Evaluation of the Effect of Nonlinear Behavior of Gusset plate of HSS Diagonal Brace on the Performance of Steel Frame Under Cyclic Loading

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Abstract
Recently the usage of concentrically braced frames (CBFs) are common for lateral-load resisting system in seismic design. In CBFs the braces are connected to the beam and column by gusset plate connection. Recent researches show that the seismic behavior of CBFs can be improved by considering yielding in the gusset plate in the performance levels. This study has indicated that buckling capacity of CBFs under a cyclic loading can be promoted by considering the behavior of gusset plate through designing its thickness and observe the free bending line and thickness of edge stiffener by the commercial finite element software Abaqus. At first the finite element and experimental result have been verified, Finally it will show the CBFs performance depends on gusset plate connections. The results indicated that increasing the thickness of gusset plate has the most effect on tolerable load of frame and promote stiffness and performance of braced frame.

Keywords: Concentrically braced framed (CBF), Gusset plate connections, Buckling capacity, cyclic loading, finite element method

1. Introduction

There are some cases for resisting in front of seismic loading in the steel frames and concentrically braced frames are more convenient than moment frames, also braced frames are more economical than moment frames, suppose that most of designer and constructor engineering use this kind of resisting system. Concentrically braced frames (CBFs) Fig. 1 [1] are commonly used as lateral-load resisting system in seismic design. The lateral loads are resisted by braces in these frames.

Depend on kind of braces the lateral loads will consistent with them. These loads transport from brace to beam and column with gusset plate connection. So the gusset plate connection transport the load to the mean component of the frame.

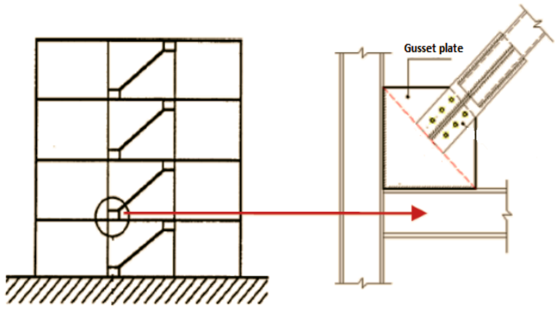


Figure 1: Typical concentrically braced steel frames [1]

2. Literature Review

First researches was concentrated on distribution of elastic stresses on gusset plates. One of the most important research was occurred by Whitmore in 1952 [2]. In his experiment, down gusset plate of truss with ¼ scaled from real model fig. 2 [2] has been modeled.
By his experience, he considered that the maximum tensile stress is located under tensile brace and the maximum compressive stress is located under compressive brace. He found out tensile and compressive stresses can be estimated by dividing the load that are acted from diagonal brace to the effective area. The effective area is equal to multiply the thickness of plate by its effective width, and the effective width will reached by drawing a thirty degree line from first row of screw and deal with the line from last row of screw, see fig. 3 [2].

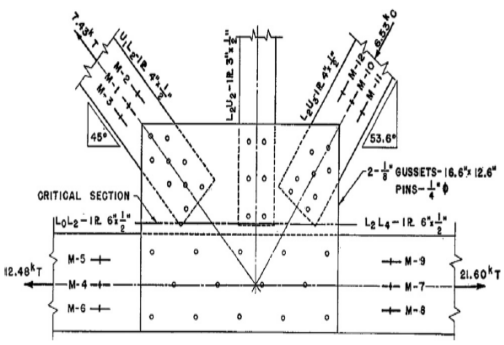


Figure 2: Connection geometry of Whitmore's model, 1952 [2]

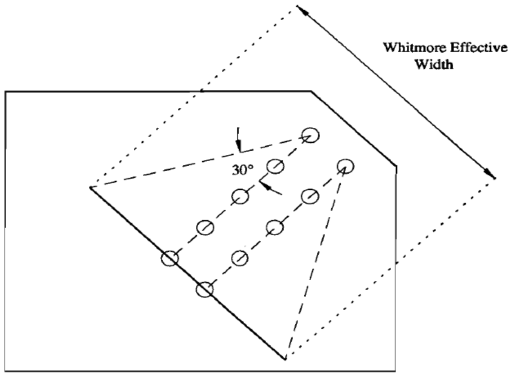


Figure 3: Whitmore effective width, 1952 [2]

