSET = LMID11
  5652, 0, 0, <Z14>
*NODE, NSET = LMID12
  6552, 0, 0, <Z16>
*NODE, NSET = LTOP13
  6802, 0, 0, <Z17>
*NFILL, NSET = NMAIN
  BOT1, TOP6, 276, 25
*NSET, NSET = NBC, GENERATE
  1, 151, 25
  776, 1026, 25
  2576, 2626, 25
  4276, 4326, 25
  5876, 6126, 25
  6751, 6901, 25
*NFILL, NSET = NANGLE
  LBOT1, LTOP13, 268, 25
*NSET, NSET = NALL
  NMAIN, NANGLE
*ELEMENT, TYPE = B33
  1, 1, 26
  15, 351, 376
  263, 6551, 6576
  277, 102, 127
*ELGEN, ELSET = EROUNDSH
  1, 14, 25, 1
  263, 14, 25, 1
*ELGEN, ELSET = EROUND
  15, 248, 25, 1
*ELGEN, ELSET = EANGLE
  277, 268, 25, 1
*ELSET, ELSET = EALL
  EROUNDSH, EROUND, EANGLE
*MPC
  PIN, MMID2, LMID2
  PIN, MMID3, LMID3
  PIN, MMID4, LMID4
  PIN, MMID5, LMID5
  PIN, MMID6, LMID6
  PIN, MMID7, LMID7
  PIN, MMID8, LMID8
  PIN, MMID9, LMID9
  PIN, MMID10, LMID10
  PIN, MMID11, LMID11
PIN, MMID12, LMID12
*BEAM SECTION, SECTION = CIRC, ELSET = EROUND, MATERIAL = ROUNDSH
  <R>
  0, 1, 0
*BEAM SECTION, SECTION = CIRC, ELSET = EROUND, MATERIAL = ROUND
  <R>
  0, 1, 0
*BEAM SECTION, SECTION = ARBITRARY, ELSET = EANGLE, MATERIAL = ANGLE
  2, 18.82, 35.92, -17.1, 0, 4.76
  18.82, -35.92, 4.76
  0, 1, 0
*MATERIAL, NAME = ROUNDSH
*ELASTIC
  200000, 0.3
*PLASTIC
  404, 0
  548, 0.045
*MATERIAL, NAME = ROUND
*ELASTIC
  200000, 0.3
*PLASTIC
  404, 0
*MATERIAL, NAME = ANGLE
*ELASTIC
  200000, 0.3
*PLASTIC
  323, 0
*IMPERFECTION, FILE = LUW3-b, STEP = 1
  1, <Modescale1>
*STEP, NAME = LOAD, NLGEOM, INC = 150
*STATIC, RIKS
  0.25, . . , 0.5
*BOUNDARY
  NBC, 1, 2
  BOT1, 3
  NALL, 2
  NALL, 4
  NALL, 6
*CLOAD
  TOP6, 3, -150000
*OUTPUT, FIELD, VARIABLE = ALL, FREQUENCY = 1
*NODE PRINT, NSET = NALL
  U
*EL PRINT, ELSET = EALL
  S11
*END STEP
C3. ABAQUS Input Files for Leg Member Reinforced with Angle using 11 U-bolts and End Welding

*HEADING
Leg Member Reinforced with Angle and End Welding
International System Unit
Eigenvalue Buckling Analysis

*PARAMETER
R = 25.4 * 1 * 0.5
Z1 = 25.4 * 1
Z2 = 25.4 * 3.5
Z3 = 25.4 * 9
Z4 = 25.4 * 12.5
Z5 = 25.4 * 17.5
Z6 = 25.4 * 22.5
Z7 = 25.4 * 26
Z8 = 25.4 * 29.5
Z9 = 25.4 * 34.5
Z10 = 25.4 * 39.5
Z11 = 25.4 * 43
Z12 = 25.4 * 46.5
Z13 = 25.4 * 51.5
Z14 = 25.4 * 56.5
Z15 = 25.4 * 60
Z16 = 25.4 * 65.5
Z17 = 25.4 * 68
Z18 = 25.4 * 69

