A Study of the Effects of Two-Way Prying Action in Bolted Connections

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Abstract

The purpose of this paper is to report on an investigation into the effects that prying action has on bolts and connecting members. The case in which a steel member is reinforced with a transverse stiffener is investigated specifically for an increase in prying action due to a combination of prying along the member's cross-section and length, referred to in this paper as *two-way prying*. The methods employed for this investigation include a critical literature review examining the background of the current AISC provisions related to prying action as well as the creation and analysis of multiple computer models using SAP 2000 software. The analysis of the models included analyzing the bolt forces, material stresses, and overall behavior of the connection for each case. The main results of the analysis indicate that the introduction of a transverse stiffener reduced the force in each bolt by 21% and redistributes the stress in the flange in a way which reduces the maximum experienced stress. The report concludes that two-way prying action did not occur based on the SAP 2000 model result. Further research is suggested to compare the results of this study to the results of both physical testing and refined finite element analysis to yield comprehensive and conclusive results.

Keywords: prying action, steel connections, bolted connections, yield line theory, bolt tension, American Institute of Steel Construction [AISC], two-way prying action, SAP 2000, finite element analysis

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The design of bolted steel connections requires multiple checks to ensure that the fitting is strong enough to resist the potential loadings that could be imposed upon it. These checks are performed by analyzing the connection's limit states. Limit states are ways in which a structural member could potentially fail based on structural engineering principles and years of observation and research. The limit states that are applicable to the design of a steel member depend on a combination of different variables, such as the type of force being applied, the local and global role of the member in the building structure, the geometry of components being connected, and the type of connection being designed. All applicable limit states for strength and serviceability must be addressed and the limit state that provides the lowest connection strength is considered the governing limit state. This limit state determines the strength of the design (American Institute of Steel Construction [AISC], 2017, p. 2-10). Prying action is a consideration in steel connection design that is necessary to consider when the connection experiences tension forces. This consideration requires checking the limit states of plate bending in the connecting member and tension rupture in the connecting bolts.

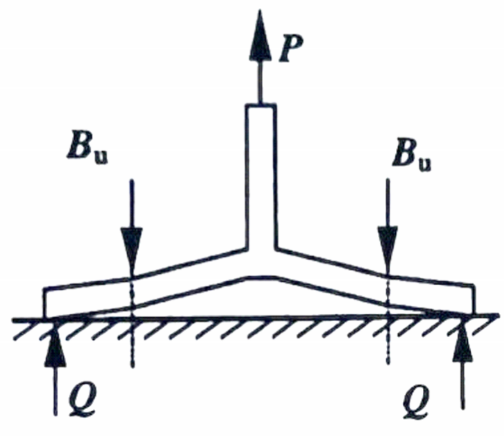
Prying action is defined by the American Institute of Steel Construction (AISC, 2017) as:

> A phenomenon (in bolted construction only, and only in connections with tensile bolt forces) whereby the deformation of a connecting element under a tensile force increases the tensile force in the bolt above that due to the direct tensile force alone. (p. 9-10)

Essentially, this definition implies that when a force pulls on a steel member and its connecting bolts, there is a potential increase in the amount of force the bolts experience due to the deflection of the connecting member. Figure 1 illustrates the deformed cross-section of a W-shape member and development of the prying action forces.

Figure 1

Cross-Section View of Prying Action in W-Shape

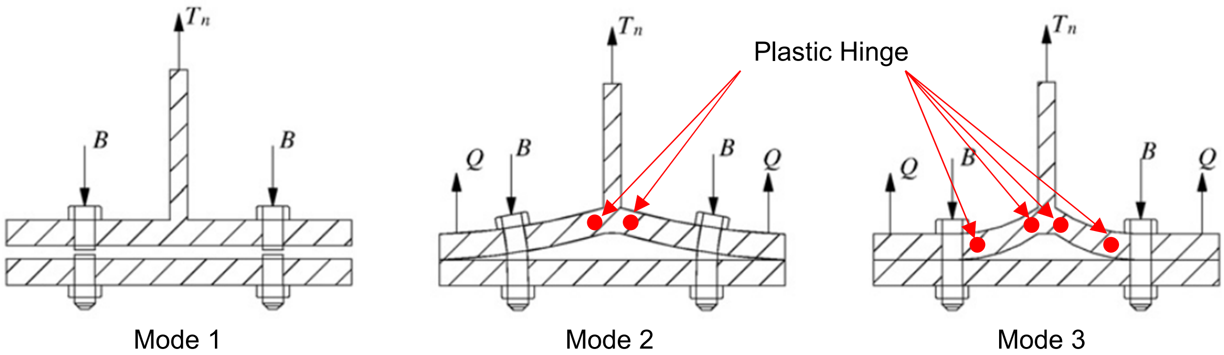


Note. Adapted from "Design Model For Bolted Moment End Plate Connections Joining Rectangular Hollow Sections" by A. T. Wheeler, M. J Clarke, G.J. Hancock, and T.M. Murray, 1998, *Journal of Structural Engineering, 124*(2), p. 165. https://doi.org/10.1061/(asce)0733-9445(1998)124:2(164)

The additional force that the bolt must resist due to prying action is known as the prying force, noted as Q in Figure 1. The magnitude of the prying force is dependent on various factors inherent in the connection geometry, such as bolt spacing along the length and cross-section of the member. However, the most important factor in determining the effects of prying action are the stiffness and thickness of the connecting member in relation to the bolt stiffness (Estrada & Huang, 2006; Kim, 2002). These properties directly affect the amount of deflection in the connecting member, or flange, and the elongation of the connecting bolts. The relationship between the bolt elongation and flange deflection helps describe the mechanical behavior of prying action. This behavior is categorized into three different modes, each of which correlate with potential failure modes of the connection (Figure 2).

Figure 2

Prying Modes



Note: Adapted from "Mechanism And Calculation Theory of Prying Force for Flexible Flange Connection" by F. Huang et al., 2017, *Journal of Construction Steel Research*, *132*(2), p. 98. https://doi.org/10.1016/j.jcsr.2017.01.014.

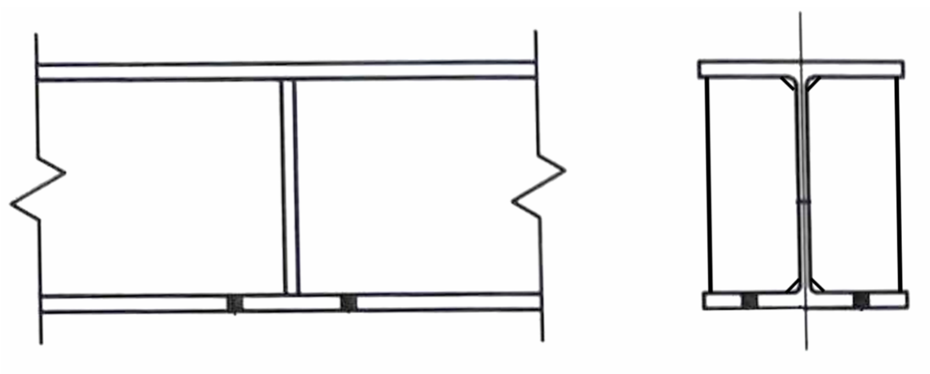
The first failure mode occurs when the flange is sufficiently stiff to resist bending deformation. In this case, no prying force exists, and the strength of the connection is governed by the combined strength of the bolts (Figure 2 – Mode 1). In the second mode, the deformation of the plate is equal to the elongation of the bolt. The deformation of the flange creates a plastic hinge on either side of the flange where the face of the web meets the flange. This deflection is said to be in single curvature between the bolt and web, which creates the prying force at the outer tip of the flange (Figure 2 – Mode 2). The third mode occurs when the flange of the connecting element is relatively thin. In this mode, the deformation of the plate is larger than that of the bolt, which forces the flange to bend in double curvature between the bolt and the web face. The deflection of the flange creates a plastic hinge in the flange at the face of the web and at the bolt line. In this mode, failure of the connection can come from bolt tensile rupture or rupture of the connecting member between its flange and web. The large deflection of the flange due to yielding of the connecting member typically means that bolt failure will govern the strength of this mode (Figure 2 – Mode 3).