Irvan (1957) [3] had conducted a model that checked primary stress in the double gusset plate in the Pratt truss. Ultimately he found the same place for maximum stress with Whitmore [2], though his method was different. More studies with Hardin 1958 [4] verified methods of previous researchers. For the first time Lavis (1967) [5] and Vasarhelyi (1971) [6] used finite element for determining the elastic stress distribution in the gusset plates, and Vasarhelyi continued their experimentation on scaled Warren truss model. He found out the differences in maximum stress in gusset plates between numerical methods are very small. Recently researches are concentrated on the behavior of gusset plates under ultimate loads, so now we will check the history of gusset plates under cyclic loads. Thornton 1984 [1] for his experimentation on gusset plates spotted all of the component of braced gusset plate, also he had reported a new lower bound method for estimating the compressive strength of connection with plate. His formula for estimating the compressive strength is:

$$p_{cr,T} = \frac{\pi^2 E}{\left(\frac{KL_c}{r}\right)^2} b_E t \tag{1}$$

Where K, t, r, be and Lc are respectively for effective length, thickness of gusset plate, radius of gyration, effective width of Whitmore, and average of L1, L2, L3 fig. 4 [1].

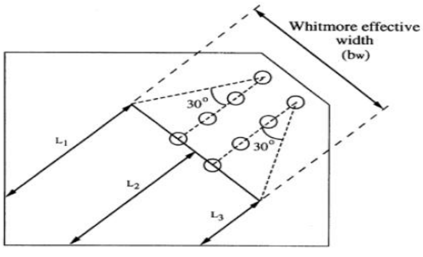


Figure 4: Thornton's method [1]

Bjorhovde and Chakrabarti (1985) [7] spotted the behavior of gusset plate under tensile loading. Their experimentation was done with whole connection of a diagonal brace that has been connected to beam and column. By their study they found out the primary mode of failure in gusset plate was located at the center of down holes. After that Bjorhovde and Hardash (1985) [8] have continued the study about gusset plates under tensile loading and they illustrated that rupturing will occurred in the last row of screw and tensile yielding will occurred on the out row of screw parallel with brace. William and Richard (1986) [9] have checked the distribution of stress in gusset plates, but in their work was some differences by other researchers and they modeled the effect of beam and column, finally they found because of exiting gusset plate the joint is assumed to be rigid, although it is ball joint in reality. Cheng and Hu (1987) [10] has modeled a complete brace and considered the buckling behavior and buckling load of connection, ultimately he concluded that the thickness and dimension of gusset plate is very important in its buckling behavior. Sheng and Yam (2002) [11] presented a new method for estimating the buckling capacity of gusset plate that depends on critical inelastic buckling stress:

$$p_U = \sigma_U . b_1 . t \tag{2}$$

$$\sigma_u = \frac{K_g \pi^2 E \sqrt{\frac{E_t}{E}}}{12\left(1-\nu^2\right)\left(\frac{b_0}{t}\right)^2} \tag{3}$$

Where Pu, , b1, t, E, , b0 and Kg are respectively for buckling capacity of gusset plate, inelastic buckling stress of gusset plate, length of moment line, thickness of gusset plate, elasticity modulus, Poisson ratio, length of the shortest gusset plate and E=50Et . Brown (1988) [12] had done one of important investigation in edge buckling of gusset plate that he reported the compressive experimental results and analysis of gusset plate edge buckling. In this investigations recommended the eq.3 for prevented the gusset plate edge buckling.

$$\frac{L_{fg}}{t} \le 0.83\sqrt{\frac{E}{F_y}} \tag{4}$$

Where E is elasticity modulus, t is thickness of gusset, Fy is failure stress of materials and L_{fg} is the length of free edge of gusset plate.

