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Predicting yielding of gusset plates in seismic frames using finite element modelling

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ABSTRACT

Gusset plates connect lateral bracing to a building by fixing two perpendicular edges into the corners of a frame. This results in a gusset plate having a non-uniform cross-sectional area and generally, each gusset plate design is bespoke. For these reasons, stress distribution through a gusset plate is complex and difficult to predict. The Whitmore width method (1952) approximates this stress distribution by defining an effective yield area used to size a gusset plate. This method originates from a small sample of experimental observations. This paper investigates the accuracy of the Whitmore width method by using finite element modelling to study the development of yielding in gusset plates with bolted connections. Seismic frames such as buckling-restrained-braced frames require accurate strength and stiffness properties of each member to ensure stability and that energy is dissipated effectively. Of interest is how different design parameters such as the size of the connection area, shape of the gusset plate and angle of inclination effect yielding behaviour. In total 184 variations of gusset plate geometries were modelled in Abaqus®. The simulated testing was under ideal conditions, applying a monotonic uniaxial load. Results show that the Whitmore width does not accurately represent the initial yielding area of gusset plate designs and is generally un-conservative for larger gusset plate designs. Subsequently a modification to the Whitmore method is proposed.

1 INTRODUCTION

In seismic building design, gusset plates connect lateral bracing within a structural frame along critical load paths. The design of gusset plates in seismic frames varies greatly between building projects. It is recognised that the stress distribution through the connection zone (beam, column, brace and gusset) is complex. Until 1952, beam formulas were used in the design of gusset plates. These beam formulas checked the stress limits along various sections of a connection zone. To examine the validity of this approach, Whitmore investigated the stress distribution of an aluminum gusset plate within a truss and he found beam formulas to be inaccurate (AISC 1974). Whitmore founded an alternative method called the Whitmore width method. He concluded that the maximum normal stress at the end of a member could be estimated adequately by assuming the member force was distributed uniformly over an effective area. This area was obtained by multiplying the thickness of the plate by an effective width. The effective width is presented in equation (1).

$$\mathrm{b_e} = \mathrm{b}_{\text{bolt array}} + 2 * \mathrm{L}_{\text{bolt array}} * \tan 30^{0} \tag{1}$$

Where, $b_{bolt\ array}$ and $L_{bolt\ array}$ is the width and length of the bolt array. Figure 1 illustrates how the effective width is calculated with 30^0 lines from the outer fasteners of the first row to their intersection with a line perpendicular to a line passing through the bottom row (ANSI/AISC 2010).

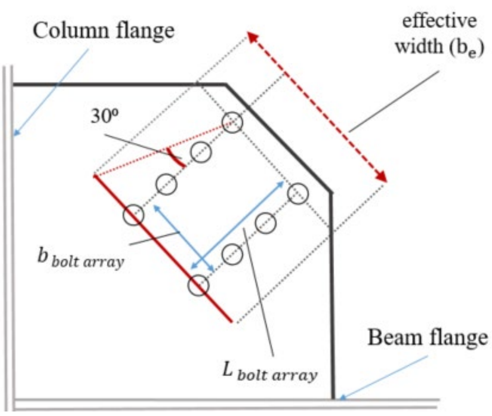

Figure 1. Schematic of Whitmore width (b_e) (ANSI/AISC 2010)

Initially, the Whitmore width method was used to check peak axial stresses at the end of the joint. Based on the aluminium gusset plate in the truss joint experiment this provided a good fit. However, the spectra of gusset plate geometries used today means its ability to accurately predict the onset of yielding for all scenarios is less likely. This is a problem when designing gusset plates using capacity based design philosophy, which relies on being able to accurately predict yielding of each member.

In traditional bracing systems, such as eccentrically and concentrically braced frames, energy is largely dissipated in tension through yielding of the brace. In compression, the brace is susceptible to global buckling behaviour and dissipates some energy through axial and bending stresses. In these systems, the tension load governs gusset plate design.

An additional consideration is hinging. If the brace buckles out-of-plane, hinging is the preferred load transfer mechanism within the gusset plate. To encourage this mechanism, seismic provisions in AISC and NZS3404 prescribe a linear clearance of two times the thickness of the gusset plate (Standards New Zealand 1997, ANSI/AISC 2010). This approach results in relatively large section sizes that are not desirable. To achieve smaller section sizes Roedar introduced another approach which assumes the gusset plate can bend about an elliptical line pattern (Roeder et al. 2011). Figure 2 illustrates the linear clearance approach for square and tapered gusset plates, and the elliptical clearance approach by Roedar.

