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Analysis and Design Procedure of Corner Gusset Plate Connection in BRBFs

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Abstract: In order to achieve the post buckling strength of BRB member, AISC seismic design provisions require that gusset plate axial capacity exceed ultimate compressive load of the BRB. The AISC code also requires that the gusset plate instability be considered because recent full scale tests demonstrated that out of plane buckling of a gusset plate occurs prior to BRB ultimate load. In this paper an analytical investigation is used to investigate inelastic compressive behavior and strength of gusset plates in BRBFs by finite element software considering plates of different dimensions. In order to verify analytical results one full scale tests was carried out on a simplified gusset plate connection. Also to increase gusset plate buckling strength and improve its energy absorption behavior, effects of adding free edge stiffeners at different sizes have been investigated and the results are presented. Finally, a design method accompanied by some design charts for rectangular type gusset plates subject to compression is proposed based on an inelastic plate buckling equation.

Key words: Buckling restrained brace · Gusset plate · Analytical investigation · Plate buckling · Gusset plate design

INTRODUCTION

Providing a continuous path so as to transfer the exerted force from the braced frame connections is of significant importance for an economic safe structural design. In proper seismic design of structures a reliable path for distribution of forces between structural members must be predicted. Accurate prediction of loading path is a difficult numerical and experimental challenge which has not been fulfilled yet. The path includes components of brace connection to the gusset plate, the gusset plate and beam to column connection which all must withstand the forces they receive and transfer to other structural components. In other words they should serve as a safe and proper path of force transference.

Whitmore [1] has reported the results of a series of experiments on gusset plates. Based on his experiments, Whitmore has determined that the location of the maximum tensile stress is near the end of the tension diagonal and the maximum compressive stress is near the end of the compressive diagonal. Whitmore has also concluded that using beam formulas to determine the direct, bending and shearing stresses on a plane through the ends of the diagonals does not accurately reflect the stress condition in gusset plates. Based on his observations, Whitmore has found that the maximum tensile and compressive stresses could be approximated quite accurately by assuming the force in each diagonal to be uniformly distributed over an area obtained by multiplying the plate thickness by an effective length normal to the axis of the diagonal. This effective length is obtained by drawing 30º lines from the outside bolts of the first row, to intersect with a line perpendicular to the member through the bottom row of bolts. This concept compares quite well to test results and has since been used as one of the primary tools in gusset plate design. An estimate of the gusset plate yield load can be determined by multiplying the yield stress by the plate area at the effective width section. Tensile stress value based on Whitmore effective length is:

$$P_w = 0.6F_y\,(2L \tan 30 + S)t \tag{1}$$

Thornton [2] has proposed that buckling load of a gusset plate is considered as the compressive strength of a fixed-fixed column strip below the Whitmore effective

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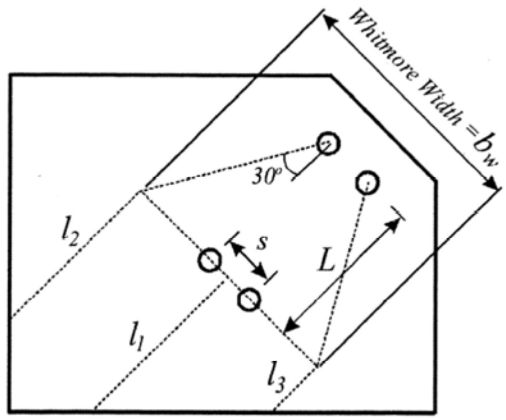

Fig. 1: Gusset plate with Whitmore width

width, b_E (Figure 1). The length of the column strip, L_C, is the maximum of lengths L_{C1}, L_{C2} and L_{C3} and the effective column length factor, K, is 0.65. A column buckling equation together with the Whitmore section area b_E t is adopted to estimate the ultimate compressive load. The Thornton expression for the critical buckling load is given as follows:

$$P_{cr} = \frac{\pi^2 E}{(\frac{KL_C}{r})^2} b_w t \quad (2)$$

Where *t* is the gusset plate thickness and *r* is the radius of gyration [3].

Yam and Cheng [4] conducted experiments on simplified models of gusset plates and found out that Thornton's proposal of 30º dispersion cannot predict the ultimate load of the gusset plate accurately and a dispersion angle of 45º is in better agreement with their experimental results. They put forward the modified Thornton's method with 45º dispersion angle.

Sheng *et al*. [5], based on inelastic plate buckling equation, proposed a design method accompanied by some design charts for rectangular type gusset plate subject to compression. They also showed that neither Thornton nor modified Thornton method can estimate the ultimate load of large gusset plates under compression correctly. That's because the effects of plate action under buckling is not considered in Thornton's approach. In addition, they concluded that addition of free-edge stiffeners considerably increases the ultimate capacity of the plate.

Most researchers used to focus on compressive capacity of gusset plates with infinite rotational restraint provided by the BRB end and the splice members, until a full-scale test [6, 7] on a buckling restrained braced frame was conducted revealing out-of-plane buckling of the central gusset plate due to lack of out-of-plane restraints by BRB end.

Tsai *et al*. [8] proposed a full scale experiment on a dual system 3 bay frame, which consist of combined BRBF and moment resistant frame (MRF) system, using hybrid pseudo-dynamic earthquake simulation. In the first phase of experiment, out of plate warping was observed in several experiments in different parts of the frame. In order to prevent this distortion in, some stiffeners were added to the connections. The first phase resulted in the yield of BRBs as a cause of out of plate buckling with a story drift of 0.025 rad. After the first phase, connection plates and BRBs were changed and some stiffeners were added to the free edges of the plates. This lead to acceptable results of BRB and connection, up to the story drift of 0.025 rad in the second phase. Then in a new experiment, on a 1 bay 2 story frame with BRBF system and strengthened connection plate was implemented which shown the same suitable results up to story drift of 0.022 rad [9].