*NODE, NSET = BOT1
  1, 0, 0, 0
*NODE, NSET = MMID2
  351, 0, 0, <Z2>
*NODE, NSET = MID2
  901, 0, 0, <Z3>
*NODE, NSET = MMID3
  1251, 0, 0, <Z4>
*NODE, NSET = MMID4
  1751, 0, 0, <Z5>
*NODE, NSET = MMID5
  2251, 0, 0, <Z6>
*NODE, NSET = MMID6
  2601, 0, 0, <Z7>
*NODE, NSET = MMID7
  2951, 0, 0, <Z8>
*NODE, NSET = MMID8
  3451, 0, 0, <Z9>
*NODE, NSET = MMID9
  3951, 0, 0, <Z10>
*NODE, NSET = MID3
  4301, 0, 0, <Z11>
*NODE, NSET = MMID10
  4651, 0, 0, <Z12>
*NODE, NSET = MMID11
  5151, 0, 0, <Z13>
*NODE, NSET = MMID12
  5651, 0, 0, <Z14>
*NODE, NSET = MID4
  6001, 0, 0, <Z15>
*NODE, NSET = MMID13
  6551, 0, 0, <Z16>
*NODE, NSET = TOP6
6901, 0, 0, <Z18>
*NODE, NSET = LBOT1
  102, 0, 0, <Z1>
*NODE, NSET = LMID2
  352, 0, 0, <Z2>
*NODE, NSET = LMID3
  1252, 0, 0, <Z4>
*NODE, NSET = LMID4
  1752, 0, 0, <Z5>
*NODE, NSET = LMID5
  2252, 0, 0, <Z6>
*NODE, NSET = LMID6
  2952, 0, 0, <Z8>
*NODE, NSET = LMID7
  3452, 0, 0, <Z9>
*NODE, NSET = LMID8
  3952, 0, 0, <Z10>
*NODE, NSET = LMID9
  4652, 0, 0, <Z12>
*NODE, NSET = LMID10
  5152, 0, 0, <Z13>
*NODE, NSET = LMID11
  5652, 0, 0, <Z14>
*NODE, NSET = LMID12
  6552, 0, 0, <Z16>
*NODE, NSET = LTOP13
  6802, 0, 0, <Z17>
*NFILL, NSET = NMAIN
  BOT1, TOP6, 276, 25
*NSET, NSET = NBC, GENERATE
  1, 151, 25
  776, 1026, 25
  2576, 2626, 25
  4276, 4326, 25
  5876, 6126, 25
  6751, 6901, 25
*NFILL, NSET = NANGLE
  LBOT1, LTOP13, 268, 25
*NSET, NSET = NALL
  NMAIN, NANGLE
*ELEMENT, TYPE = B33
  1, 1, 26
  5, 101, 126
  273, 6801, 6826
  277, 102, 127
*ELGEN, ELSET = EROUNDSH
  1, 4, 25, 1
  273, 4, 25, 1
*ELGEN, ELSET = EROUND
  5, 268, 25, 1
*ELGEN, ELSET = EANGLE
  277, 268, 25, 1
*ELSET, ELSET = EALL
  EROUNDSH, EROUND, EANGLE
*MPC
  TIE, 101, 102
  PIN, 351, 352
  PIN, 1251, 1252
  PIN, 1751, 1752
  PIN, 2251, 2252
  PIN, 2951, 2952
  PIN, 3451, 3452
PIN, 3951, 3952
PIN, 4651, 4652
PIN, 5151, 5152
PIN, 5651, 5652
PIN, 6551, 6552
TIE, 6801, 6802

*BEAM SECTION, SECTION = CIRC, ELSET = EROUNDSH, MATERIAL = ROUNDSH
  <R>
  0, 1, 0
*BEAM SECTION, SECTION = CIRC, ELSET = EROUND, MATERIAL = ROUND
  <R>
  0, 1, 0
*BEAM SECTION, SECTION = ARBITRARY, ELSET = EANGLE, MATERIAL = ANGLE
  2, 18.82, 35.92, -17.1, 0, 4.76
  18.82, -35.92, 4.76
  0, 1, 0
*MATERIAL, NAME = ROUNDSH
  *ELASTIC
  200000, 0.3
  *PLASTIC
  404, 0
  548, 0.045
*MATERIAL, NAME = ROUND
  *ELASTIC
  200000, 0.3
  *PLASTIC
  404, 0
*MATERIAL, NAME = ANGLE
  *ELASTIC
  200000, 0.3
  *PLASTIC
  323, 0
*STEP
  *BUCKLE
  5
*BOUNDARY
  NBC, 1, 2
  BOT1, 3
  NALL, 2
  NALL, 4
  NALL, 6
*CLOAD
  TOP6, 3, -150000
*NODE FILE
  U
*OUTPUT, FIELD, VARIABLE = ALL, FREQUENCY = 1
*END STEP
HEADING
Leg Member Reinforced with Angle and End Welding
International System Unit
Post-buckling Analysis

PARAMETER
R = 25.4 * 1 * 0.5
Z1 = 25.4 * 1
Z2 = 25.4 * 3.5
Z3 = 25.4 * 9
Z4 = 25.4 * 12.5
Z5 = 25.4 * 17.5
Z6 = 25.4 * 22.5
Z7 = 25.4 * 26
Z8 = 25.4 * 29.5
Z9 = 25.4 * 34.5
Z10 = 25.4 * 39.5
Z11 = 25.4 * 43
Z12 = 25.4 * 46.5
Z13 = 25.4 * 51.5
Z14 = 25.4 * 56.5
Z15 = 25.4 * 60
Z16 = 25.4 * 65.5
Z17 = 25.4 * 68
Z18 = 25.4 * 69
L = Z18
Modescale1 = L/750