Bolted connections that experience prying action can be designed in almost limitless different configurations and geometries due to varying base material thickness, bolt diameters, and bolt layouts. In practice, an efficient approach to designing for prying action requires the use of generalized or simplified methods that idealize the conditions of design. However, this general approach typically leads to conservative design solutions (Dranger, 1977; Thornton, 1985). Some geometries and configurations defy full comprehension through the application of generic and straightforward design equations. In such instances, an independent design approach grounded in engineering principles may be necessary for arriving at a viable design solution.

An example of this geometry is the case of a W-shape girder supporting a W-shape beam with a hanger connection that is reinforced by transverse stiffeners (Figure 3). In this configuration, the stiffeners reinforce the web and transfer a portion of the tension load from the bottom flange to the web. The transverse stiffener reinforces the bottom flange and is centered between the bolts on either side. It can then be inferred that the transverse stiffener behaves similarly to the web of the girder, but in a perpendicular plane (Figure 3 – Side View). If this is the case, and the principles of mechanical behavior for prying action are correct, then it can also be inferred that prying action will occur about the stiffeners in the beam. Altogether, this implication leads to the conclusion that prying action happens about both the web of the girder and the transverse stiffener. This phenomenon will be referred to as two-way prying action.

Figure 3

W-Shape Girder Hanger Connection with Transverse Stiffener



Side View Cross-Section

Note. Adapted from "A Yield Line Component Method for Bolted Flange Connections" by B. Dowswell, 2011, *Engineering Journal, 48*(2), p. 98. https://www.aisc.org/A-Yield-Line-Component-Method-for-Bolted-Flange-Connections

In the case of two-way prying, the prying action about the web and about the stiffener have the potential to interact in the girder flange. This interaction can change the behavior of the connection, particularly the predicted failure mode, if it is not accounted for in design. Research from Agerskov (1977) and Dranger (1977) show that different prying modes exhibit a substantial difference in overall connection strength. Therefore, it is vital that the prying mode that describes a fitting be thoroughly understood to guarantee a strong and safe connection design. Failure to do so can result in a connection that is designed inefficiently, or worse, a connection that fails.

The current design provisions in the AISC *Manual* are applicable only to the standard case of prying action. Consequently, two-way prying action is not considered. This paper addresses the knowledge gap in the AISC manual associated with two-way prying and reports on the results of an investigation in current literature pertaining to two-way prying. Additionally, the paper provides background on the development of the current prying force equations in the AISC manual.

Background

A comprehensive understanding of material science, structural mechanics, structural statics, and the behavior of connected elements is necessary to analyze the effects of prying action. These topics create rise to crucial inquiries that need to be addressed first to develop the current understanding of standard prying action, as well as to provide guidance for understanding the effects of two-way prying action. These questions include the following: How were the current AISC prying action provisions derived? How do these provisions guide design scenarios that experience two-way prying action? Additionally, how does the occurrence of two-way prying action affect the behavior of a bolted connection when subjected to tension force? This paper answers these questions and provides further context regarding the specific scenario of two-way prying action.

Prying Action in Bolted Steel Connections

Prying action has been studied over the past 60 years to understand the effects it has on bolted steel connections. Many experiments have been performed in an effort to enhance and modify the understanding of prying action, such as those conducted by Thornton (1985, 1992), Douty and McGuire (1965), Agerskov (1976, 1977), Wheeler et al. (1998), (Willibald et al., 2002), and Dranger (1977). Through the process of continually refining experimental results, the AISC *Steel Construction Manual* (2017) has curated the current provisions for calculating the effects of prying action. These provisions are laid out in a way which allows easy use of the equations for both design and analysis. Within the provisions, there are multiple different ways prying action may be analyzed. The different forms of analysis correspond to the failure modes previously illustrated in Figure 2. The decision for which method is appropriate is dependent on the stiffness of the connecting member relative to the magnitude of the applied tension load. This relationship will dictate which limit state will be checked for the effects of prying (Estrada & Huang, 2006).

The effects of prying action can be eliminated by using a connecting member that is thick enough to resist deflection under the loading. In this case, the deflection of the member is minimal, so prying action has a negligible effect on the connection and therefore will not impart any prying force on the bolts. This case is illustrated by Mode 1 in Figure 2, where the strength of the bolts governs the strength of the connection. The first equation given by AISC (2017) checks the minimum thickness of the connecting member flange to eliminate prying action, which is calculated as

$$t_{np} = \sqrt{\frac{4T_u b'}{\phi p F_u}}, \tag{1}$$

where t_{np} is the minimum flange thickness, T_u is the required tension force per bolt, and b' is the distance from the edge of the bolt hole to the face of the web (Figure 4) and calculated as

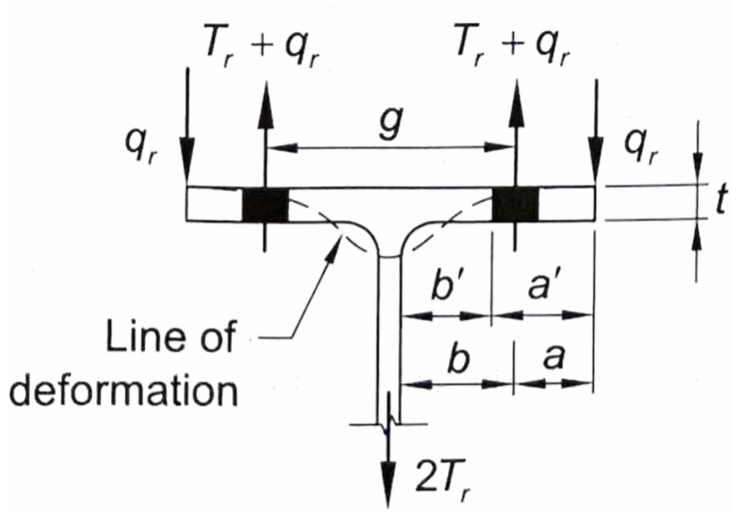
$$b' = b - \frac{d_b}{2}, \tag{2}$$

and d_b is the bolt diameter. The variable ϕ is the LRFD strength reduction factor, F_u is the ultimate tensile strength of the connecting member, and p is the tributary length which can be taken as the lesser of 3.5 times b and the transverse bolt spacing, s, written as

$$p = min\ (3.5b, s). \tag{3}$$

Figure 4

W-Shape Prying Force Diagram



Note. Adapted from *Steel Construction Manual* (Fifteenth ed.), by AISC, 2017, Chicago, IL: American Institute of Steel Construction, p. 9-11.