Christopulos [10] tested five full-scale one-bay one-story BRBFs under cyclic displacement histories. The bracing was pinned to the connection plate and the beams are connected to columns using single-plate shear tabs. The effects of the shape of plate, type of pinned connection between the plate and bracing and the direction of core plate of the BRB settlement has been observed in this experiment. The changes show almost no effect, resulting 4 out of 5 frames to fail as a cause of out of plate deformation of BRB in story drift between 0.022 and 0.024 rad. The BRB failure was mostly the result of yielding and buckling of beams and columns near the connection plate.

Then Chou and Chen [3] assessed the behavior of central gusset plates carrying out an analytical study on central gusset plates in BRBF without rotational restraints by the bracing member. Applying free-edge stiffeners, they also proposed a method accompanied by design charts to choose stiffeners of optimum dimensions.

Considering previous researches on gusset plates [11-27] the behavior of corner gusset plates in BRBFs remain unclear. Therefore, in this paper an analytical study has been done to estimate the compressive strength of corner gusset plates in BRBFs without applying rotational restraints on the end of the gusset plate. To do so, finite element modeling process is explained and then experimental model is introduced and the results are presented to verify the analytical study.

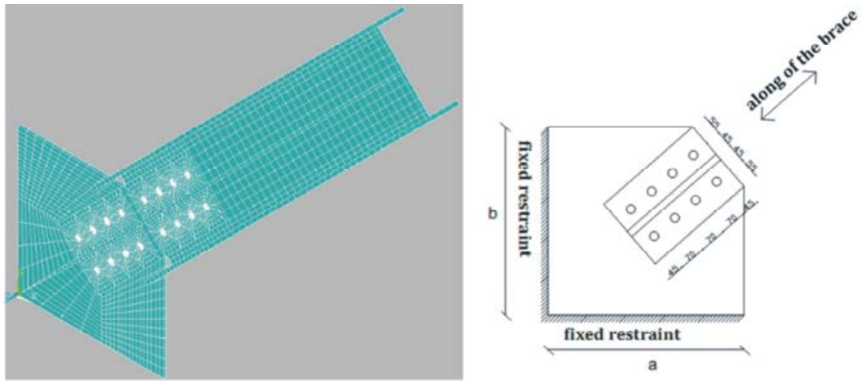

Fig. 2: Gusset plate boundary condition and a finite element model along with the meshing pattern.

Finally, based on analytical studies an approach accompanied by some charts is propounded to design corner gusset plates.

Modeling: In order to carry out the analytical study, corner gusset plate connections in diagonal braced frames are chosen. The case under study is a gusset plate with fixed restraints as boundary conditions with both beam and column. The studied buckling restrained brace is an I section in which instead of using a surrounding system to make it buckling restrained; it is chosen of a short length with such big section area that the slenderness value reaches a small number. Thus, yielding is considered as the capacity determination criterion. Two Tee-sections on both sides of the gusset plate are used as the brace connection to the gusset plate. Tee-sections are of 200 mm widths and thicknesses that equal that of the gusset plate. Their lengths can vary as a function of the number of bolts used along them. Furthermore, in order to connect the Tee-sections to the gusset plate, ASTM A325 bolts are used. The distance between bolts along and perpendicular to the direction of the axial force is 70 and 90 mm, respectively. The distance from the Tee-section edge is 45mm and 55mm along and perpendicular to the force direction respectively. For simplification, heads and nuts of the bolts were ignored and only the rods are modeled which are attached to the Tee-section and gusset plate and all degrees of freedom are glued together. The steel used in the gusset plate and Tee-sections is ST37. Figure 2 schematically shows the connection zone and a finite element model along with the meshing pattern.

Large Displacement Control analysis with push over loading was used in ANSYS software. Solid 95 elements (cubic 20 nodes elements) were used for the modeling of elements such as pins, T shapes, braces and connection plates. Also for modeling of frictions between the surfaces target 170 and contact 174 were used. Steel to steel friction coefficient was considered 0.6.

Table1: Material properties used in experiments

	Material 1	Material 2
Density (N/m^3)	78500	78500
Modulus of Elasticity (N/m^2)	2.1×10^{11}	2.1×10^{11}
Poisson's ratio	0.3	0.3
Yield Stress (N/m^2)	300×10^6	630×10^6
Failure Stress (N/m^2)	370×10^6	800×10^6

Table 2: Stress-Strain result from the material type1

Stress	Strain
300×10^6	0.00143
370×10^6	0.0067
370×10^6	0.0304

Table 3: Stress-Strain result from the material type1

Stress	Strain
630×10^6	0.003
800×10^6	0.014
800×10^6	0.03

Two types of material were used in the prototype. Type 1 was used in connection plates, T shapes and bracing and type 2 was used in pins. The material properties of type 1 have been acquired using standard test. Table 1 shows the material properties of these two material types.

Stress-strain curve for type1 material is shown in Table 2 and for type 2 material in Table 3.

Assessment of the Modeling Validity: In order to assess the accuracy of the modeling, a simplified full-scale model of the gusset plate connection to beam and column was fabricated and the results were compared with those obtained from the software. For this purpose, the experiments were carried out.