NODE, NSET = BOT1
1, 0, 0, 0

NODE, NSET = MMID1
102, 0, 0, <Z1>

NODE, NSET = MMID2
351, 0, 0, <Z2>

NODE, NSET = MID2
901, 0, 0, <Z3>

NODE, NSET = MMID3
1251, 0, 0, <Z4>

NODE, NSET = MMID4
1751, 0, 0, <Z5>

NODE, NSET = MMID5
2251, 0, 0, <Z6>

NODE, NSET = MID3
2601, 0, 0, <Z7>

NODE, NSET = MMID6
2951, 0, 0, <Z8>

NODE, NSET = MMID7
3451, 0, 0, <Z9>

NODE, NSET = MMID8
3951, 0, 0, <Z10>

NODE, NSET = MID4
4301, 0, 0, <Z11>

NODE, NSET = MMID9
4651, 0, 0, <Z12>

NODE, NSET = MMID10
5151, 0, 0, <Z13>

NODE, NSET = MMID11
5651, 0, 0, <Z14>

NODE, NSET = MID5
6001, 0, 0, <Z15>

NODE, NSET = MMID12
6551, 0, 0, <Z16>

NODE, NSET = TOP6
6901, 0, 0, <Z18>

NODE, NSET = LBOT1
102, 0, 0, <Z1>
*NODE, NSET = LMID2
352, 0, 0, <Z2>
*NODE, NSET = LMID3
1252, 0, 0, <Z4>
*NODE, NSET = LMID4
1752, 0, 0, <Z5>
*NODE, NSET = LMID5
2252, 0, 0, <Z6>
*NODE, NSET = LMID6
2952, 0, 0, <Z8>
*NODE, NSET = LMID7
3452, 0, 0, <Z9>
*NODE, NSET = LMID8
3952, 0, 0, <Z10>
*NODE, NSET = LMID9
4652, 0, 0, <Z12>
*NODE, NSET = LMID10
5152, 0, 0, <Z13>
*NODE, NSET = LMID11
5652, 0, 0, <Z14>
*NODE, NSET = LMID12
6552, 0, 0, <Z16>
*NODE, NSET = LTOP13
6802, 0, 0, <Z17>
*NFILL, NSET = NMAIN
BOT1, TOP6, 276, 25
*NSET, NSET = NBC, GENERATE
1, 151, 25
776, 1026, 25
2576, 2626, 25
4276, 4326, 25
5876, 6126, 25
6751, 6901, 25
*NFILL, NSET = NANGLE
LBOT1, LTOP13, 268, 25
*NSET, NSET = NALL
NMAIN, NANGLE
*ELEMENT, TYPE = B33
1, 1, 26
5, 101, 126
273, 6801, 6826
277, 102, 127
*ELGEN, ELSET = EROUNDSH
1, 4, 25, 1
273, 4, 25, 1
*ELGEN, ELSET = EROUND
5, 268, 25, 1
*ELGEN, ELSET = EANGLE
277, 268, 25, 1
*ELSET, ELSET = EALL
EROUNDSH, EROUND, EANGLE
*MPC
TIE, 101, 102
PIN, 351, 352
PIN, 1251, 1252
PIN, 1751, 1752
PIN, 2251, 2252
PIN, 2951, 2952
PIN, 3451, 3452
PIN, 3951, 3952
PIN, 4651, 4652
PIN, 5151, 5152
PIN, 5651, 5652
PIN, 6551, 6552
TIE, 6801, 6802
*BEAM SECTION, SECTION = CIRC, ELSET = EROUND, MATERIAL = ROUNDSH
  <R>  
  0, 1, 0
*BEAM SECTION, SECTION = CIRC, ELSET = EROUND, MATERIAL = ROUND
  <R>  
  0, 1, 0
*BEAM SECTION, SECTION = ARBITRARY, ELSET = EANGLE, MATERIAL = ANGLE
  2, 18.82, 35.92, -17.1, 0, 4.76
  18.82, -35.92, 4.76
  0, 1, 0
*MATERIAL, NAME = ROUNDSH
*ELASTIC
  200000, 0.3
*PLASTIC
  404, 0
  548, 0.045
*MATERIAL, NAME = ROUND
*ELASTIC
  200000, 0.3
*PLASTIC
  404, 0
*MATERIAL, NAME = ANGLE
*ELASTIC
  200000, 0.3
*PLASTIC
  323, 0
*IMPERFECTION, FILE = LW-b, STEP = 1
  1, <Modescale1>
*STEP, NAME = LOAD, NLGEOM, INC = 50
*STATIC, RIKS
  0.25, , , 0.5
*BOUNDARY
  NBC, 1, 2
  BOT1, 3
  NALL, 2
  NALL, 4
  NALL, 6
*CLOAD
  TOP6, 3, -150000
*OUTPUT, FIELD, VARIABLE = ALL, FREQUENCY = 1
*NODE PRINT, NSET = NALL
  U
*EL PRINT, ELSET = EALL
  S11
*END STEP
C4. ABAQUS Input Files for Leg Member Reinforced with Angle using 11 U-bolts (50% Compressive Pre-loading)

*HEADING
Leg Member Reinforced with Angle without End Welding (3 bolts in middle panel)
50% Compressive Pre-load
International System Unit
Eigenvalue Buckling Analysis

*PARAMETER
R = 25.4 * 1 * 0.5
Z1 = 25.4 * 1
Z2 = 25.4 * 3.5
Z3 = 25.4 * 9
Z4 = 25.4 * 12.5
Z5 = 25.4 * 17.5
Z6 = 25.4 * 22.5
Z7 = 25.4 * 26
Z8 = 25.4 * 29.5
Z9 = 25.4 * 34.5
Z10 = 25.4 * 39.5
Z11 = 25.4 * 43
Z12 = 25.4 * 46.5
Z13 = 25.4 * 51.5
Z14 = 25.4 * 56.5
Z15 = 25.4 * 60
Z16 = 25.4 * 65.5
Z17 = 25.4 * 68
Z18 = 25.4 * 69