If the thickness of the connecting material is not greater than t_{np}, the flange is not sufficient to support the load without deflecting and imparting a prying force on the bolts and prying action must be accounted for. In this case, it is possible to find a lesser required thickness for the connecting member by factoring the strength and stiffness of the fitting with the bolt strength simultaneously. This case is illustrated by Mode 2 in Figure 2. The minimum thickness equation to be satisfied for the condition when prying action occurs is given as

$$t_{min} = \sqrt{\frac{4T_u b'}{\phi p F_u (1+\delta\alpha')}}\,, \tag{4}$$

where

$$\delta = 1 - \frac{d'}{p}, \tag{5}$$

$$\alpha' = 1.0 \; if \; \beta \geq 1 = lesser \; of \; 1 \; and \; \frac{1}{\delta}\left(\frac{\beta}{1-\beta}\right) \; if \; \beta \leq 1, \tag{6}$$

$$\beta = \frac{1}{\rho}\left(\frac{B_c}{T_r} - 1\right), \tag{7}$$

and

$$\rho = \frac{b\prime}{a\prime}. \tag{8}$$

In Equation (5), *d'* is the width of the bolt hole along the length of the fitting, and *a'* is taken as

$$a' = \left(a + \frac{d_b}{2}\right) \leq \left(1.25b + \frac{d_b}{2}\right), \tag{9}$$

where *a* and *b* are the distance from the center of the bolt hole to the edge of the flange tip and the face of the web, respectively (Figure 4). In Equation (7), B_c is the available tension strength per bolt, and T_r is the required tension strength per bolt. If the connection is found to have $t \leq t_{min}$ as found in Equation (4), then the connection is not strong enough as a whole to resist the effects of prying action. A fitting with a thicker flange or a change in geometry is required.

AISC also provides a method to determine the prying force per bolt, q_r, which is given as

$$q_r = B_c\left[\delta\alpha\rho\left(\frac{t}{t_c}\right)^2\right], \tag{10}$$

where

$$\alpha = \frac{1}{\delta}\left[\frac{T_r}{B_c}\left(\frac{t_c}{t}\right)^2 - 1\right] \text{ with } 0 \leq \alpha \leq 1.0 \tag{11}$$

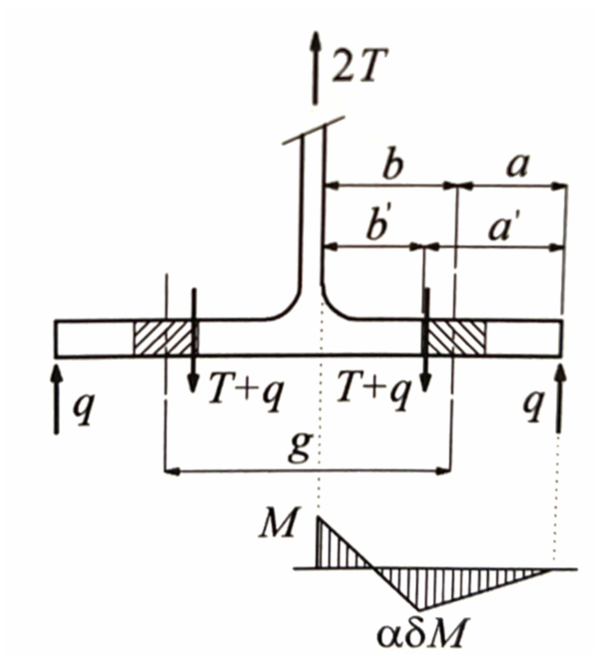
and

$$t_c = \sqrt{\frac{4B_c b\prime}{\phi p F_u}} \tag{12}$$

In Equation 12, t_c is the thickness required to develop the available strength of the bolt with no prying action. The value α is given as a ratio of the moment at the bolt line to the moment at the face of the web. When $\alpha = 0$, there is no prying action considered in the connection design. When $\alpha > 1$, the connection is not adequate to resist prying action. This is illustrated in the moment diagram for half of the flange in Figure 5.

Figure 5

Moment Diagram of Flange Under Prying Forces



Note: Adapted from "A Yield Line Component Method For Bolted Flange Connections" by B. Dowswell, 2011, *Engineering Journal*, *48*(2), p. 94. https://www.aisc.org/A-Yield-Line-Component-Method-for-Bolted-Flange-Connections

If the connection geometry is known, the total available tensile strength per bolt including the effects of prying action can also be determined. This is valuable when the total load that the bolt is experiencing needs to be known, such as in the case of fatigue or serviceability checks (Thornton, 1992). This value is found with the equation

$$T_c = B_c Q, \tag{13}$$

where T_c is the total available tensile strength of the bolt considering prying action, B_c is the available tensile strength of the bolt without considering prying action, and Q is the prying action reduction factor which can be found as

$$1 \text{ if } \alpha' < 0\,, \tag{14}$$

$$\left(\frac{t}{t_c}\right)^2 (1 + \delta\alpha') \text{ if } 0 \leq \alpha' \leq 1\,, \tag{15}$$

$$\left(\frac{t}{t_c}\right)^2 (1 + \delta) \text{ if } \alpha' > 1\,, \tag{16}$$

where α' is given as the best case of α or

$$\frac{1}{\delta(1+\rho)}\left[\left(\frac{t_c}{t}\right)^2 - 1\right]. \tag{17}$$

The value of T_c can be valuable for understanding the effects that prying action has on the total strength of a bolt in a connection. In some cases, prying action can reduce the capacity of the bolts by upwards of 30% of the bolts' typical design strength (Packer et al., 2012).

Two-Way Prying Scenario

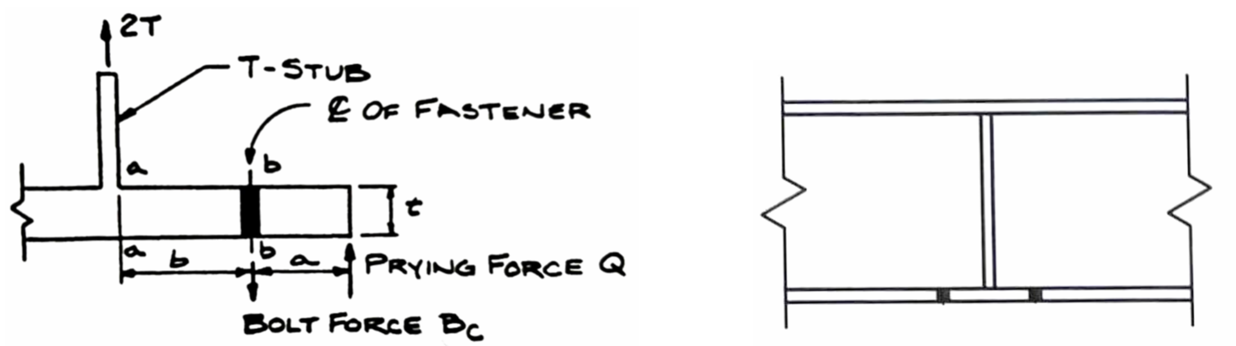
As previously mentioned, prying action is not easily represented by a simple model and design equations. This is due to the fact that connections which experience prying action behave as a semi-rigid assemblage, where the various components, their configurations, and their associated stresses exhibit overall nonlinear behavior (Maggi et al., 2005). For these reasons, there remains consistent research done on prying action, starting with the earliest lab tests of Douty and McGuire (1965) to the modern finite element models being analyzed today by the likes of Fidalgo (2023). These investigations constantly improve the understanding of prying action behavior and the design regulations that are recognized in professional practice. The library of literature and theory regarding prying action does, however, outline the basic principles that are inherent to the propagation of prying action. The primary component that leads to prying action is the separation, or flexural deformation, of the connecting member flange. When this separation occurs at the bolt line, the outer portion of the connecting member develops contact forces that are resolved through the bolt in the form of prying forces (Kulak et al., 2001). When this occurs, prying action must be a design consideration.