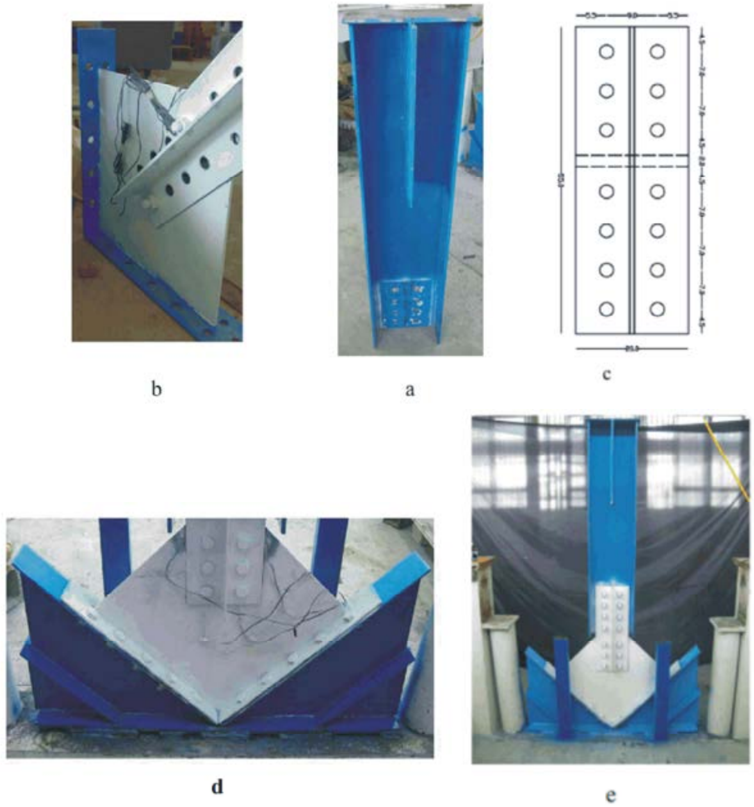

Fig. 3: Details of the components used in the experimental model

Properties of the Model under Study: Models consist of five elements namely braces, gusset plates, Tee-sections, supporting frame and bolts.

Braces: Brace is an I section. Web of the brace is a 123×25×0.8 cm plate and its flanges are 123×20×0.8 cm plates with slenderness of 28.6 designed to elastically resist an axial force of 80 tones. To take into account of concentrated load exerted to the brace under hydraulic jack, two stiffeners (45 × 17 × 102 cm) perpendicular to the web on both sides of the brace were used. On the brace end, under the jack, was welded a plate (30 × 24 × 1 cm). On the other side of the brace, connected to the Tee-section, there are eight, 24 mm diameter holes with center-to-center distance of 7 cm and as for side holes the distance from their center to the edge of the plate is 4.5 cm. Details of braces are displayed in Figure 3.

Properties of Models under Study: The model in the experiment has dimensions of 50×50×0.8cm, having six 24 mm holes and a 45° cut-off on one corner for the bracing member to be connected at an angle of 45°. For simplicity the gusset plate is connected to the supporting frame using bolt connections. To do this, the gusset plate, on its two edges, is welded to splice plates of dimensions of 60 ×11 ×0.8 cm each having 10 holes with a diameter of 22mm which will be later bolted to the flanges of the beam and column. The details of the plate are shown in Figure 3b.

Tee-Section: The Tee-section consists of two plates, a 55 ×20 ×0.8 cm plate as the flange and a 55 ×8 ×0.8 cm plate serving as the web, welded together. There are 14 holes of a diameter of 24mm to connect the bracing member to the gusset plate. Arrangement of holes and their distances from each other and the edges is depicted in Figure 3c.

Supporting Frame: The supporting frame is represented by two sections as the stub beam and column members welded to a plate (110 ×14 ×1.5 cm) serving as a base. The beam and column are made of plates of the same dimensions, 75 ×20×0.8 cm plate as the web and 75 ×11 ×0.8 cm as the flange being cut off at 45 angle and welded to a plate of the pre-mentioned dimensions underneath (Figure 3d). Flanges of the beam and column are connected to the gusset plate via 10 bolt connections to a splice plate that was previously welded to its edges. The empty space under the beam and column is filled with triangular stiffener plates (25 ×25 ×1 cm) in the same plane as the beam and column's web.

Bolts: All bolts used in the experiment are ASTM A325. Bolts M20 were used to connect the gusset plate to the supporting frame and bolts M22 were the connectors between Tee-sections and the gusset plate as well as the Tee-section and the bracing member. The full-scale experimental model is shown in (Figure 3e).

Assessment of the Accuracy of the Model: In order to investigate the behavior of the gusset plate, an initial imperfection should be imposed. The obtained buckling load for the gusset plate will be a function of the considered imperfection. If the initial imperfection is considered to be small, the buckling capacity of the gusset plate will be overestimated while a big initial imperfection will lead to underestimation of the buckling capacity. Thus, in order to reach a proper value, initial imperfections are imposed on the finite element model and each of the resulting buckling loads is compared with that obtained from the experiment. This imperfection is exerted to the gusset plate as a coefficient of out of plane deflection corresponding to the first buckling mode of the gusset plate. The buckling load for 8mm gusset plate is 403.3 KN. The corresponding buckling load in finite element model estimated for the maximum displacement of 0.5mm happening at the gusset plate end where it is connected to the brace for 8mm gusset plate is 415.63 KN which is in good agreement with the experimental model. Therefore, this initial imperfection was used in other finite element models.

Force-out of plane displacement curves for experimental and finite element model corresponding to the mentioned initial imperfection for the 8 mm gusset plate is illustrated in Figure 4. As it can be seen, there is a roughly good agreement between the experimental and the finite element model.

Figure 5 shows buckling of the model after the experiments.