*NODE, NSET = BOT1
  1, 0, 0, 0
*NODE, NSET = MMID2
  351, 0, 0, <Z2>
*NODE, NSET = MID2
  901, 0, 0, <Z3>
*NODE, NSET = MMID3
  1251, 0, 0, <Z4>
*NODE, NSET = MMID4
  1751, 0, 0, <Z5>
*NODE, NSET = MMID5
  2251, 0, 0, <Z6>
*NODE, NSET = MID3
  2601, 0, 0, <Z7>
*NODE, NSET = MMID6
  2951, 0, 0, <Z8>
*NODE, NSET = MMID7
  3451, 0, 0, <Z9>
*NODE, NSET = MMID8
  3951, 0, 0, <Z10>
*NODE, NSET = MID4
  4301, 0, 0, <Z11>
*NODE, NSET = MMID9
  4851, 0, 0, <Z12>
*NODE, NSET = MMID10
  5151, 0, 0, <Z13>
*NODE, NSET = MMID11
  5651, 0, 0, <Z14>
*NODE, NSET = MID5
  6001, 0, 0, <Z15>
*NODE, NSET = MMID12
  6551, 0, 0, <Z16>
*NODE, NSET = TOP6
6901, 0, 0, <Z18>
*NODE, NSET = LBOT1
102, 0, 0, <Z1>
*NODE, NSET = LMID2
352, 0, 0, <Z2>
*NODE, NSET = LMID3
1252, 0, 0, <Z4>
*NODE, NSET = LMID4
1752, 0, 0, <Z5>
*NODE, NSET = LMID5
2252, 0, 0, <Z6>
*NODE, NSET = LMID6
2952, 0, 0, <Z8>
*NODE, NSET = LMID7
3452, 0, 0, <Z9>
*NODE, NSET = LMID8
3952, 0, 0, <Z10>
*NODE, NSET = LMID9
4652, 0, 0, <Z12>
*NODE, NSET = LMID10
5152, 0, 0, <Z13>
*NODE, NSET = LMID11
5652, 0, 0, <Z14>
*NODE, NSET = LMID12
6552, 0, 0, <Z16>
*NODE, NSET = LTOP13
6802, 0, 0, <Z17>
*NFILL, NSET = NMAIN
BOT1, TOP6, 276, 25
*NSET, NSET = NBC, GENERATE
1, 151, 25
776, 1026, 25
2576, 2626, 25
4276, 4326, 25
5876, 6126, 25
6751, 6901, 25
*NFILL, NSET = NANGLE
LBOT1, LTOP13, 268, 25
*NSET, NSET = NALL
NMAIN, NANGLE
*ELEMENT, TYPE = B33
1, 1, 26
15, 351, 376
283, 6551, 6576
277, 102, 127
*ELGEN, ELSET = EROUNDSH
1, 14, 25, 1
263, 14, 25, 1
*ELGEN, ELSET = EROUND
15, 248, 25, 1
*ELGEN, ELSET = EANGLE
277, 268, 25, 1
*ELSET, ELSET = EALL
EROUNDSH, EROUND, EANGLE
*MPC
PIN, MMID2, LMID2
PIN, MMID3, LMID3
PIN, MMID4, LMID4
PIN, MMID5, LMID5
PIN, MMID6, LMID6
PIN, MMID7, LMID7

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PIN, MMID8, LMID8
PIN, MMID9, LMID9
PIN, MMID10, LMID10
PIN, MMID11, LMID11
PIN, MMID12, LMID12

*BEAM SECTION, SECTION = CIRC, ELSET = EROUNDSH, MATERIAL = ROUNDSH
  <R>
  0, 1, 0

*BEAM SECTION, SECTION = CIRC, ELSET = EROUND, MATERIAL = ROUND
  <R>
  0, 1, 0

*BEAM SECTION, SECTION = ARBITRARY, ELSET = EANGLE, MATERIAL = ANGLE
  2, 18.82, 35.92, -17.1, 0, 4.76
  18.82, -35.92, 4.76
  0, 1, 0

*MATERIAL, NAME = ROUNDSH
  *ELASTIC
  200000, 0.3
  *PLASTIC
  404, 0
  548, 0.045

*MATERIAL, NAME = ROUND
  *ELASTIC
  200000, 0.3
  *PLASTIC
  404, 0

*MATERIAL, NAME = ANGLE
  *ELASTIC
  200000, 0.3
  *PLASTIC
  323, 0

*STEP
  *BUCKLE
  5

*BOUNDARY
  NBC, 1, 2
  BOT1, 3
  NALL, 2
  NALL, 4
  NALL, 6

*CLOAD
  TOP6, 3, -150000

*NODE FILE
  U

*OUTPUT, FIELD, VARIABLE = ALL, FREQUENCY = 1
*END STEP
**HEADING**
Leg Member Reinforced with Angle without End Welding (3 bolts in middle panel)
50% Compressive Pre-load
International System Unit
Post-buckling Analysis

**PARAMETER**
\[ R = 25.4 \times 1 \times 0.5 \]
\[ Z_1 = 25.4 \times 1 \]
\[ Z_2 = 25.4 \times 3.5 \]
\[ Z_3 = 25.4 \times 9 \]
\[ Z_4 = 25.4 \times 12.5 \]
\[ Z_5 = 25.4 \times 17.5 \]
\[ Z_6 = 25.4 \times 22.5 \]
\[ Z_7 = 25.4 \times 26 \]
\[ Z_8 = 25.4 \times 29.5 \]
\[ Z_9 = 25.4 \times 34.5 \]
\[ Z_{10} = 25.4 \times 39.5 \]
\[ Z_{11} = 25.4 \times 43 \]
\[ Z_{12} = 25.4 \times 46.5 \]
\[ Z_{13} = 25.4 \times 51.5 \]
\[ Z_{14} = 25.4 \times 56.5 \]
\[ Z_{15} = 25.4 \times 60 \]
\[ Z_{16} = 25.4 \times 65.5 \]
\[ Z_{17} = 25.4 \times 68 \]
\[ Z_{18} = 25.4 \times 69 \]
\[ L = Z_{18} \]