Consider the earlier case of a W-shape girder supporting a W-shape beam by means of a bolted hanger connection with the support of transverse stiffeners in the girder. The addition of transverse stiffeners is typically done so to support the bottom flange and web of the girder, typically resulting in an increase in the tensile capacity of the fitting. This support can also help reinforce the bottom flange against the flexural deformation that would normally cause prying action along the cross-section of the member to occur. In this sense, a stiffener helps to increase the tensile capacity of the connection.

However, in performing a thorough engineering analysis of the connection using simple statics properties, it can be noted that the stiffener creates behavior within the connection that must be considered. The role of the stiffener in the connection is a stiffened, vertical member, so its behavior and properties must be analyzed in accordance with this classification. Note that this behavior is similar to the function of the girder web that is encountered when analyzing the cross-section of the girder. Treating the stiffener as though it is the web of a W-shape and applying the equilibrium equations as Thornton (1985, p. 67) does reveals that the same geometric parameters which cause prying action in his model are present in the longitudinal axis of the girder (Figure 6). That is, the tensile force is being resisted by two elements: the stiffened vertical element (the stiffener) and the bolts in the flange. These elements do not act along the same line of action, therefore allowing prying action to commence at a large enough tension force. When compared to similar studies of prying action such as those by Nair (1969), Nair et al. (1974), and DeSimone (2012), it is confirmed that this method of analyzing prying action is valid and accepted.

Figure 6

Thornton's Prying Action Model



Thornton Prying Model

Transverse Prying Case

Note: Adapted from "Prying Action - A General Treatment" by W. Thornton, 1985, *Journal of Structural Engineering*, *22*(2), p. 67, https://www.aisc.org/globalassets/product-files-not-searched/engineering-journal/1985/22_2_067.pdf.

Understanding the behavior of two-way prying action is important in the case of a W-shape beam bolted to the bottom flange of a W-shape girder with transverse stiffeners. The cases in which standard prying action is analyzed are well defined within the AISC *Manual* (2017) for the standard case of prying. However, these methods do not directly translate as means to analyze the case of two-way prying action. The following section outlines the limiting effects of the current AISC provision as it pertains to analyzing two-way prying action.

Limitations of Current AISC Guidelines

Utilizing the current AISC prying action provisions to analyze the two-way prying case provides an inadequate assessment of the potential behavior of the connection based on the background literature cited by AISC in these provisions. The provisions only guide the design of prying action in the standard case, which has been established to be about the web, in the cross-sectional plane of the girder. If a two-way prying action assessment were to be performed using the current provisions, the equations would need to be applied in both the standard case, as well as the case of prying action about the transverse stiffener, or along the longitudinal axis of the girder.

The most important aspect in analyzing any structural connection is whether the connection has enough strength to resist the loads it experiences. In order to interpret the outcomes of any analysis, and determine if this criterion is met, an understanding of the design equation fundamentals is necessary. For the case of two-way prying, Load and Resistance Factored Design (LRFD) will be utilized. The LRFD method is based on a multifactor statistical approach. Both the strength of the member and its loading are factored independently using a simple statistical analysis, and those values are compared to see if the design is viable. A structure is deemed satisfactory if the factored strength is greater than the factored loading effects. However, the statistical nature of this design method implies that it is not an absolute certainty that the structure will not experience loads greater than its capacity, even if it passes the inspection of LRFD design. This caveat leads to generally conservative solutions that do not utilize the absolute maximum capacity of the member (Galambos, 1981). In the case of two-way prying action, the load being analyzed is the tension load at the connection, which is determined from structural analysis. The strengths being checked within the prying action equations are the tensile strength of the bolts and the flexural strength of the girder flange.

The AISC provisions for prying action are formed using equations that utilize a lower bound value for the determination of the connections' ultimate strength. Therefore, the equations predict a stress that is always less than or equal to the actual strength of the connection. This lower bound is used to create a more simplified design process that is not iterative (Swanson, 2002). The lower bound strength assumption paired with the conservative design procedures of AISC ensure that prying action is adequately considered in design (Swanson & Leon, 2001; Thornton, 1992).

The analysis starts with a determination of the tensile force that acts in the bolts on either side of the stiffener and the transverse stiffener. The determination of these loads allows for the creation of a simple statics model, such as the one by Thornton (1985), and determination of values of variables needed for the AISC equations. Equation (1) calculates the minimum required thickness to prevent prying action and allows for an analysis of prying Mode 1. However, an issue arises with the determination of the variable a, the distance from the bolt centerline to the edge of the fitting. This variable cannot be determined by inspection as it would in the standard case of prying because the edge of the fitting along the longitudinal axis is not geometrically defined. This is the first limitation of the AISC prying provisions. The determination of the bolt spacing, p, can be performed using the "edge bolt" case per AISC (2017, p. 9-11).

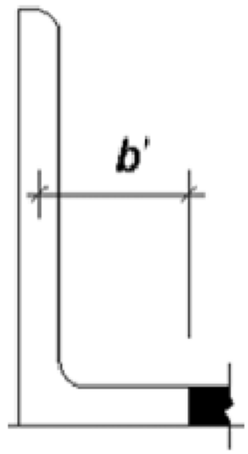
In the case of two-way prying, it is assumed that standard prying action is present. The spacing of the bolts about the web of the girder is typical to the spacing about the transverse girder. Therefore, with the inability to accurately calculate if prying action is present about the transverse stiffener, it is assumed that it does occur due to the geometric and material parameters being similar. Therefore, the prying effects must be accounted for in the longitudinal direction. The calculations shift to assume prying Mode 2 and calls for a check of the minimum thickness considering prying action — Equation (4).

The calculation of Equation (4) requires the determination of the variables α' –Equations (14), (15), and (16)– b'–Equation (2)– δ—Equation (5). The determination of α' relies on the values of a', which is undetermined, so this expression cannot be evaluated as well. Beyond the scope of determining the variables in this idealized model, the behavior of the connection in this mode of prying action is more important to understand and perhaps brings into question the validity of applying these equations to the two-way prying case.

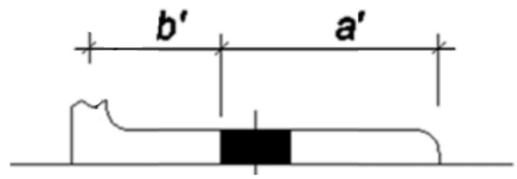
In the standard case, when prying action occurs (Equation (1) not satisfied), the required thickness of the connecting member is reduced to a lesser value. This is due to a change of the limit state parameters that are checked during prying action. In particular, the limit state of plate buckling switches from being analyzed as a moment cantilever element (Mode 1) to a supported cantilever element (Mode 2). This behavior is illustrated in Figure 7. The supported cantilever element exhibits more rigidity than the moment cantilever element, which increases its flexural strength and decreases its required thickness (Lini, 2016). The supported cantilever model also results in a larger bolt force. If an increased bolt force requires a larger bolt diameter, the parameters of b' and a' will change in Equation (4), which constitutes another check of the flange thickness. This iterative process creates a complex design situation that cannot efficiently be done without the use of computer software while also failing to provide a clear definition of the required variables that allow for a simplified approach.