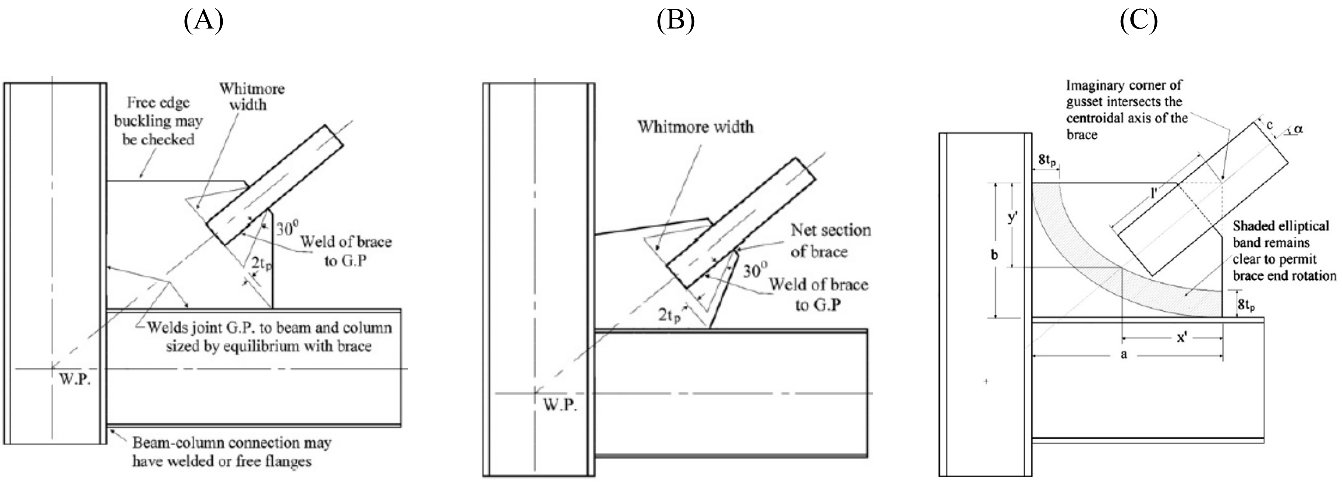

Figure 2. Schematic of gusset plate geometries allowing for end rotation (A) 2tp clearance generic, (B) 2tp clearance tapered, (C) Elliptical clearance

In a Buckling-Restrained-Brace, a slender steel core plastically deforms inside a restrainer. This restrainer prevents the global buckling exhibited in traditional bracing. These systems have increased in popularity in recent times as they dissipate larger amounts of energy through yielding of the brace in both tension and compression. The behaviour of the slender steel core deforming inside a restrainer causes additional frictional and Poisson effects in compression. These additional compression effects mean local buckling and global instability need to be considered in gusset plate design. To prevent local instability of a gusset plate, design codes treat them as an equivalent column and use stipulated buckling limits to size them. In general, these buckling limits are based on column buckling curves using the Whitmore width to determine the yield section. Ideally, gusset plates in these systems would be compact and stiffened to reduce local and global instability. However, internationally, few design codes enforce this, which has led to a large range of gusset plate variations on the market.

This paper uses finite element analysis (FEA) to study how yielding develops in gusset plates with bolted connections. The models predict the initial yield area for a large spectrum of gusset plate designs that have a bolted connection. Of interest is how different design parameters such as the size of the connection area and angle of inclination affect performance. This will indicate the level of safety over a range of commonly adopted designs.