3. Finite element modeling and verification

In this study for building the analytical model, commercial finite element program Abaqus 6.13-1 [13] is used and is verified by Jung-Han Yoo [14] fig. 5 experimental model.

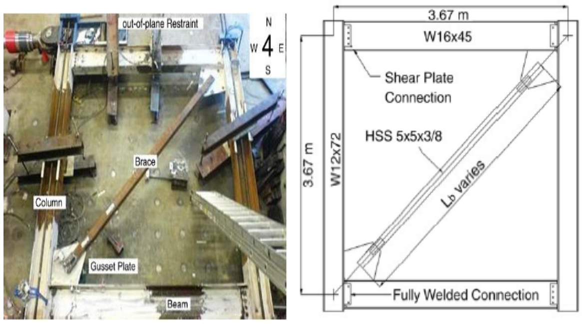


Figure 5: Jung-Han Yoo experimental model [13]

The materials that are used are like experimental model and All elements are modeled by shell (S4R) element with four nodes that each node has six degree of freedom. Beams are W16X45 and columns are W12X72 from A992 steel and brace is from HSS 5X5X3/8 section with type of steel A500 with 45 (degree) angle. All connection are welded and kind of welding is solid. The meshes dimension are 50*50 milimeter.

The frame is under cyclic loading by instrument of ATC-24 [15]. The history of loading is shown in fig. 6, according to this loading the deformation of some elastic cycles are assumed for creating primary stiffness and yielding stresses, after that the deformation domain of cycles are increased to consider inelastic behavior.

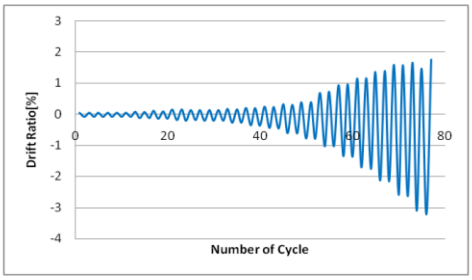


Figure 6: history of loading [15]

In the following figure the computer model under cyclic load is shown fig. 7:

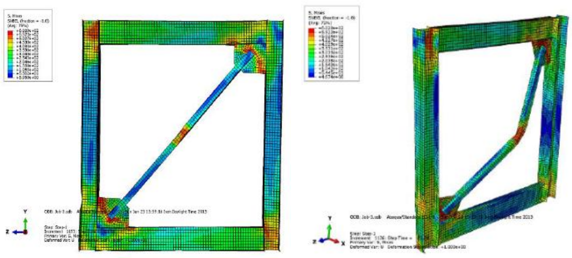


Figure 7: analytical model and deformed shape of frame

The comparison between analytical and experimental models are shown in fig 8. According to this all result such as curves, out-of-plane bending and stress in members special in gusset plate in experimental and analytical model are almost the same and there is good consistent between its.

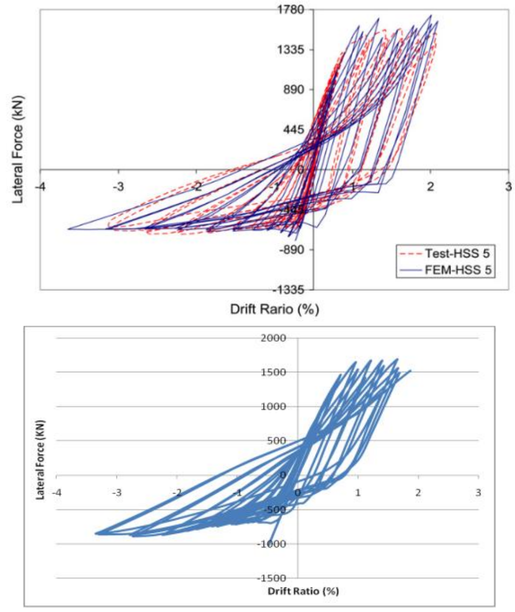
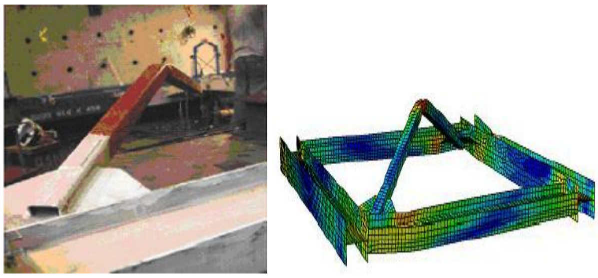
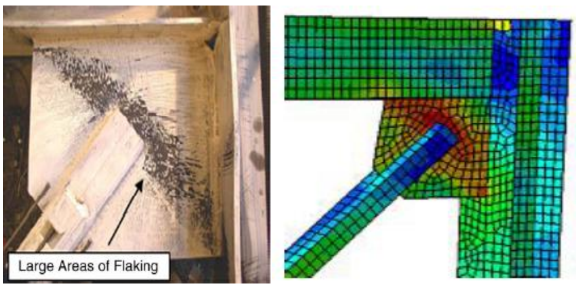