Figure 7

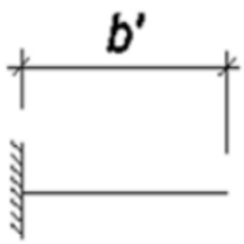
Mode 1 and 2 Prying Models



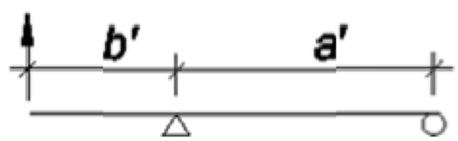
Mode 1 Flange and Web



Mode 2 Flange



Mode 1 Analytical Representation



Mode 2 Analytical Representation

Note: Adapted from "A Quick Look at Prying" by C. Lini, July 2016, *Modern Steel Construction*, pp. 17 and 18.

The parameters in question are most notably the bending stress in the girder flange and the bolt force in the connecting bolts. If the behavior of the standard prying action model can be applied to the two-way prying case, then one may present the following questions: 1.) does two-way prying allow for an even lesser minimum required flange thickness than standard prying action due to the combined strength of the fitting when two-way prying action is present? 2.) how does the addition of a transverse stiffener affect the tension force experienced in the bolts of the connection?

Altogether, the AISC provisions are inadequate in the two-way prying case and do not provide an acceptable design solution. The application of standard prying action principles to the two-way prying case creates further questions regarding how to resolve the forces in the two-way prying case. Although the design of prying action provides a conservative solution, the behavior of two-way prying action cannot be accurately designed using the current AISC provisions and further research is required.

Literature Review

A comprehensive literature review of databases was performed to highlight the knowledge gap in current literature regarding two-way prying. The literature review was conducted using the MSOE Library's online database collection in addition to various websites such as Google Scholar, as well as ASCE and AISC journal archives. The scope of the literature review is limited to peer reviewed scientific and/or academic works of English-language literature. The methods of locating relevant and reputable sources include keyword searches of databases, citation searching within literature sources, and utilization of peer-recommended sources. The keyword search of databases was thoroughly conducted using methodical keywords and phrasing. Some of the key phrases used in the database searching include, but are not limited to, "prying action" and "steel connections", "bolted connections" and "tension" and "prying force", and "yield line" and "tension" and "bolts". Citation searching within sources provided further information related to the search phrases and allowed further repetitive searches to continue. Peer-recommended sources came from a citation search of the AISC *Steel Construction Manual* (2017).

The types of literature reviewed in this critical literature review include scholarly journals, academic textbooks, master's thesis papers published and unpublished, doctoral dissertations published and unpublished, and serial publications and periodicals. Literature was selected solely from academic peer reviewed sources deemed reputable by the author and respective supervisors.

For this investigation, several sources of literature pertaining to prying action and the development of the current AISC equations were studied. Many of these sources have been previously referenced in the introduction and background sections. These sources are expounded on and deliberated further in this section. The emphasis of the study focused primarily on the sources cited by the AISC *Manual* (2017) in the prying action provisions (pp. 9-10, 9-12), which include: “Strength and Serviceability of Hanger Connections” (Thornton, 1992), “Stiffness Modeling of Bolted T-Stub Connection Components” (Swanson & Leon, 2001), “A Yield Line Component Method for Bolted Flange Connections” (Dowswell, 2011), and “Design Model for Bolted Moment End Plate Connections Joining Rectangular Hollow Structural Sections” (Wheeler et al., 1998). These sources inform on prying action behavior as a whole and the types of yielding the connecting member experiences with prying action. The topics of yield line analysis and general prying behavior are discussed further regarding their impact on the two-way prying case.

The results of the critical literature review indicate a knowledge gap in current literature regarding the effects of two-way prying action in bolted steel connections. AISC credits the work done by Thornton (1992) and Swanson and Leon (2001) for contributing to the development of the prying action equations in its prying action provisions of Chapter 9. In his study titled “Strength and Serviceability of Hanger Connections,” Thornton performs an investigation on whether the yield strength or ultimate strength of members in a hanger connection best represent its true behavior. Thornton focuses his efforts on determining the “separation point” of the member when the flange of the connecting member begins to deflect under the tensile loads. At the time of the study, the yield strength of the member was used in practice to calculate the capacity of hanger connections. However, his results indicated that the member's ultimate strength provided very good correlation with his own physical testing results, which he confirms later in a statistical analysis (Thornton, 2017). His findings led to the use of the connecting members' ultimate strength, F_u, in the calculation of prying action.

Thornton states that the effects of prying are to be analyzed at a global level. This aligns with the behavior of prying Mode 2 where the strength of the connection is determinant on a combination of fitting strength, fitting stiffness, and bolt strength (AISC, 2017, p. 9-12). This theory also supports the notion that two-way prying can exist as a global phenomenon in a connection. The behavior of two-way prying happens unequivocally at a global level and is caused by the deflection of the flange in different planes. While this serves as support for the notion of two-way prying, none of Thornton's results confirm the presence of two-way prying or allude to the case involving a transverse stiffener.

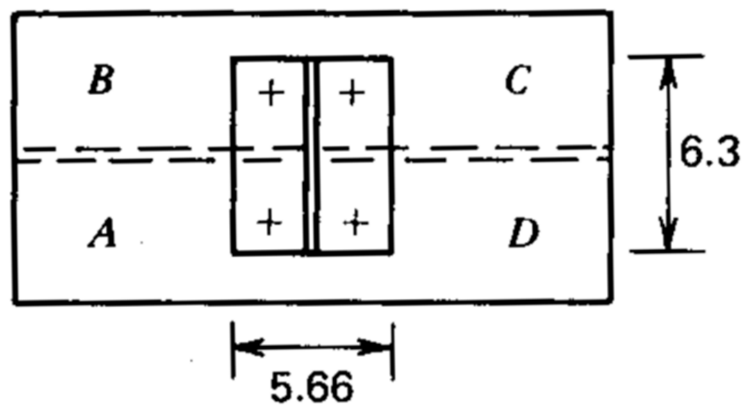
Building on the concept of flange deflection, Swanson and Leon (2001) analyze the rigidity of T-stub moment connections using a monotonic stiffness model. The study first finds the factors that contribute to the behavior of the T-stub overall, such as panel zone deformations, flange bending in the T-stub and connecting member, and shear connection behavior, and combines these mechanisms into force-deformation responses over the entire T-stub component. Through the manipulation of theoretical spring placement and element end fixity types, the experiment yielded results for multiple different T-stub connection models. The model develops a series of theoretical equations used to accurately predict deformations in the T-stub based on the stiffnesses of the respective elements within the connection, the bolts and the connecting members.

This method of analysis provides insight into the derivation of the prying force equations and provides a foundation to potentially analyze two-way prying. The application of the monotonic stiffness model is valuable in analyzing complex connections such as the case of two-way prying, stating that it provides accurate deformation predictions for the T-stub connection and components. The model may not apply well to the case of two-way prying due to the linear nature that the stiffness model behaves in. Similar to AISC provisions, analyzing the components of the two-way prying case as a rigid beam element may not fully capture their true behavior.