2 FINITE ELEMENT MODEL DEVELOPMENT

The non-uniform geometry and large variation of gusset plate designs make it difficult to analytically predict how stresses distribute through a gusset plate and connection zone. This is because the yielding of the material develops in different sections of the gusset plate as loading increases. The different sections of yielding can be difficult to capture in experimental testing. The Whitmore width method approximates this yielding behaviour. Since the conception of the Whitmore width method (1952), advances in FEA now enable detailed analysis of stress-strain behaviour. To study the yielding behaviour of different gusset plates, a series of finite element models were developed using Abaqus®. All the finite element models were the same except for geometric dimensions. Each model contained a brace end connected to a gusset plate. Solid (C3D8I) elements were used to capture the stress-strain response through the thickness of each member (Dassault Systems 2014). To capture buckling behaviour, non-linear geometric analysis was performed. The gusset plate boundaries were idealized as being fixed. Surface-surface contact between the gusset plate and brace end connection was included to simulate the interaction between those parts. Each bolted connection was approximated using a coupling constraint, which coupled the inner surface of each bolthole to a centre node. To capture local bolt bearing deformation only half the inner surface of each bole hole was constrained to this centre node in order to capture local bolt bearing deformation. A tabulated multi-linear isotropic hardening material model was applied. This model was deemed suitable as only monotonic axial loading is applied. Validation of these modelling selections is shown through direct simulation of the experimental testing conducted by Yam (Yam et al. 1993). Three gusset plate sizes were selected for validation. The sizes selected resembled geometries investigated in this paper. For each simulated test, the peak load was found to be within 5% of experimental results. Figure 3 presents the experimental set up and finite element model of testing.

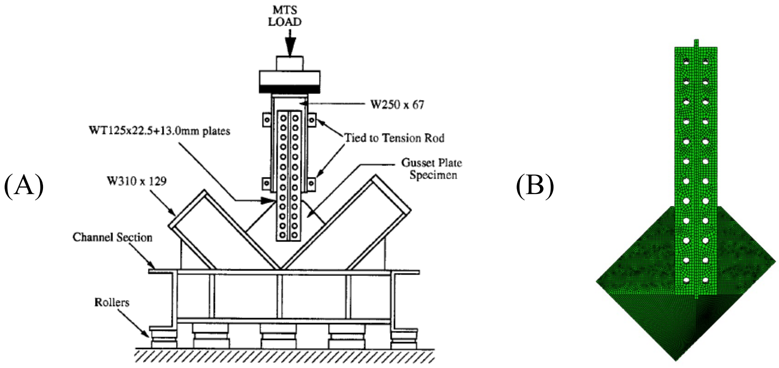

Figure 3: (A) experimental test setup (Yam et al. 1993), (B) visualization of FEA model

Following validation, a total of 184 gusset plate models were developed in Abaqus®. Common gusset plate designs used in practice, such as those shown in Figure 4, guided the selection of geometries investigated. Variations include tapered and regular designs, the size of the bolted connection and number of bolts, angle of inclination, gusset plate thickness and length of bolted connection from the working point. Table 1 presents a summary of all the variations investigated. These parameters combine to create 512 possible variations. However, combinations that seemed unrealistic or repetitive were not modelled.

Figure 4. Various lengths of bolted connection arrays used in BRBF design
(A) 16 bolt array. (B) 12 bolt array and (C) 10 bolt array

Table 1: Variations in gusset plate geometries investigated.

Geometric description	Values/types
Shape of gusset plate	Regular, tapered
Size of bolted connection (in contact with gusset plate)	4 bolts (125x210) 6 bolts (125x210) 6 bolts (61x100) 8 bolts (125x210) 10 bolts (125x210) 12 bolts (250x436) 14 bolts (250x436) 16 bolts (250x675)
Angle of inclination	22.5^0 45^0
Thickness	6mm, 15mm, 25mm, 32mm
Length - from edge of end connection to flange (along angle of inclination)	~100mm, ~300mm, ~500mm, ~1000mm

Figure 5 illustrates three examples of the gusset plates described in Table 1. These vary in geometric slenderness (L/r) from 60, being very slender to 2, being compact.

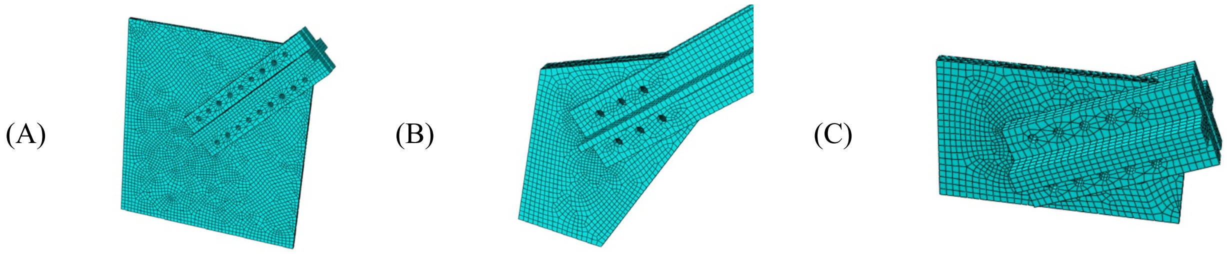

Figure 5. Example of gusset plates modelled in FEA
(A) 16 bolt array – 45 ^{o}- non tapered – L/r = 60, (B) 6 bolt array - 45 ^{o}- tapered – L/r = 13
(C) 10 bolt array – 22.5 ^{o}non tapered – L/r = 2