Modescale1 = L/750

*NODE, NSET = BOT1
1, 0, 0, 0

*NODE, NSET = MMID2
351, 0, 0, <Z2>

*NODE, NSET = MID2
901, 0, 0, <Z3>

*NODE, NSET = MMID3
1251, 0, 0, <Z4>

*NODE, NSET = MMID4
1751, 0, 0, <Z5>

*NODE, NSET = MMID5
2251, 0, 0, <Z6>

*NODE, NSET = MID3
2801, 0, 0, <Z7>

*NODE, NSET = MMID6
2951, 0, 0, <Z8>

*NODE, NSET = MMID7
3451, 0, 0, <Z9>

*NODE, NSET = MMID8
3951, 0, 0, <Z10>

*NODE, NSET = MID4
4301, 0, 0, <Z11>

*NODE, NSET = MMID9
4851, 0, 0, <Z12>

*NODE, NSET = MMID10
5151, 0, 0, <Z13>

*NODE, NSET = MMID11
5651, 0, 0, <Z14>

*NODE, NSET = MID5
6001, 0, 0, <Z15>

*NODE, NSET = MMID12
6551, 0, 0, <Z16>

*NODE, NSET = TOP6
6901, 0, 0, <Z18>

*NODE, NSET = LBOT1
102, 0, 0, <Z1>
*NODE, NSET = LMID2
352, 0, 0, <Z2>
*NODE, NSET = LMID3
1252, 0, 0, <Z4>
*NODE, NSET = LMID4
1752, 0, 0, <Z5>
*NODE, NSET = LMID5
2252, 0, 0, <Z6>
*NODE, NSET = LMID6
2952, 0, 0, <Z8>
*NODE, NSET = LMID7
3452, 0, 0, <Z9>
*NODE, NSET = LMID8
3952, 0, 0, <Z10>
*NODE, NSET = LMID9
4652, 0, 0, <Z12>
*NODE, NSET = LMID10
5152, 0, 0, <Z13>
*NODE, NSET = LMID11
5652, 0, 0, <Z14>
*NODE, NSET = LMID12
6552, 0, 0, <Z16>
*NODE, NSET = LTOP13
6802, 0, 0, <Z17>
*NFILL, NSET = NMAIN
BOT1, TOP6, 276, 25
*NSET, NSET = NBC, GENERATE
1, 151, 25
776, 1026, 25
2576, 2626, 25
4276, 4326, 25
5876, 6126, 25
6751, 6901, 25
*NFILL, NSET = NANGLE
LBOT1, LTOP13, 268, 25
*NSET, NSET = NALL
NMAIN, NANGLE
*ELEMENT, TYPE = B33
1, 1, 26
15, 351, 376
263, 6551, 6576
277, 102, 127
*ELGEN, ELSET = EROUNDSH
1, 14, 25, 1
263, 14, 25, 1
*ELGEN, ELSET = EROUND
15, 248, 25, 1
*ELGEN, ELSET = EANGLE
277, 268, 25, 1
*ELSET, ELSET = EALL
EROUNDSH, EROUND, EANGLE
*MPC
PIN, MMID2, LMID2
PIN, MMID3, LMID3
PIN, MMID4, LMID4
PIN, MMID5, LMID5
PIN, MMID6, LMID6
PIN, MMID7, LMID7
PIN, MMID8, LMID8
PIN, MMID9, LMID9
PIN, MMID10, LMID10
PIN, MMID11, LMID11
PIN, MMID12, LMID12
*BEAM SECTION, SECTION = CIRC, ELSET = EROUNDSH, MATERIAL = ROUNDSH
 0, 1, 0
*BEAM SECTION, SECTION = CIRC, ELSET = EROUND, MATERIAL = ROUND
 0, 1, 0
*BEAM SECTION, SECTION = ARBITRARY, ELSET = EANGLE, MATERIAL = ANGLE
 2, 18.82, 35.92, -17.1, 0, 4.76
 18.82, -35.92, 4.76
 0, 1, 0
*MATERIAL, NAME = ROUNDSH
  *ELASTIC
  200000, 0.3
  *PLASTIC
  404, 0
  548, 0.045
*MATERIAL, NAME = ROUND
  *ELASTIC
  200000, 0.3
  *PLASTIC
  404, 0
*MATERIAL, NAME = ANGLE
  *ELASTIC
  200000, 0.3
  *PLASTIC
  323, 0
*IMPERFECTION, FILE = LUW3-b, STEP = 1
  1, <Modescale1>
*STEP, NAME = LOAD1, NLGEOM
  *STATIC
  *MODEL CHANGE, REMOVE
  EANGLE
  *BOUNDARY
  NBC, 1, 2
  BOT1, 3
  NALL, 2
  NALL, 4
  NALL, 6
  *CLOAD
  TOP6, 3, -82600
  *OUTPUT, FIELD, VARIABLE = ALL, FREQUENCY = 1
  *NODE PRINT, NSET = NALL
  U
  *EL PRINT, ELSET = EALL
  S11
  *END STEP
*STEP, NAME = LOAD2, NLGEOM
  *STATIC
  *MODEL CHANGE, ADD
  EANGLE
  *BOUNDARY
  NBC, 1, 2
  BOT1, 3
  NALL, 2
  NALL, 4
  NALL, 6
  *CLOAD
  TOP6, 3, -82600
  *OUTPUT, FIELD, VARIABLE = ALL, FREQUENCY = 1
  *NODE PRINT, NSET = NALL
U
*EL PRINT, ELSET = EALL
S11
*END STEP
*STEP, NAME = LOAD3, NLGEOm, INC = 150
*STATIC, RIKS
0.25, , , 0.5
*BOUNDARY
NBC, 1, 2
BOT1, 3
NALL, 2
NALL, 4
NALL, 6
*CLOAD
TOP6, 3, -150000
*OUTPUT, FIELD, VARIABLE = ALL, FREQUENCY = 1
*NODE PRINT, NSET = NALL
U
*EL PRINT, ELSET = EALL
S11
*END STEP
C5. ABAQUS Input Files for Unreinforced Bracing Member