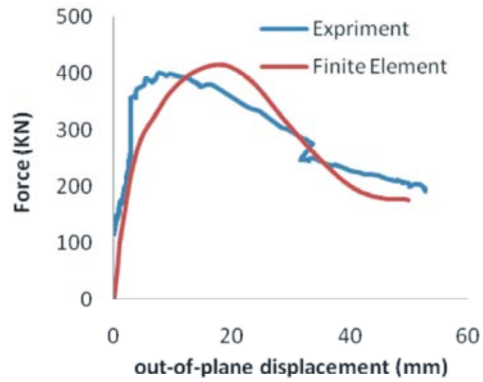

Fig. 4: Force-out of plane displacement curve

Fig. 5: Buckling of the model

Parametric Study: Numerous parameters influence the buckling behavior of gusset plates including its dimensions (length, width and thickness), connection type (weld or bolts), shape and dimension of splice members, angle of the bracings, location of the splice member end on the gusset plate, whether it is near, inside or outside the bending line, number and type of bolts used and many other factors. But what is more important is the extent to which any of these factors can affect the behavior of the gusset plate. Considering extensive studies conducted on aforementioned factors, the effects of the following parameters are going to be investigated.

- Gusset plate thickness.
- Width (a) and length to width ratio (b/a), (Figure 2).
- Tee-section length (TL).

To carry out the experiments four gusset plate thicknesses (t_g), 0.4, 0.8, 1.2 and 1.6 cm were chosen. In addition, length to width ratios (b/a) of 1 and 1.5 were chosen for gusset plates with width of 50 and 60 cm (50 ×50 cm, 50 ×75 cm, 60 ×60 cm, 60 ×90 cm gusset plates). For b/a=1 the brace angle is 45° so that the brace crosses the intersection of beam and column while for b/a=1.5 the brace angle equals 35° (Figure 2). Tee-section length is chosen such that the splice member end is located near, inside and outside the bending line. So for 50 ×50 cm gusset plate, four lengths (TL= 23, 30, 37 and 44cm) were chosen, calculated according to limitation of bolt to bolt and bolt to edge minimum distance which is 7 and 4.5 cm respectively. To make it clearer, the 23 cm Tee-section has 6 bolts (two rows of three bolts) while the 30, 37 and 44 cm Tee-sections consist of 8, 10 and 12 bolts respectively. For 50 ×75 cm, 60 ×60 cm, 60 ×90 cm gusset plates a Tee-section of 51 cm of length was assigned in addition to those for 50×50cm.

RESULTS AND DISCUSSIONS

The discussions on parameter study are described as followings:

Deformation and Stress Distribution in the Plate Due to Buckling: The shape of buckled plate and Von Mises stress contour of model 500 × 500 × 8 mm with 300 mm T-section length, are shown in Figures 6 and 7, respectively. It is clear from Figure 6 that with increasing distance from the restraint, the out of plane displacement of the plate increases, So in the end of plate at the junction of the BRB it reaches to the maximum value. It is also clear that the plate has not twisted due to the gusset plate symmetry. Figure 7 implies that in the points close to the last row of bolts- in Whitmore effective length- stress in the gusset plate reaches to its yielding stress and buckling starts from these points of the plate. It also can be seen that the maximum stress is created around the bending line (the line that connects the two corner of the plate) and the minimum stress is created around the restraint areas especially in the areas that brace elongation reaches to the beam and column intersection.

Effect of Thickness on Buckling Capacity of the Gusset Plate: As it was expected, as the thickness of the gusset plate increases, the corresponding buckling load rises. Buckling load variations for 50×50cm and 50 ×75 cm plate for different lengths, of Tee-sections are illustrated in Figure 8. It can be observed that there is a more significant increase in the buckling load capacity of the gusset plate when thickness increases from 8 to 12 mm. This is because as the thickness increases, the buckling criterion, which is instability for slender and long plates, changes to yielding criterion resulting in a noticeable increase in the buckling capacity of the gusset plate. In Figure 8, TL represents the Tee-section length and the number following it is its length in cm.

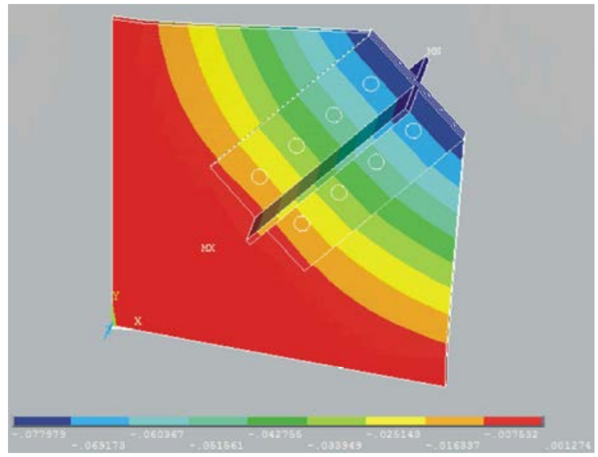

Fig. 6: The buckled shape of model 500 × 500 × 8 with 300 mm T-section length (units in the shape are in meters)

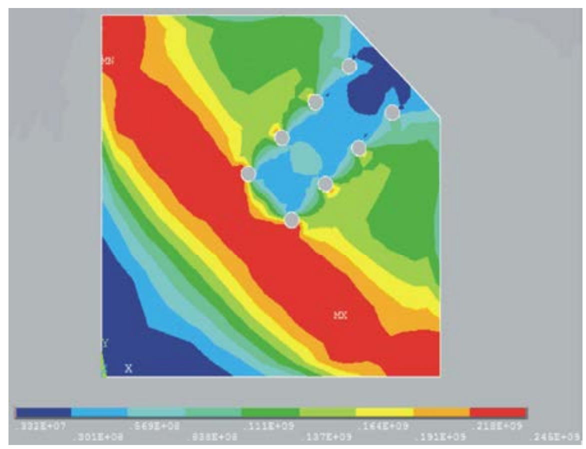

Fig. 7: Von Mises stress contour of model 500 × 500 × 8 with 300 mm T-section length (units in the shape are N/m2)