Figure 8: comparison of diagram of lateral force versus drift ratio between experimental and numerical models [13]



(i)



(ii)

Figure 9: comparison of inelastic analysis and theoretical predictions: (i) typical brace buckling deformation, and (ii) typical yielding of gusset plate.

4. Evaluation result of finite element analyzing

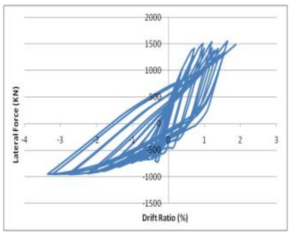
4.1. Evaluation the effect of gusset plate thickness on its buckling behavior:

In this section we survey various thickness of gusset plate and find its effect on ultimate load and stiffness of gusset plate that stiffness is base shear force per frame displacement. Typical thicknesses of plates that we used for numerical analyzing on Abaqus [13] are 8,12,16,20 and 25 millimeters.

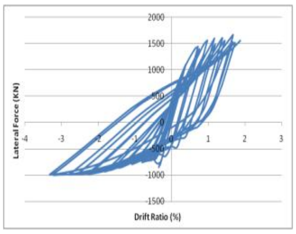
Table 1: Thickness of gusset plates

Models name	Thickness of gusset plates (mm)
FRAME1	8
FRAME2	12
FRAME3	16
FRAME4	20
FRAME5	25

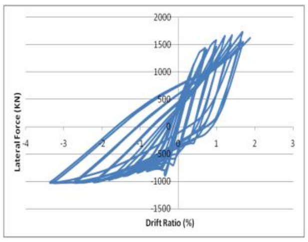
After nonlinear analysis of frames under cyclic loading, diagram of Lateral load-drift is shown for five frame in figures 1,2,3,4,5,.



FRAME1



FRAME2



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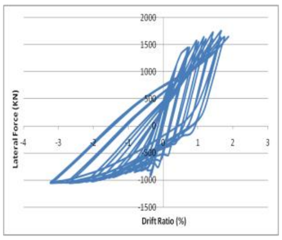
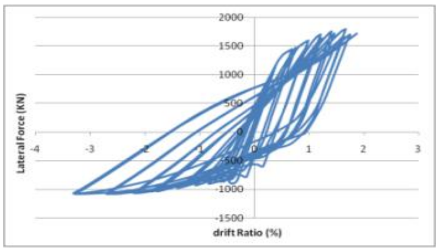


FRAME4



FRAME5

Table 2: results of analysis of various thicknesses of gusset plate

Models Name	Lateral Force (KN)	Stiffness of frame (KN/mm)
FRAME1	1550.26	23.14
FRAME2	1668.96	24.91
FRAME3	1731.02	25.84
FRAME4	1753.11	26.17
FRAME5	1793.42	26.77