*HEADING
  Unreinforced Bracing Member
  International System Unit
  Eigenvalue Buckling Analysis

*PARAMETER
  L = 25.4 * 29
  Rleg = 25.4 * 0.5 * 5 / 8

*NODE, NSET = BOT
  1, 0, 0, 0

*NODE, NSET = TOP
  2901, 0, <L>, 0

*NFILL, NSET = NALL
  BOT, TOP, 116, 25

*ELEMENT, TYPE = B23
  1, 1, 26

*ELGEN, ELSET = EMAIN
  1, 116, 25, 1

*BEAM SECTION, SECTION = CIRC, ELSET = EMAIN, MATERIAL = ROUND
  <Rleg>

*MATERIAL, NAME = ROUND
*ELASTIC
  200000, 0.3

*PLASTIC
  343, 0

*STEP
*BUCKLE
  5

*BOUNDARY
  BOT, 1, 2
  TOP, 1

*CLOAD
  TOP, 2, -100000

*NODE FILE
  U

*OUTPUT, FIELD, FREQUENCY = 1
*NODE OUTPUT
  U

*END STEP
*HEADING
Unreinforced Bracing Member
International System Unit
Post-buckling Analysis

*PARAMETER
L = 25.4 * 29
Rleg = 25.4 * 0.5 * 5 / 8
Modescale1 = L / 400

*NODE, NSET = BOT
1, 0, 0, 0
*NODE, NSET = TOP
2901, 0, <L>, 0
*NFILL, NSET = NALL
BOT, TOP, 116, 25
*ELEMENT, TYPE = B23
1, 1, 26
*ELGEN, ELSET = EMAIN
1, 116, 25, 1
*BEAM SECTION, SECTION = CIRC, ELSET = EMAIN, MATERIAL = ROUND
<Rleg>
*MATERIAL, NAME = ROUND
*ELASTIC
200000, 0.3
*PLASTIC
343, 0
*IMPERFECTION, FILE = BU-b, STEP = 1
1, <Modescale1>
*STEP, NAME = LOAD, NLGEOM, INC = 100
*STATIC, RIKS
0.01, , 0.05
*BOUNDARY
BOT, 1, 2
BOT, 6
TOP, 1
TOP, 6
*CLOAD
TOP, 2, -100000
*OUTPUT, FIELD, VARIABLE = ALL, FREQUENCY = 1
*NODE PRINT, NSET = NALL
U
*EL PRINT, ELSET = EMAIN
S11
*END STEP

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C6. ABAQUS Input Files for Bracing Member Reinforced with Rod

*HEADING
Bracing Member Reinforced with Rod
International System Unit
Eigenvalue Buckling Analysis

*PARAMETER
L1 = 25.4 * 0.5
L2 = 25.4 * 4
L3 = 25.4 * 10
L4 = 25.4 * 10
L5 = 25.4 * 4
L6 = 25.4 * 0.5
Rleg = 25.4 * 0.5 * 5 / 8
Rrod = 25.4 * 0.5 * 5 / 8
Y1 = L1
Y2 = Y1 + L2
Y3 = Y2 + L3
Y4 = Y3 + L4
Y5 = Y4 + L5
Y6 = Y5 + L6
L = Y6