Effect of Tee-Section Length: The Tee-section length considerably affects the value of buckling load of the gusset plate. When the Tee-section length increases so that it goes beyond the bending line, a stiffer lateral restraint is provided which increases the out of plane stiffness and consequently the compressive strength of the gusset plate. In addition, for models with longer Tee-sections, the gusset plate material gradually yields, so the gusset plate can undergo greater inelastic deformations without loss of compressive capacity. This post-buckling response of the gusset plate can improve energy absorption of the plate as well as its cyclic behavior. Figure 9 shows how Tee-section length affects compressive strength of 4 and 8mm gusset plates.

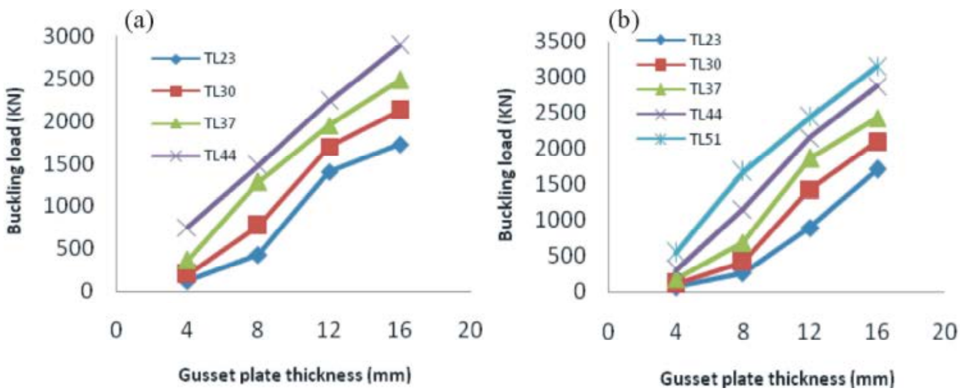

Fig. 8: The effect of thickness on the buckling capacity of the gusset plate for a) 50×50cm, b) 50×75cm

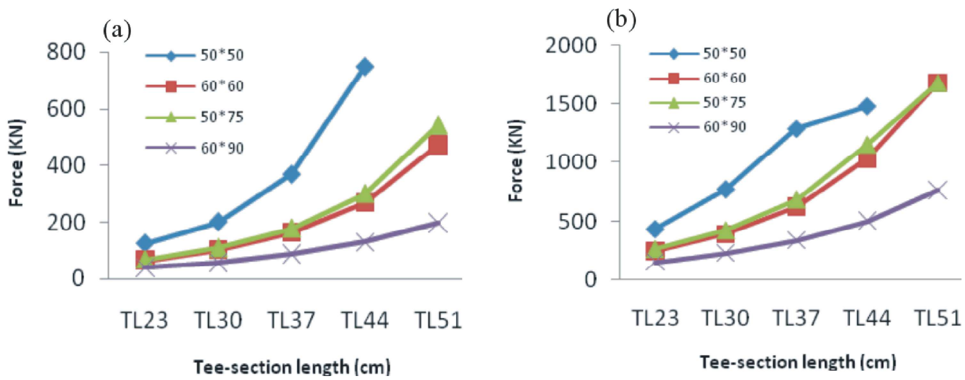

Fig. 9: Buckling load variations for different Tee-section lengths a) 4mm gusset plate b) 8mm gusset plate

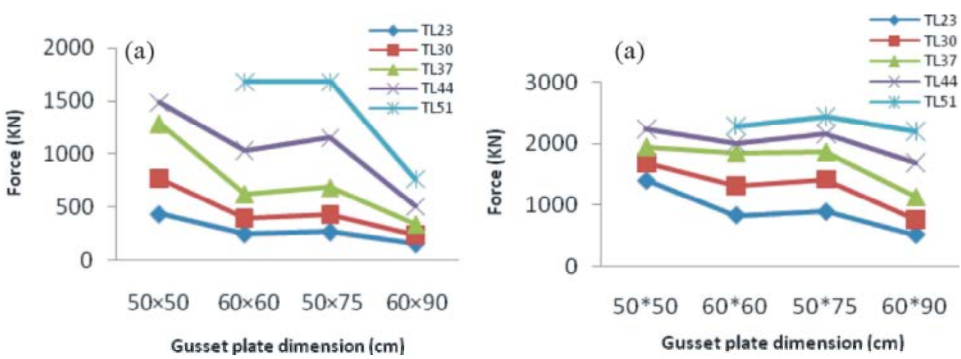

Fig. 10: Buckling load variation for different dimensions of the gusset plate a) t=8mm, b) t=12mm

Effect of Width and Length to Width Ratio on Buckling Capacity of the Gusset Plate: As the dimension of the gusset plate increases, unsupported length of the gusset plate also increases. Thus lateral stiffness of the plate will decrease resulting in a lower buckling capacity. For comparison, Figure10 shows 8mm and 12mm gusset plates of different dimensions and their corresponding buckling capacities.

Comparison of the Buckling Load Obtained from Finite Element Analysis with That of Thornton: Table 4 provides a comparison between buckling loads obtained from finite element analysis with those obtained from Thornton method. It is obvious from the Table that buckling loads of finite element models in BRBFs is larger than those obtained from Thornton method which applies to ordinary braced frames which means that it is not possible to achieve the buckling load of the gusset plates in BRBFs using Thornton method. Since no procedure to design gusset plates in BRBFs is proposed in AISC [28], a method based on inelastic plate buckling equation is propounded in the following section.