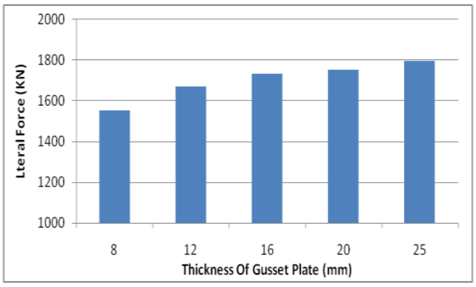


Figure 10: Comparison of results for thicknesses of gusset plate

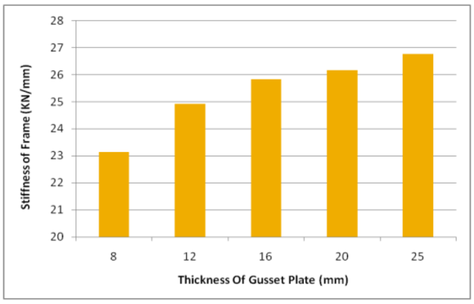


Figure 11: Comparison of results for stiffness of frames

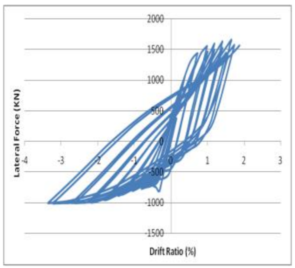
As shown in figures 10 and 11, it's specified that by increasing the gusset plate thickness its compressive strength in buckling load and stiffness of frame will rise because By increasing in gusset plate thickness, required force for displace of frame is increasing so we can see rising in amount of ultimate load and stiffness of frame.

4.2. Evaluation the effect of observance of free bending line on frame buckling behavior:

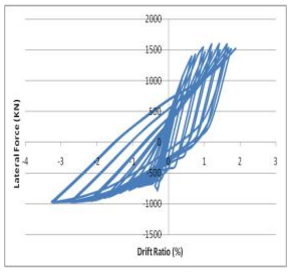
Surveying is for gusset plate with thickness of 9.5 mm and specifications of frame is constant. distance of free bending line of gusset plate is 8tp (ellipse shape) and length of wedge of brace to gusset plate is 375 (mm). specifications of models is shown in Table 3.

Table 3: Specifications of frames

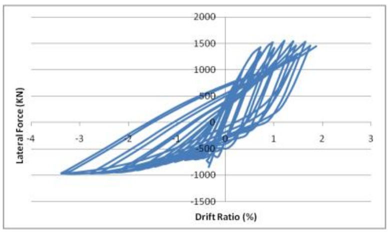
Models name	Braces cutting conditions
FRAME6	after the free bending line
FRAME7	On free bending line
FRAME8	ago the free bending line



FRAME6



FRAME7



FRAME8

Table 4: Results of analysis of frames for observance of free bending line

Model name	Lateral force (KN)	Stiffness of frame (KN/mm)
FRAME6	1659.92	24.77
FRAME7	1601.57	23.90
FRAME8	1550.92	23.15

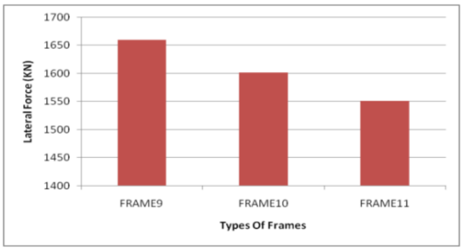


Figure 12: Comparison of results for observance of free bending line

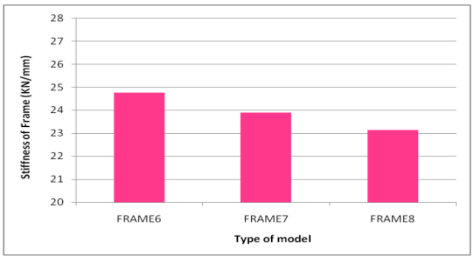


Figure 13: Comparison of results for stiffness of frames

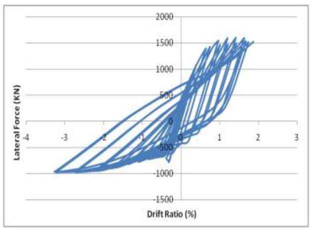
As shown in figures 12 and 13, with near the point of intersecting of brace to region of intersection of beam and column, its compressive strength and stiffness of frame was increased. That's because of by increasing length of brace, required force for frame displacement is rise, So tolerable load of frame and stiffness of frame is increasing.