*NODE, NSET = BOT1
  1, 0, 0, 0

*NODE, NSET = MID2
  451, 0, <Y2>, 0

*NODE, NSET = MID3
  1451, 0, <Y3>, 0

*NODE, NSET = MID4
  2451, 0, <Y4>, 0

*NODE, NSET = TOP5
  2901, 0, <Y6>, 0

*NODE, NSET = BOT1R
  52, 0, <Y1>, 0

*NODE, NSET = MID2R
  452, 0, <Y2>, 0

*NODE, NSET = MID3R
  1452, 0, <Y3>, 0

*NODE, NSET = MID4R
  2452, 0, <Y4>, 0

*NODE, NSET = TOP5R
  2852, 0, <Y5>, 0

*NFILL, NSET = NMAIN
  BOT1, TOP5, 116, 25

*NFILL, NSET = NROD
  BOT1R, TOP5R, 112, 25

*NSET, NSET = NALL
  NMAIN, NROD

*ELEMENT, TYPE = B23
  1, 1, 26
  117, 52, 77

*ELGEN, ELSET = EMAIN
  1, 116, 25, 1

*ELGEN, ELSET = EROD
  117, 112, 25, 1

*ELSET, ELSET = EALL
  EMAIN, EROD

*MPC
  PIN, MID2, MID2R
  PIN, MID3, MID3R
  PIN, MID4, MID4R
*BEAM SECTION, SECTION = CIRC, ELSET = EMAIN, MATERIAL = ROUND
<Rleg>
*BEAM SECTION, SECTION = CIRC, ELSET = EROD, MATERIAL = ROD
<Rrod>
*MATERIAL, NAME = ROUND
*ELASTIC
200000, 0.3
*PLASTIC
343, 0
*MATERIAL, NAME = ROD
*ELASTIC
200000, 0.3
*PLASTIC
405, 0
*STEP
*BUCKLE
5
*BOUNDARY
BOT1, 1, 2
TOP5, 1
*CLOAD
TOP5, 2, -100000
*NODE FILE
U
*OUTPUT, FIELD, FREQUENCY = 1
*NODE OUTPUT
U
*END STEP
*HEADING
Bracing Member Reinforced with Rod
International System Unit
Post-buckling Analysis
*PARAMETER
L1 = 25.4 * 0.5
L2 = 25.4 * 4
L3 = 25.4 * 10
L4 = 25.4 * 10
L5 = 25.4 * 4
L6 = 25.4 * 0.5
Rleg = 25.4 * 0.5 * 5 / 8
Rrod = 25.4 * 0.5 * 5 / 8
Y1 = L1
Y2 = Y1 + L2
Y3 = Y2 + L3
Y4 = Y3 + L4
Y5 = Y4 + L5
Y6 = Y5 + L6
L = Y6
Modescale1 = L / 400
*NODE, NSET = BOT1
  1, 0, 0, 0
*NODE, NSET = MID2
  451, 0, <Y2>, 0
*NODE, NSET = MID3
  1451, 0, <Y3>, 0
*NODE, NSET = MID4
  2451, 0, <Y4>, 0
*NODE, NSET = TOP5
  2901, 0, <Y6>, 0
*NODE, NSET = BOT1R
  52, 0, <Y1>, 0
*NODE, NSET = MID2R
  452, 0, <Y2>, 0
*NODE, NSET = MID3R
  1452, 0, <Y3>, 0
*NODE, NSET = MID4R
  2452, 0, <Y4>, 0
*NODE, NSET = TOP5R
  2852, 0, <Y5>, 0
*NFILL, NSET = NMAIN
  BOT1, TOP5, 116, 25
*NFILL, NSET = NROD
  BOT1R, TOP5R, 112, 25
*NSET, NSET = NALL
  NMAIN, NROD
*ELEMENT, TYPE = B23
  1, 1, 26
  117, 52, 77
*ELGEN, ELSET = EMAIN
  1, 116, 25, 1
*ELGEN, ELSET = EROD
  117, 112, 25, 1
*ELSET, ELSET = EALL
  EMAIN, EROD
*MPC
  PIN, MID2, MID2R
  PIN, MID3, MID3R
  PIN, MID4, MID4R
*BEAM SECTION, SECTION = CIRC, ELSET = EMAIN, MATERIAL = ROUND
  <Rleg>
*BEAM SECTION, SECTION = CIRC, ELSET = EROD, MATERIAL = ROD
<Rrod>
*MATERIAL, NAME = ROUND
*ELASTIC
200000, 0.3
*PLASTIC
343, 0
*MATERIAL, NAME = ROD
*ELASTIC
200000, 0.3
*PLASTIC
405, 0
*IMPERFECTION, FILE = BR-b, STEP = 1
1, <Modescale1>
*STEP, NAME = LOAD, NLGEOM, INC = 100
*STATIC, RIKS
0.01, , 0.05
*BOUNDARY
BOT1, 1, 2
BOT1, 6
TOP5, 1
TOP5, 6
*CLOAD
TOP5, 2, -100000
*OUTPUT, FIELD, VARIABLE = ALL, FREQUENCY = 1
*NODE PRINT, NSET = NALL
U
*EL PRINT, ELSET = EALL
S11
*END STEP
C7. ABAQUS Input Files for Bracing Member Reinforced with Angle

*HEADING
Bracing Member Reinforced with Angle
International System Unit
Eigenvalue Buckling Analysis

*PARAMETER
L1 = 25.4 * 0.5
L2 = 25.4 * 4
L3 = 25.4 * 10
L4 = 25.4 * 10
L5 = 25.4 * 4
L6 = 25.4 * 0.5
Rleg = 25.4 * 0.5 * 5 / 8
Z1 = L1
Z2 = Z1 + L2
Z3 = Z2 + L3
Z4 = Z3 + L4
Z5 = Z4 + L5
Z6 = Z5 + L6
L = Z6