Table 4: Comparison of the buckling load obtained from finite element analysis with that of Thornton.

Model No.	t_g [1](cm)	TL [2] (cm)	$P_{cr,F}$ [3] (KN)	$P_{cr,T}$ [4](KN)
1	50×50×0.4	23	112.7236	39.94434
2	50×50×0.4	30	201.0653	73.14266
3	50×50×0.4	37	368.7539	140.5524
4	50×50×0.4	44	750.6402	295.7439
5	60×60×0.8	23	247.1161	174.7408
6	60×60×0.8	30	391.4325	297.0928
7	60×60×0.8	37	625.4483	497.3874
8	60×60×0.8	44	1032.251	848.5373
9	60×60×0.8	51	1677.353	1413.353
10	50×75×1.2	23	893.182	631.5873
11	50×75×1.2	30	1428.885	1084.508
12	50×75×1.2	37	1867.462	1538.061
13	50×75×1.2	44	2156.266	1829.046
14	50×75×1.2	51	2433.368	2120.03
15	60×90×1.6	23	1219.833	862.5688
16	60×90×1.6	30	1819.913	1381.294
17	60×90×1.6	37	2228.947	2050.748
18	60×90×1.6	44	2657.407	2438.728
19	60×90×1.6	51	3069.456	2826.707

[1]Gusset plate dimension [2]Tee-section length
[3]Finite element buckling load [4]Thornton's buckling load

The Proposed Design Method: In order to assess the buckling load of the gusset plate, the equation applied by Sheng *et al*. [13] based on the inelastic plate buckling equation is used. This equation, considering the plate's properties of the plate and its boundary conditions gives the gusset plate's critical inelastic buckling tension as follows:

$$\sigma_u = \frac{K_g \pi^2 E \sqrt{E_t / E}}{12(1-\upsilon^2)(a / t_g)^2} = \frac{P_u}{b_w t_g} \qquad (3)$$

In the above equation *a* represents the gusset plate's width, t_g is its thickness, E_t is the tangent modulus, E is the modulus of elasticity, _ν is the Poisson's ratio and K_g is a constant which is a function of types of stress and supporting conditions of the gusset plate. It should be noted that in the equation used in researches by Sheng *et al*, the whole length of bending was taken into account to determine the buckling capacity of the gusset plate. Since stress concentration in the gusset plate occurs near the Tee-section end, in our study the Whitmore effective width was used instead of the bending line length. Replacing the assumed values in equation (2), K_g for plates of different dimensions can be achieved.

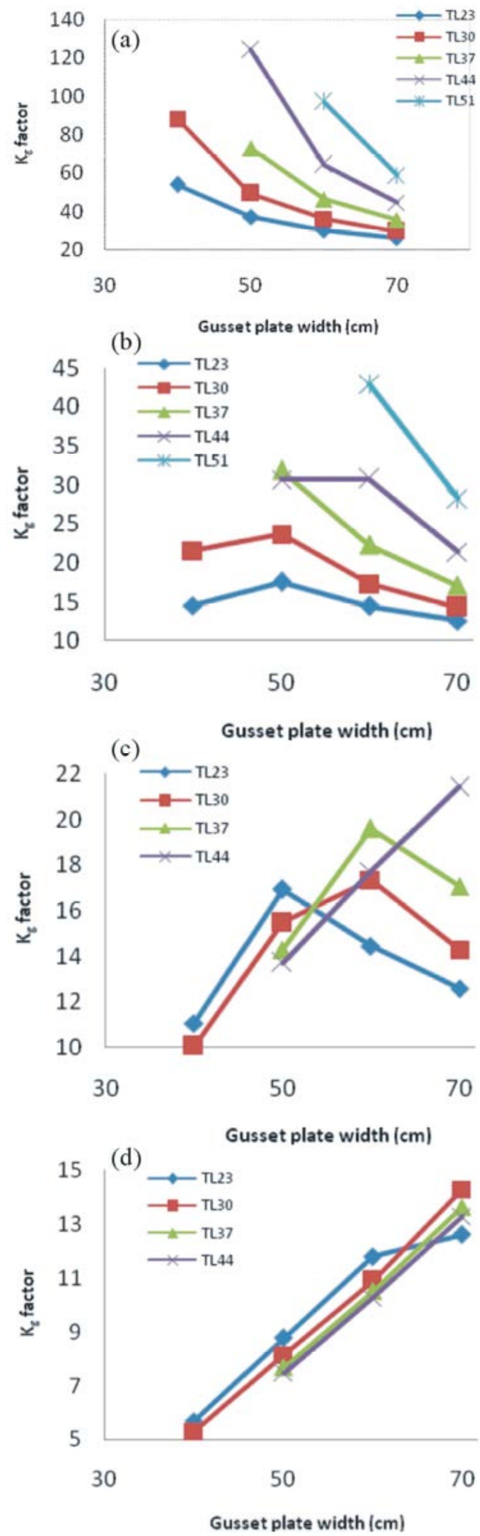

Fig. 11: K_g for gusset plates of different thicknesses and length to width ratio of 1. a) t=4mm b) t=8mm c) t=12mm d) t=16mm