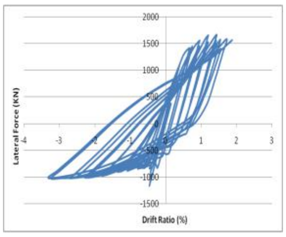
4.3. Evaluation the effect of edge stiffener on behavior of gusset plate:

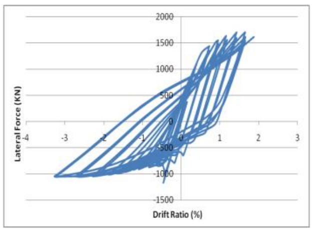
Controlling the mode of buckling of gusset plate by edge stiffeners is important agent in control the compressive capacity and base shear and stiffness of this plates. In this study for surveying the effect of edge stiffeners thickness on behavior of buckling of gusset plate with 9.5 millimeters thickness, as shown in Table 5, we used from edge stiffeners with 0 (without stiffener), 5, 10, 15, and 20 millimeters thickness.

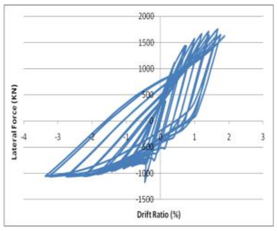
Table 5: Thickness of edge stiffeners

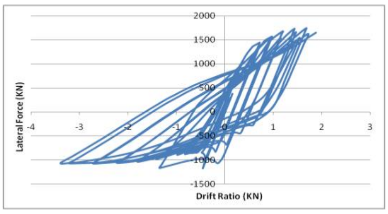
Models name	Thickness of edge stiffener (mm)
FRAME9	Without stiffener
FRAME10	5
FRAME11	10
FRAME12	15
FRAME13	20


FRAME 9


FRAME10


FRAME11


FRAME12



FRAME 13

Table 6: Results of stiffeners analysis

Models name	Lateral Force (KN)	Stiffness of frame (KN/mm)
FRAME12	1601.57	23.90
FRAME13	1663.27	24.82
FRAME14	1709.09	25.51
FRAME15	1761.24	26.29
FRAME16	1744.64	26.04

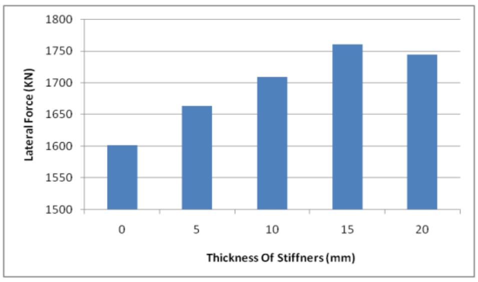


Figure 14: Comparison of results for thickness of edge stiffeners

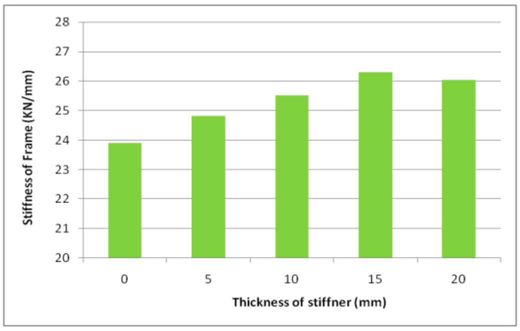


Figure 15: Comparison of results of Stiffness of specimens

By analyzing these models under cyclic loading, as shown in figures 14 and 15, with increasing the thickness of edge stiffener, buckling of gusset plate keeps out from its edge and transports to middle of gusset plate but with increase the thickness from 15 to 20 (mm), tolerable load of frame is decrease. so if optimum thickness of stiffeners be considered, bearing capacity and stiffness of frame will increase.