Prying action operates on the assumption that the flange experiences yielding. The way in which this yielding occurs is different for each connection based on many variables within the connection geometry. Kulak et al. (2001) investigate the way in which a member subject to prying forces yields based on the rigidity of the connecting members. They hypothesize that the location of the prying force shifts from a yield line defined by standard prying to one that encapsulates the entire fitting surface, stating that systems without adequate connecting material stiffness can experience a change in the location of prying forces from the line AB and CD to the line AC and BD (Figure 8). This hypothesis supports the theory of prying action occurring in a more complex manner than just across the girder cross-section, which is true for the case of two-way prying. The theory by Kulak et al. (2001) fails to recognize the effects that a transverse stiffener may have in the development of prying forces. Kulak et al. (2001) also clarify that this occurrence is not based on testing but theory alone, going on to state that connections of this sort are "highly complex and [have] not been studied extensively" (p. 269).

Figure 8

Proposed Prying Behavior Model



Note: Adapted from *Guide To Design Criteria For Bolted And Riveted Joints* (Second Ed.) by G. Kulak, J. Fisher, and J. Struik, 2001, Chicago, IL: American Institute of Steel Construction, p. 270.

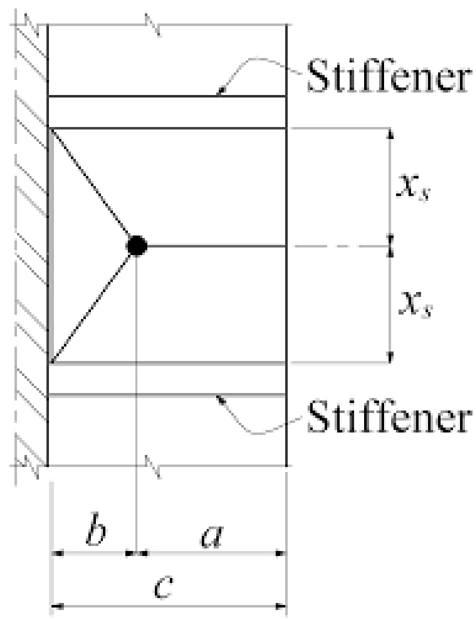
Yield line analysis has been a topic of interest as it relates to prying action. The work of Wheeler et al. (1998, 2000) provided validation to the theoretical yield line analyses performed by Nair et al. (1974), Douty and McGuire (1965), Kato and McGuire (1973). The experimental results, however, did not consider the mode in which prying action occurred, but rather focused on the experimental capacities of the connections in relation to their theoretical capacities. This study doesn't provide any indication of a potential yield line pattern for a two-way prying scenario and therefore does not validate its existence based on a yield line analysis.

Doswell's (2011) yield line analysis focused more on the yield line of bolted components in W-shape beams and fittings. His research focused on connections that have large bolt spacing and edge distances, along with the case of a stiffened W-shape. Doswell (2011) verified his yield line method of predicting connection strength through independent testing and concludes that the bolt forces within a group are distributed through the fitting in accordance with the equivalent length attributed to each individual bolt, requiring that the strength of each bolt be calculated independently. Doswell (2011) presents the case of a stiffened W-shape that is very similar to the established case of two-way prying action with the only difference being that his model has stiffeners on both sides of the bolt.

The results of Doswell's (2011) stiffened case provides guidance on how to calculate the tributary length associated with each bolt that is adjacent to a transverse stiffener in a beam. However, he provides a tributary length used to calculate the effects of standard cross-sectional prying forces. Figure 9 illustrates the test case, which is most similar to the configuration of two-way prying action. This analysis doesn't resolve the issue associated with calculating the outer flange tip length, *a*, that is needed to perform the Mode 2 prying action calculations.
Also, the scope of Doswell's (2011) investigation into the yield line pattern of the stiffened case is limited to the effects of simplified yield line patterns. The two-way prying scenario, or the case of prying action along the longitudinal axis of the component flange, is not considered.

Figure 9

Yield Line Pattern for Stiffened Flange in Bending



Note. Adapted from "A Yield Line Component Method for Bolted Flange Connections," by B. Dowswell, 2011, *Engineering Journal, 48*(2), p. 99. https://www.aisc.org/A-Yield-Line-Component-Method-for-Bolted-Flange-Connections

Methods

The following section of the report outlines the methods employed to create finite element models with the purpose of determining whether two-way prying action occurs. The process of analyzing the models to obtain experimental values for the bending stress in the beam flanges and tensile bolt stress in each scenario is outlined. These experimental values from the finite element analysis (FEA) are validated and compared against expected values which are calculated using equations from the AISC Manual. The comparison of experimental and expected values from each case serve to validate the accuracy of the model as well as answer the question of whether two-way prying action occurs.

Finite Element Analysis Software

The FEA was conducted using SAP2000 *Ultimate*, Version 23.0.0. The model was created using layered shell elements to provide a more accurate description of the stress distribution through the thickness of the shell element. SAP requires the use of *Ultimate* product licensure to run an analysis on a model which contains layered shell elements. The use of SAP *Ultimate* also mitigated limitations on the size and number of nodes that the model was allowed to contain.

Analysis Overview

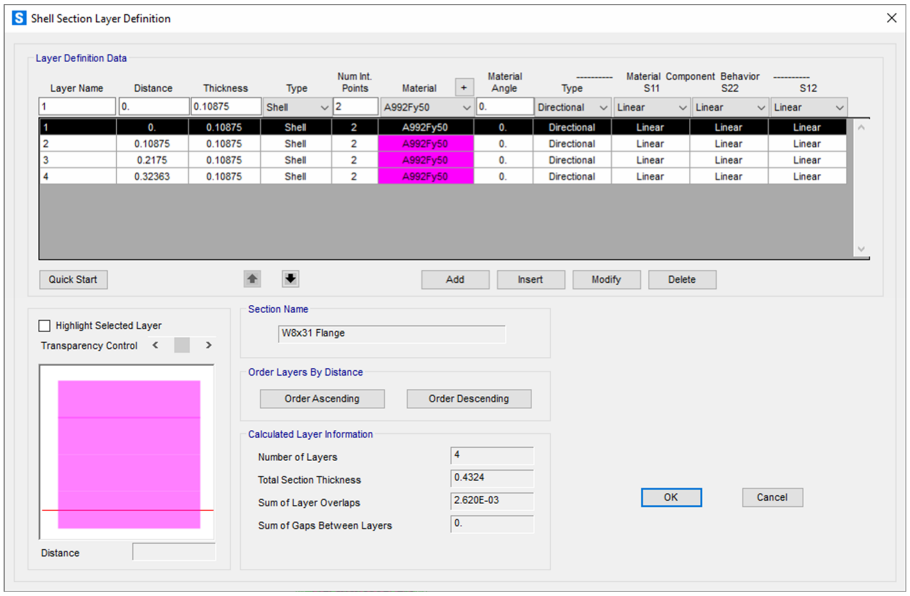
The basis of the FEA model setup was to recreate a connection in which a W8x31 beam is bolted to the top flange of a W12x50 with both members running parallel in length to one another. The connection between the two beams consisted of four 3/4-inch diameter A325 bolts, type N. Both members were assumed to accommodate the bolts with standard, 13/16-inch diameter holes. The bolt hole spacing in each member was taken to be at a 5-1/2 inch gage and 6 inches along the length of both members. The location of the bolt holes was chosen so that the centroid of the bolt hole group coincided with the midspan of each beams' length and width respectively. Both members were taken to have a length of two feet. The design of the finite element model was performed in hopes that physical testing will be conducted at a future time to confirm the results of the finite element analysis. Specifically, the experimental boundaries were created to be compliant with the beam testing capabilities of the large beam testing frame at the Milwaukee School of Engineering.