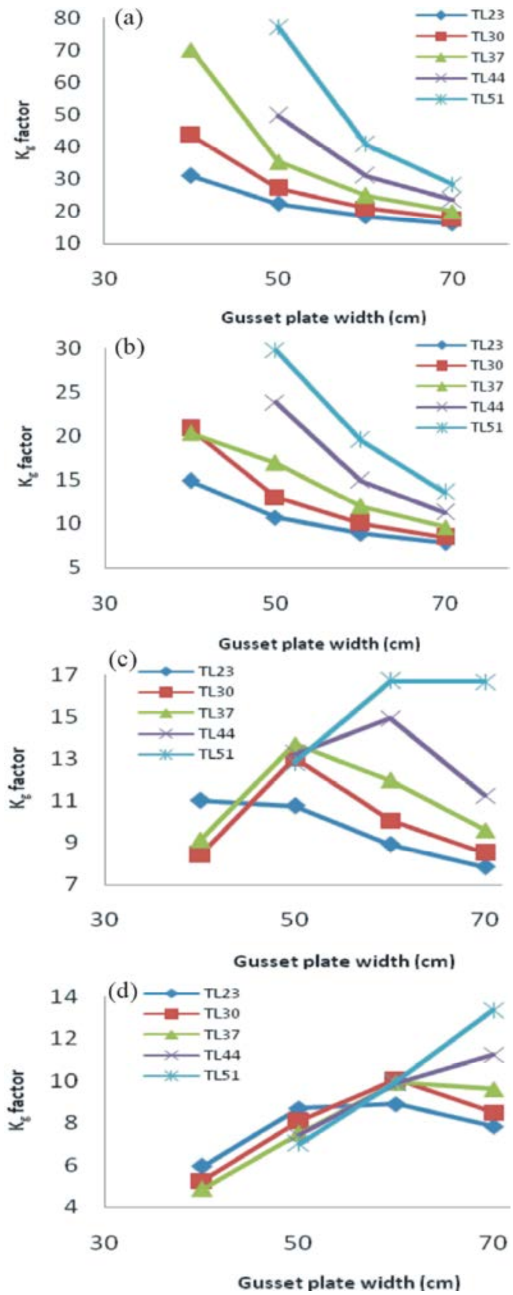

Fig. 12: K_g for plates of thicknesses a) 4 mm b) 8 mm c) 12 mm d) 16 mm and length to width ratio of 1.5

Design Charts: In order to have a more comprehensive range of models, gusset plates 40×40cm, 70×70 cm, 40×60 cm and 70×105 cm with same thicknesses and Tee-sections lengths as mentioned in the beginning of the chapter were also studied. K_g variations for different dimensions of the gusset plate, considering various thicknesses and length to width ratios, are illustrated in Figures 11 and 12.

In thin gusset plates, t=4 and t=8 mm, in Figures 11a, 11b, 12a and 12b the plate's instability is the governing criterion in determination of buckling load, so increase in the gusset plate's width will decrease its buckling capacity. On the other hand, compressive strength of thicker gusset plates, t=12 and t=16 mm, is mainly governed by yielding of gusset plate's material and its inelastic buckling. It is clear from Figures 11c, 11d, 12c and 12d that the values of K_g increase when width is increased in the initial portion of the K_g curves. This phenomenon is due to the fact that when width is increased, a larger area in the plate yields due to load redistribution and as result, the ultimate loads and the corresponding K_g values are increased.

Proposed Design Method: To design a rectangular type gusset plate, the first step is to assume the width of the gusset plate as well as the brace angle. For brace angles of 45 and 35º, length to width ratios 1 and 1.5 are employed respectively and K_g value can be evaluated according to the plate thickness (t_g) and the tee-section length (TL). The linear interpolation method can be applied when the plate width, length to width ratio, t_g and TL are not equal to the specified values corresponding to the curves. After determining K_g value and substituting it into equation 3 the critical stress ($\acute{o}_u$) of the gusset plate can be calculated and using the following equation the buckling load of the gusset plate can be obtained.

$$P_u = \sigma_u b_w t, \ \sigma_u = F_y \tag{4}$$

Where b_w is the Whitmore effective width. In addition, the maximum value of σ_u is the yielding stress of the gusset plate's material. It should be noted that to obtain curves 10 and 11 the following requirements must be met:

- Modulus of elasticity of the material is 2.1×10^6 (Kg/cm^2).
- Tangent modulus to modulus of elasticity ratio (E_t/E) is assumed 0.063.
- Poisson ratio equals 0.3.
- Brace is connected to the gusset plate via splice members of the same thickness as the gusset plate.
- Bolt connection is used to connect the tee-section to the gusset plate and the brace member.

As can be seen, the present design method with the above assumptions has limitations on use and more detailed studies are required to improve the design method.

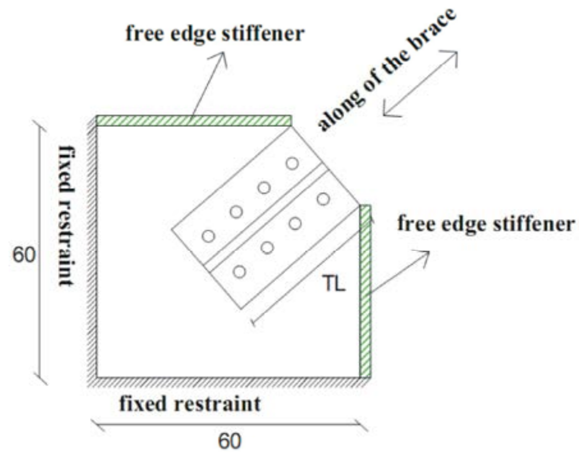

Fig. 13: Placement of free-edge stiffeners

Use of Free-Edge Stiffeners and Their Effect on the Compressive Strength of the Gusset Plate: In the previous section it was shown how plate thickness (t_g), its width and length to width ratio and the tee-section length can affect the compressive strength of the gusset plate. In studies carried out by other researchers, Yum and Sheng in particular, the effect of stiffeners in corner gusset plates in ordinary braced frames has been investigated while the bracing members impose infinite rotational restraint on the gusset plate, but the effect of stiffeners when no rotational spring is provided at the edge of the steel core in BRBFs remains unclear.