3 METHOD FOR DETERMINING YIELD AREA

High fidelity FEA modelling enables close examination of stress-strain behaviour. This can be used to study how yielding occurs and develops through a gusset plate under loading. Understanding the onset and development of yielding in structural members is required for safe seismic design. Generally, slender sections are governed by elastic buckling. However, the majority of gusset plate designs are compact and the likelihood of elastic buckling is low. In this case, the design is governed by yielding and non-linear buckling.

In the majority of structural members governed by axial loading, the yield area is simply the cross sectional area. However, the geometric features of a gusset plate make it more difficult to determine. At the one end of the gusset plate, a brace connects diagonally by an array of bolts. At the opposite end, a gusset plate has two edges fixed to the beam and column flanges of a frame at perpendicular angles, which means the cross-sectional area throughout the gusset plate is not the same. To illustrate this, Figure 6 displays a schematic of gusset plate with several cuts made perpendicular to the direction of loading. Upon comparison, it is easy to see these cuts are all different lengths. This change in cross-sectional width makes it difficult to predict the cross-sectional area upon yielding.

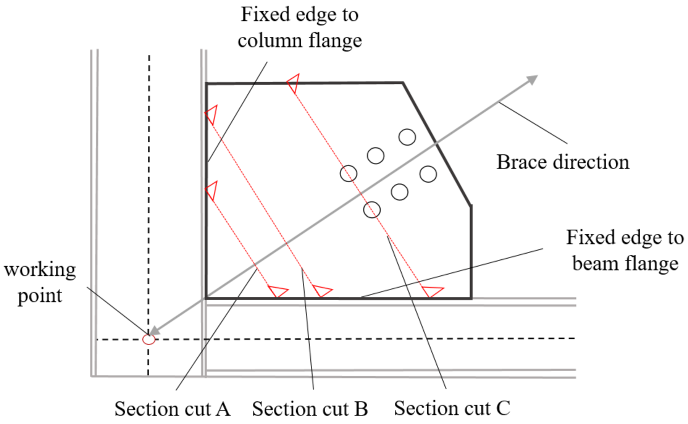

Figure 6. Schematic showing change in cross-section width of a gusset plate – Section A < Section B < Section C

The geometric features of a gusset plate also influence how stress develops through a gusset plate to the boundary conditions. This is difficult to observe in experiments however, FEA offers a way to do this. Figure 7A-C shows the development of stresses in a gusset plate, where red indicates yielding and blue indicates low levels of stress. These images represent snapshot locations on the force-displacement plot in Figure 8. This illustrates that yielding does not occur throughout the entire cross section evenly, and that it changes as loading is applied.

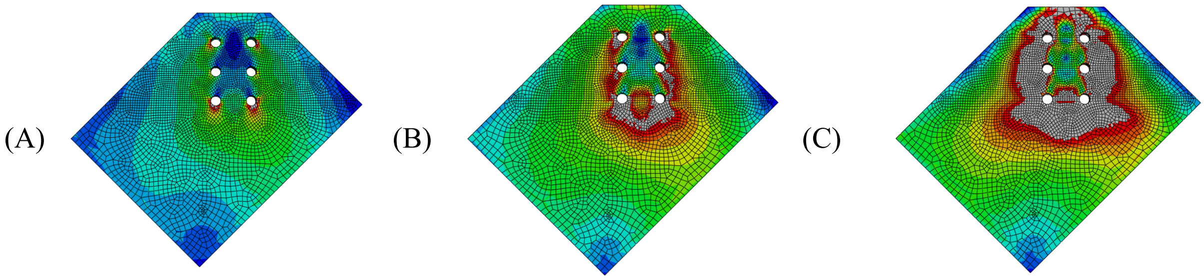

Figure 7. FEA images of stress distribution in gusset plates (A) yielding of area at edge of bolts, (B) development of yield around bolt array (C) yield surface expanded to flange interface