FEA Shells

The beam models were constructed in SAP by using three separate shell elements: one representing the web, and one representing the top and bottom flanges. This method of modelling neglects the radius of the rolled shape where the flange and web meets, which has the potential to cause very minor inaccuracies in the model when the distribution of stress between the elements is considered. This factor is irrelevant for the purpose of this analysis as the radius dimension of rolled w-shapes is specified as a range of acceptable values as specified by AISC and can generally be neglected for strength purposes (AISC Advisory, 2001). The beam flange dimensions for the W8x31 beam were modeled as specified in the AISC *Manual* (p.1-28) but the W12x50 flange width was reduced slightly to have a width of eight inches, which varies slightly from the AISC *Manual* table value of 8.08 inches (p.1-28). The flanges of the beams were divided into layers based on four equally spaced divisions along the elements' thicknesses (Figures 10 and 11). The layer division calculations can be found in Appendix C. Each layer of the layered shell element for each beam flange was defined as A992 steel with a yield strength of 50 ksi. The shell representing each beam's web was modelled as a thin shell element. The stresses in the web were not the focal point of analysis and modelling these elements with simpler parameters reduced the file size of the model and allowed for quicker analysis runs.

Figure 10

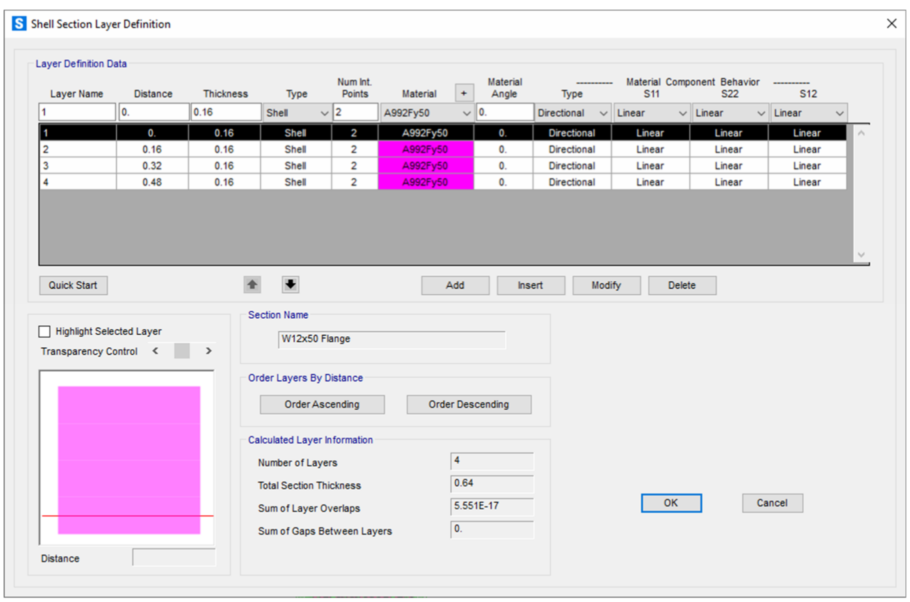
W8x31 Flange Shell Layer Properties



Note. By the author of this report, Excel calculation sheet in Appendix A

Figure 11

W12x50 Flange Shell Layer Properties



Note. By the author of this report, Excel calculation sheet in Appendix A

Shell Element Mesh Layout

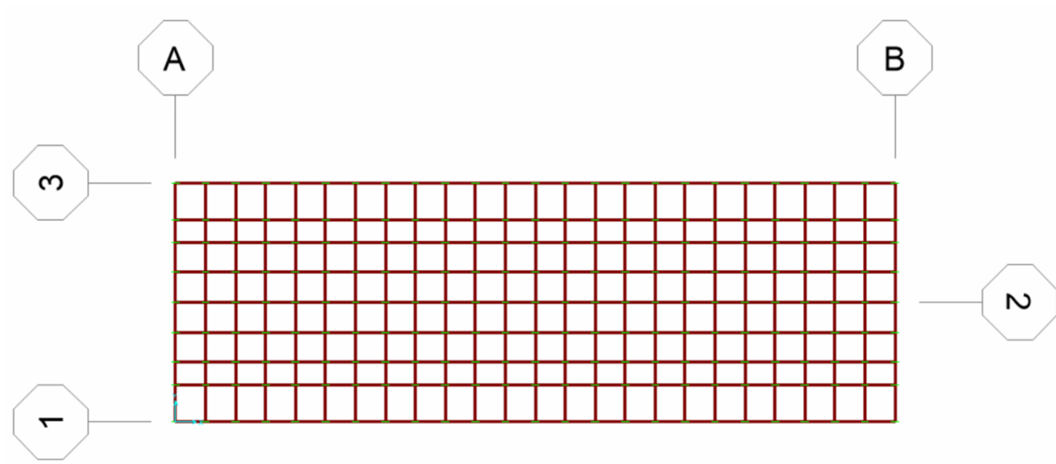
Each shell element needed to be divided into a mesh to allow for the FEA to be performed. It was recommended that an aspect ratio of less than four be achieved when doing so, with the most accurate results obtained at an aspect ratio near unity. Guidance for the dividing of elements was found by referencing a similar FEA conducted by Abidelah et al. (2014) and Wheeler et al. (2000). The main emphasis of the mesh division was to align all edges and corners of mesh elements to eliminate the need to add edge constraints for SAP to interpolate values of element stresses (Computers & Structures, Inc. [CSI] 2017, pp. 180-183). This would ensure more accurate results when analyzing the shell stresses of the model. For this FEA, there were two different meshes used to analyze two-way prying.

The first mesh consisted of flanges that were divided into one-inch by one-inch area and which was called “Version 1 Mesh”. This created a flange shell element that was divided into twenty-four divisions along its length and eight divisions along its width. The bolt hole configuration that was desired did not allow for the bolt location to land on the intersection of the meshes along the width of the flanges, so the mesh subsequently was modified by adjusting the width of the area mesh shell closest to the tip of the flange so that its edge aligned with the desired location of the bolt hole. This adjustment changed the total width of the outermost element from one inch to one and a quarter inch while reducing the width of the adjacent mesh element from one inch to three quarters of an inch. This process allowed the bolts to be modeled at the desired location along this mesh line (Figure 12). The webs of the beams were divided into one-inch segments along the length of the beam. The vertical divisions of the web were determined by finding the equal number of divisions that created mesh elements closest to one inch in height. For the W8x31 beam, this meant eight divisions resulting in members that were

0.963 inches tall. For the W12x50 beam, this meant 12 divisions resulting in members that were 0.946 inches tall. The equal division along the length of the webs and flanges created shared nodes between the webs and flanges to ensure proper model behavior.