Parametric Study: In order to further understand the buckling behavior of corner gusset plates equipped with free-edge stiffeners in BRBFs, a parametric study has been conducted. To do so, the gusset plate 60×60 cm with varying thicknesses and different lengths of tee-sections were used. The parameters under study include thickness and width of the stiffener. Placement of stiffeners on the gusset plate's free edges is shown in Figure 13. Stiffener's thickness to gusset plate thickness ratio (β_1=t_s/t_g), along with stiffener's width to gusset plate thickness ratio (β_2=w_s/t_g) are considered as variable parameters in order to study the effect of stiffener size. The investigation was conducted with four gusset plate thicknesses (t_g= 4, 8, 12 and 16 mm) and four tee-section lengths (TL= 23, 30, 37 and 44 cm). Moreover, β_1 can take the values of 0.5, 1 and 1.5 while β_2 can be chosen between 5, 10 and 15.

Effects of Using Free-Edge Stiffeners: As it was expected, the addition of free-edge stiffeners increased the compressive strength of the gusset plate. The bigger the size of the stiffener, the more the compressive strength increases. Figure 14 shows buckling load variations of the 16 mm gusset plate against axial displacement with and without the free-edge stiffeners. In Figure 14 the letters G and S represent gusset plates and stiffeners respectively and the following numbers show the corresponding thicknesses. The letter W represents the stiffener width and the number following it is the value of â$_2$. Finally TL and the following number represent the tee-section and its length in cm respectively.

As it can be seen in Figure 14 that addition of free-edge stiffeners increases the compressive strength of the gusset plate. What is more important is how far the tee-section exceeds the bending line. In the case of TL=44 cm, the increase in the capacity of the gusset plate is accompanied by less sever strength loss than other models with shorter tee-section length.

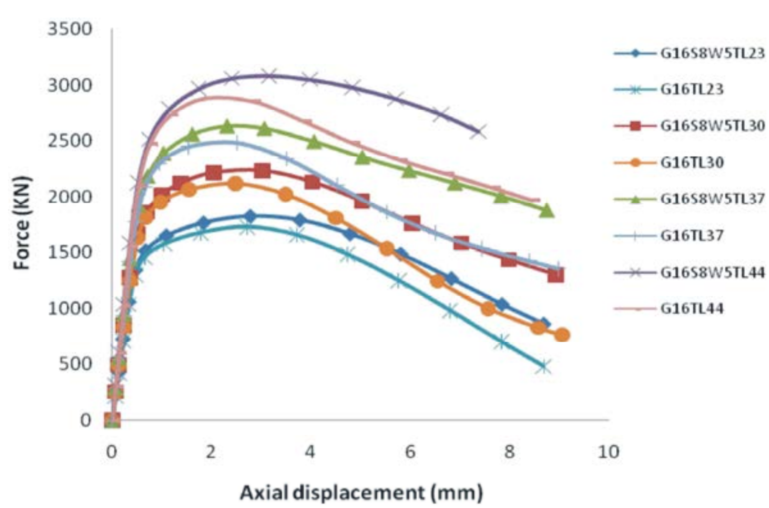

Fig. 14: Force-axial displacement curves in gusset plate with and without free-edge stiffeners.

CONCLUSIONS

In this study the behavior and compressive strength of corner gusset plates in BRBFs was investigated. Since in AISC-LRFD [29] no design procedure to determine the compressive strength of corner gusset plates in BRBFs is proposed and only recommendations are given to avoid local and overall buckling of the gusset plate, a parametric study was conducted on the compressive strength of BRBF corner gusset plate connections with different gusset plate dimensions and free edge stiffeners. The parameters under study include the gusset plate thickness, its width and length to width ratio and the tee-section length. In order to verify the accuracy of the analytical results one experiment on 50×50 cm gusset plate with thickness of 8 mm and a 23 cm tee-section were carried out. The following conclusions can be drawn from the present study:

- The results of the experiment show that the simplified finite element model assumed for the parametric study can reliably assess the ultimate load and buckling behavior of the gusset plate.
- When the gusset plate thickness is increased, the governing criterion for buckling which is instability for thin and long gusset plates will change to yielding criterion and the gusset plate capacity is significantly increased.
- Axial displacement in finite element models increases as the plate thickness is increased. This is because in thick plates buckling occurs after the gusset plate has yielded, providing the chance of further development of axial displacement in the gusset plate while in thin plates buckling happens due to instability without a chance for further axial displacements to develop.
- When the dimension of the gusset plate increases (length and width), its unsupported length along the tee-section is consequently increased which reduces the lateral stiffness of the gusset plate and its capacity is thus reduced.
- The tee-section length has significant effect on buckling capacity of the gusset plate. If the tee-section length is long enough to exceed the bending line, a higher compressive strength is achieved. In addition, for models with longer Tee-sections, the gusset plate can undergo greater inelastic deformations without loss of compressive capacity. This post-buckling response of the gusset plate can improve energy absorption of the plate as well as its cyclic behavior.
- Addition of free-edge stiffeners will increase the compressive strength of the gusset plate. Bigger dimensions of free-edge stiffeners will result in higher compressive strengths of the gusset plate.
- Finally a design method accompanied by some design charts for rectangular type gusset plates subject to compression is proposed based on an inelastic plate buckling equation. It should also be noted that the proposed method can be applied to gusset plates with certain properties and under certain circumstances. In case the assumed conditions and requirements are not met, separate charts for different conditions must be prepared.

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