5. Summary and conclusions

In this study the finite element model with concentrated braced frame has been produced according to previous researchers work, and base on it has been verified. The analytical model has simulated buckling capacity under cyclic loading exactly. In this research the gusset plates with various thicknesses and effect of observe free bending line and edge stiffeners with different thickness has been considered in Abaqus [13] software and the conclusions from this parameter study include the following:

1. The thickness of gusset plate had a significant effect on buckling capacity of it, also the ultimate loads of the specimens increase almost linearly proportional to the gusset plate thickness also increase the thickness of the gusset plate resulted in an increase in the stiffness of frame.

2. Increasing the length of brace and near the intersecting point of brace to region of intersection of beam and column, has high effect on compressive capacity of it, and leading to increase the tolerable load and stiffness of frame.

3. The edge stiffener has high effect on promote the gusset plate behavior and stiffness of frame so that if appropriate and optimum thickness of stiffener be considered for gusset plate, these results have been achieved:

a. The ductility of gusset plate and stiffness of frame will increase and this lead to change the buckling mode.

b. The compressive bearing capacity and the energy dissipation in gusset plate will increase linearly.

5. References

1. Thornton WA. “Bracing connections for heavy construction. Engineering” Journal (AISC) 1984;139_48. Third Quarter, 1984.
2. Whitmore R.E., (1952), “*Experimental Investigation of Stresses in Gusset Plates*”, Bulletin No. 16. Engineering Experiment Station, University of Tennessee, Knoxville.
3. Irvan, W.G., (1957). “*Experimental Study of Primary Stresses in Gusset Plates of Double Plane Pratt Truss*,’’ Bulletin No. 46, University of Kentucky Engineering Experiment Station.
4. Hardin, B. O. (1958), “*Experimental Investigation of the Primary Stress Distribution in Gusset Plates of a Double Plane Pratt Truss Joint with Chord Splice at the Joint*,” Bulletin No. 49, University of Kentucky Engineering Experiment Station.
5. Lavis, C. S. (1967), “*Computer Analysis of the Stresses in a Gusset Plate*,” Masters Thesis, University of Washington.
6. Vasarhelyi, D. D. (1971), *“Tests of Gusset Plate Models,”* Journal of the Structural Division, Proceedings of the American Society of Civil Engineers, 97, No. ST2, pp. 665-679.
7. Bjorhovde, R. and Chakarbarti, S.K., 1985. “*Tests of Full-Size Gusset Plate Connections*.” Journal Engineering, ASCE, Vol.111, NO.3, March, pp.667-684.
8. Hardash, S.G. and Bjorhovde, R., 1985. “*New Design Criteria for Gusset Plates in Tension*.” Engineering Journal, AISC, Vol. 22,No.2, pp.77-94.
9. Williams, G.C. and RiCHard,R.M.,1986.“*Steelv Connection Design based on Inelastic Finite Element Analysis*.” Report of Department of Civil Engineering and Engineering Mechanics, The University of Arizona.
10. Cheng JJR, Hu. “*Behavior and design of gusset plate connections in compression*”. Journal of Constructional Steel Research 1987;58:1143_59
11. Sheng N, Yam CH, Iu VP. “*Analytical investigation and the design of the compressive strength of steel gusset plate connections*”. Journal of Constructional Steel Research 2002; 58:1473_93.
12. Brown.V.L.S, (1988), “Stability of gusset connections in steel structures ”, Doctoral Dissertation, Department of civil Engineering, University of Delaware.
13. ABAQUS, standard user's manual version 6.3. Pawtucket, RI: Hibbitt, Karlsson & Sorensen, Inc; 2003.
14. Yoo JH, Roeder C, Lehman D. FEM simulation and failure analysis of special concentrically braced frame tests, ASCE, Journal of Structural Engineering (2007) [approved and awaiting publication].
15. ATC 24. “*Guidelines for cyclic seismic testing of components of steel structures*”. Applied Technology Council; 1992.
16. AISC. Steel construction manual. 13th ed. Chicago (IL): American Institute of Steel Construction; 2005.