*NODE, NSET = BOT1
1, 0, 0, 0

*NODE, NSET = MID2
451, 0, 0, <Z2>

*NODE, NSET = MID3
1451, 0, 0, <Z3>

*NODE, NSET = MID4
2451, 0, 0, <Z4>

*NODE, NSET = TOP5
2901, 0, 0, <Z6>

*NODE, NSET = BOT1A
52, 0, 0, <Z1>

*NODE, NSET = MID2A
452, 0, 0, <Z2>

*NODE, NSET = MID3A
1452, 0, 0, <Z3>

*NODE, NSET = MID4A
2452, 0, 0, <Z4>

*NODE, NSET = TOP5A
2852, 0, 0, <Z6>

*NSET, NSET = NMAIN
BOT1, TOP5, 116, 25

*NSET, NSET = NANGLE
BOT1A, TOP5A, 112, 25

*SET, NSET = NALL
NMAIN, NANGLE

*ELEMENT, TYPE = B33
1, 1, 26
117, 52, 77

*ELGEN, ELSET = EMAIN
1, 116, 25, 1

*ELGEN, ELSET = EANGLE
117, 112, 25, 1

*ELSET, ELSET = EALL
EMAIN, EANGLE

*MPC
PIN, MID2, MID2A
PIN, MID3, MID3A
PIN, MID4, MID4A

*BEAM SECTION, SECTION = CIRC, ELSET = EMAIN, MATERIAL = ROUND

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<Rleg>
0, 1, 0
*BEAM SECTION, SECTION = ARBITRARY, ELSET = EANGLE, MATERIAL = ANGLE
2, 16.27, 31.47, -15.2, 0, 3.18
16.27, -31.47, 3.18
0, 1, 0
*MATERIAL, NAME = ROUND
*ELASTIC
200000, 0.3
*PLASTIC
343, 0
*MATERIAL, NAME = ANGLE
*ELASTIC
200000, 0.3
*PLASTIC
330, 0
*STEP
*BUCKLE
5
*BOUNDARY
BOT1, 1, 3
TOP5, 1, 2
NALL, 2
NALL, 4
NALL, 6
*CLOAD
TOP5, 3, -100000
*NODE FILE
U
*OUTPUT, FIELD, FREQUENCY = 1
*NODE OUTPUT
U
*END STEP
*HEADING
Bracing Member Reinforced with Angle
International System Unit
Post-buckling Analysis
*PARAMETER
L1 = 25.4 * 0.5
L2 = 25.4 * 4
L3 = 25.4 * 10
L4 = 25.4 * 10
L5 = 25.4 * 4
L6 = 25.4 * 0.5
Rleg = 25.4 * 0.5 * 5 / 8
Z1 = L1
Z2 = Z1 + L2
Z3 = Z2 + L3
Z4 = Z3 + L4
Z5 = Z4 + L5
Z6 = Z5 + L6
L = Z6
Modescale1 = L / 400
*NODE, NSET = BOT1
1, 0, 0, 0
*NODE, NSET = MID2
451, 0, 0, <Z2>
*NODE, NSET = MID3
1451, 0, 0, <Z3>
*NODE, NSET = MID4
2451, 0, 0, <Z4>
*NODE, NSET = TOP5
2901, 0, 0, <Z6>
*NODE, NSET = BOT1A
52, 0, 0, <Z1>
*NODE, NSET = MID2A
452, 0, 0, <Z2>
*NODE, NSET = MID3A
1452, 0, 0, <Z3>
*NODE, NSET = MID4A
2452, 0, 0, <Z4>
*NODE, NSET = TOP5A
2852, 0, 0, <Z5>
*NFILL, NSET = NMAIN
BOT1, TOP5, 116, 25
*NFILL, NSET = NANGLE
BOT1A, TOP5A, 112, 25
*NSET, NSET = NALL
NMAIN, NANGLE
*ELEMENT, TYPE = B33
1, 1, 26
117, 52, 77
*ELGEN, ELSET = EMAIN
1, 116, 25, 1
*ELGEN, ELSET = EANGLE
117, 112, 25, 1
*ELSET, ELSET = EALL
EMAIN, EANGLE
*MPC
PIN, MID2, MID2A
PIN, MID3, MID3A
PIN, MID4, MID4A
*BEAM SECTION, SECTION = CIRC, ELSET = EMAIN, MATERIAL = ROUND
<Rleg>
0, 1, 0

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*BEAM SECTION, SECTION = ARBITRARY, ELSET = EANGLE, MATERIAL = ANGLE
2, 16.27, 31.47, -15.2, 0, 3.18
16.27, -31.47, 3.18
0, 1, 0
*MATERIAL, NAME = ROUND
*ELASTIC
200000, 0.3
*PLASTIC
343, 0
*MATERIAL, NAME = ANGLE
*ELASTIC
200000, 0.3
*PLASTIC
330, 0
*IMPERFECTION, FILE = BA-b, STEP = 1
1, <Modescale1>
*STEP, NAME = LOAD, NLGEOM, INC = 100
*STATIC, RIKS
0.01, , 0.05
*BOUNDARY
BOT1, 1, 6
TOP5, 1, 2
TOP5, 4, 6
NALL, 2
NALL, 4
NALL, 6
*CLOAD
TOP5, 3, -100000
*OUTPUT, FIELD, VARIABLE = ALL, FREQUENCY = 1
*NODE PRINT, NSET = NALL
U
*EL PRINT, ELSET = EALL, POSITION = CENTROIDAL
S11
*END STEP
VITA AUCTORIS

The author was born in 1980 on Surabaya, Indonesia. She has a S.T. (B.Sc. equivalent) degree in Structural Engineering from Petra Christian University, Surabaya, Indonesia in 2002. She had worked for one year (2002-2003) as a Civil Engineer at CH Contractor and Engineering, Surabaya, Indonesia. She came to Canada in 2003 and she is currently registered as an M.A.Sc. student in Civil and Environmental Engineering Department at the University of Windsor. She expects to graduate in Summer 2004.