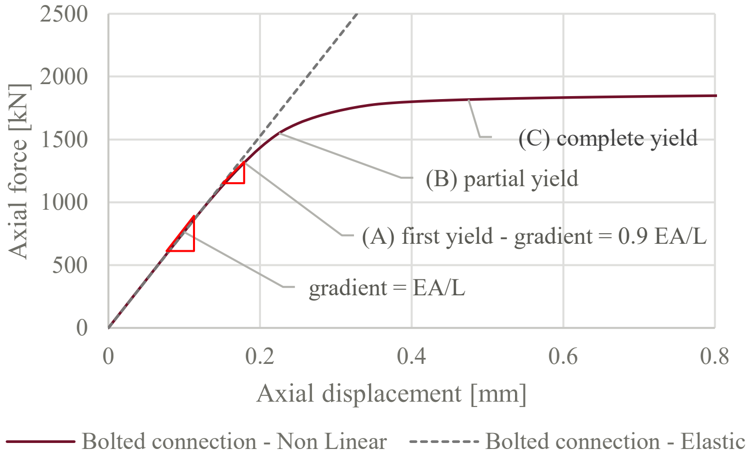

Figure 8. Force vs displacement response of an axially loaded gusset plate – showing the response locations associated with yielding images in figure 9.

There is no standardised method to establish the first yield point of a gusset plate. For the analysis conducted in this study, first yield is defined as the point where the linear-elastic stiffness reduces to 90% of its initial value. The effective yield area can then be calculated by dividing the initial yield force by the yield strength of the material. The effective yield width is then calculated by dividing the initial yield area by its thickness. By using the FEA results from the different gusset plate models set out in this study we can establish the applicability of the Whitmore width method and investigate how different gusset plate features such as angle of inclination, length and tapering influence the initial yield. Displayed in Figure 9 are the results from the simulated testing showing the effective yield width for the different sizes of bolted connections modelled.

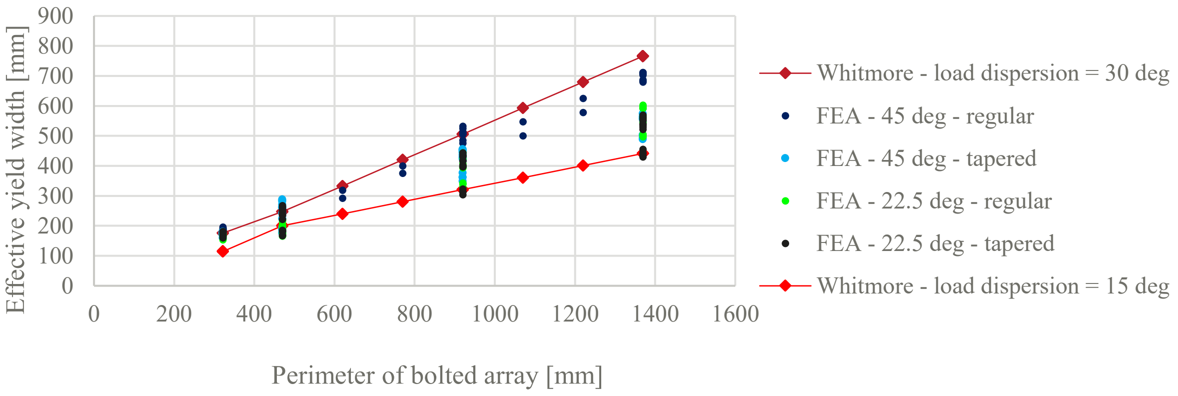

Figure 9. Gusset plate width (at first yield)

It was found that the Whitmore width method generally overestimates the onset of yielding, especially for gusset plates with larger connections. This is indicated in Figure 8 as the FEA results are generally below the prediction made by the Whitmore method (using a load dispersion angle of 30 degrees). By changing the load dispersion angle, used in Whitmore width method, from 30^0 to 15^0, the prediction of initial yielding generally became conservative. This modification to the Whitmore width method is presented in Equation (2).

$$b_e = b_{bolt\ array} + 2 * L_{bolt\ array} * tan\ 15^{0} \quad (2)$$

4 DISCUSSION

Finite element analysis was used to explore the effect different gusset plate features have on the yielding behaviour of the gusset plate for a range of geometries. Finite element analysis was necessary as investigating the detailed stress-strain behaviour of the plate experimentally is to too difficult. Observations between the different gusset plate features suggest the following:

1. Both the thickness and size of the gusset plate influence the size of the initial yield width. For thicker and larger gusset plates, the normalised yield point (90% of initial stiffness) is higher compared to thinner and smaller gusset plates with the same bolted array. This is because the secant stiffness after yield varies between sizes. A more complicated approach is required to further improve upon the Whitmore width method. This would take into account more geometric features of a gusset plate including the stiffness ratio of the brace end to gusset plate.
2. A smaller angle of inclination slightly reduces the yielding area, particularly for compact designs. The size of a frame (bay) within a commercial building governs the angle of inclination and largely influences the size and aspect ratio of the gusset plate. Commonly, this angle ranges from 22.5 degrees, being a relatively wide frame, to 45 degrees, being a square frame. By changing the angle of inclination, the overall size of the gusset plate changes. This affects the stress distribution in the gusset plate. With a smaller angle of inclination, the stiffness of gusset plate from the end of brace to the working point is less symmetrical. As stress flows through the stiffest path, it travels to the closest weld zone creating a reduced yielding area than if it was symmetrical (Figure 10a).
3. Tapering reduces elastic axial stiffness of a gusset plate but has little effect on the initial yield point (Figure 10b). This suggests that tapering increases the elastic buckling length. Tapering is common among gusset plate designs. It helps accommodate bending and seeks to improve the aesthetic nature of the design. However, the effect this has on yielding and buckling is not considered in design codes

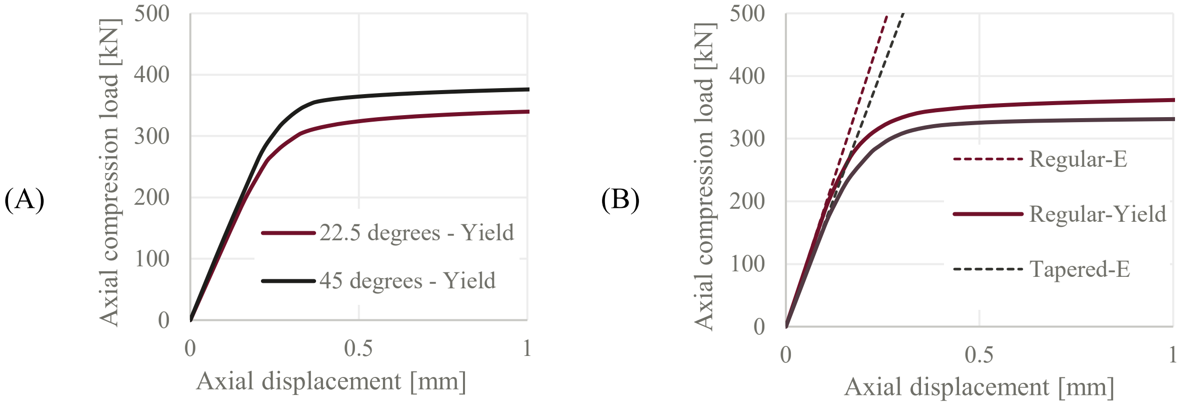

Figure 10 effect of gusset plate features (force-displacement plot)
(a) effect of angle of inclination, (b) effect of tapering

Analytical methods used to predict the buckling load of a gusset plate first calculate a yield capacity and then reduce this by a factor based on observations of column buckling behaviour. This yield capacity is calculated using the Whitmore width method. These simplifications are a coarse approximation of the elastic-plastic behaviour of gusset plates under compression. By using the FEA modelling selections in this paper, we can study the buckling behaviour and improve upon methods used in current design codes.

5 CONCLUSION

FEA was used to virtually test a series of gusset plates. In total 184 variations of gusset plate geometries were investigated. Simulated testing was under ideal conditions, applying a monotonic uniaxial load. Results show that the Whitmore width does not accurately represent the initial yielding area of gusset plate designs and is generally un-conservative. By simply modifying the load dispersion angle in the Whitmore width method from 30^0 to 15^0, estimates of initial yield in gusset plates became conservative.

FEA was used to illustrate how stresses distribute through a gusset plate after yield. Important observations include 1) the initial yield area is influenced by the shape and size of the gusset plate and not only the size of the bolt array, 2) the angle of inclination effects yielding, whereby a smaller angle can reduce the yield area and 3) that tapering of a gusset plate can decrease axial stiffness of a gusset plate. Results are being used in continued research to improve upon current methods that predict buckling limits of gusset plates. Currently they treat gusset plates as an equivalent column and use the Whitmore width method to estimate yield.

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