Figure 12

Version 1 Mesh Flange Layout

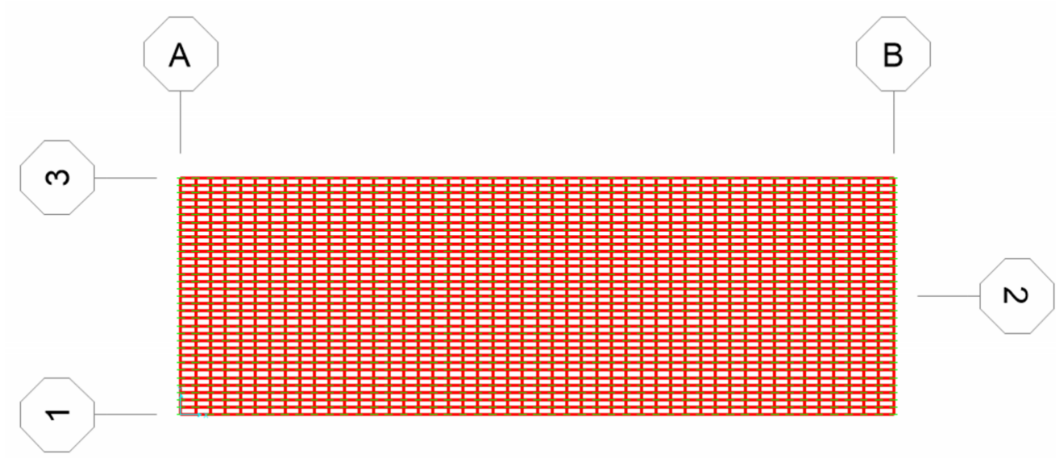


Note. By the author of this report.

The second mesh divided the flanges of the beams into smaller elements and was called "Version 2 Mesh". This mesh created elements that were a quarter inch wide and a half inch long, resulting in 48 divisions along the length of the member and 32 divisions along the width of the beams. This configuration allowed for the mesh lines to fall where the desired bolt locations were to be and therefore did not require any adjustment (Figure 13). The webs of the beams were divided into half-inch segments along the width of the beam to align the web divisions with that of the flanges. The vertical divisions of the web were determined similarly by finding the equal number of divisions that created mesh elements closest to a half-inch in height. For the W12x50 beam, this meant 23 divisions resulting in members that were 0.503 inches tall. For the W8x31 beam, this meant 15 divisions resulting in members that were 0.504 inches tall.

Figure 13

Version 2 Mesh Flange Layout



Note. By the author of this report.

It was also recommended that at the edges of the shell elements that are adjacent to one another, edge constraints should be added to allow for interpolation between shell meshes that do not intersect (CSI, 2017, pp. 180-183).

Link Configuration

The FEA model used links in SAP to represent the connection between the two beam flanges in the setup. Linear links were used between the bottom flange of the W8x31 and the top flange of the W12x50. The links were placed at the desired spacing of 5-1/2-inch gage and 6-inch spacing lengthwise at the center of each beam, which coincided with the center of the bolts. These links were fixed in all directions for translation, but free from rotational fixity. The stiffness of the bolts was initially calculated using mechanical properties of the bolts and the equation for the elongation at an arbitrary load of 10 kips:

$$\Delta = \frac{(Load)(Length)}{(E)(Area\ of\ Bolt)} = \frac{(10\ kips)(1.1 inches)}{(29000\ ksi)(0.442 in^2)} = 0.0021\ in, \qquad (18)$$

$$k = \frac{P}{\Delta} = \frac{10\ kips}{0.0021in} = 11{,}600\ kip/in. \quad (19)$$

The flange nodes that were not connected using the linear links were linked with gap links to model the bearing behavior that occurs between the two beams. These links were fixed only in the vertical direction and were initially given a stiffness roughly equal to double the stiffness of the bolt links, or 22,000 kip/in. This assumption provided more stiffness to the bearing of the members and was done so to more accurately induce prying action in the model.

Loading Cases

The loading on the beam was applied so that the top W8x31 beam received tension force in the form of two point loads. The point loads were each applied at the center of the beam's width and spaced six inches apart along the beam's web, each three inches offset from center of the beam lengthwise. The location of the point loads at this location coincides with the beam test setup available for physical testing in the future. The model was fixed by the nodes in the flange of the bottom W12x50 beam. Like the bolting geometry between the two beams, the W12x50 beam was modeled as being bolted in the same configuration on its bottom flange. This was done by using only translational fixity in all directions at the location of the bolts and restricting only vertical translation at all other nodes along the bottom flange to mimic bearing behavior.

The load increments for the FEA were chosen so that the beam would be analyzed under various loadings both greater than and less than the expected load at which prying would occur. Equation (1) gives the plate thickness at which prying action will occur. This analysis used an adaptation of Equation (1) to eliminate design factors, which is given as,

$$t_{np} = \sqrt{\frac{4T_r b'}{pF_u}}, \quad (20)$$

where T is the required tension force per bolt, F_u is the ultimate tensile strength of the connecting element, b' is the distance from the inner edge of the bolt hole to the face of the connecting member web, and p is the tributary length of the plate. Rearranging this equation using the flange thickness for a W8x31 and solving for the load gives the tensile load per bolt, T_r, at which prying occurs:

$$T_r = \frac{t_f^2 p F_u}{4b'} = 7.58\ kips. \tag{21}$$

Since the value of T_r is for one bolt in the connection, the total applied load should be multiplied by four to account for the geometry of the bolted connection. Therefore, the total applied load that would cause prying action to occur is

$$(7.58\ kips) \times 4 = 30.3\ kips. \tag{22}$$

The loading was determined to be applied in 5-kip increments, starting from 10-kips and maxing out at 50 kips. Each load increment was named after the loading that was applied at each point load location. For instance, the "10-kip" load case describes when two 10-kip loads are applied at the point load locations, equaling a total of 20 kips on the configuration. The loading was applied considering the force that the bolted connection will need to resist, since this coincides with the T_r value calculated above. Therefore, it was expected that the model would experience prying action around the "15 kip" load interval, when there would be approximately 7.5 kips of tension in each bolt.

The load cases were run as nonlinear static load cases. This allowed the analysis to utilize the properties of the layered shell elements and the link elements properly. The nonlinear parameters of each load case were modified so that the Iterance Convergence Tolerance of each load case was changed from the default value of 1.000E^-3 to a value of 1.000E^-6. This was found to produce more accurate analysis results considering the nonlinear nature of the model. Failure states associated with other load cases other than the nonlinear static loading were not examined in this analysis.

Comparison and Analysis

The goal of the FEA was to determine whether the presence of a transverse stiffener induces the phenomenon of two-way prying action. To reach this conclusion, there was a need to compare two different models—one with a stiffener and one without—and compare the values of bolt forces from each. The first model was built as previously described without a stiffener and was referred to as the “unstiffened model”. The unstiffened model was created utilizing both Version 1 and the Version 2 meshes.

The second model was created identically to the unstiffened model but featured the addition of transverse stiffeners. Each beam in the second model contained a transverse stiffener located at its midspan. Each stiffener was modelled to be 3/8-inch thick, grade 50 steel, fully fitted within the flanges of each beam and extending to the flange tips. This setup allowed the full force to be transmitted effectively into the connection and it mirrors the typical configuration of a connection as it would be designed in practice. This model was referred to as the “stiffened model” and was also created utilizing both Version 1 and Version 2 meshes.

The objective outcomes of the finite element analysis were to obtain experimental values for the plate bending stress and bolt tension stress for both the unstiffened and the stiffened case. The values of bolt stress were verified for the unstiffened case by hand calculating the bolt force and prying force at the given load increments using the AISC equations for prying action (see the hand calculations in Appendix A). A comparison of these values helped to validate the accuracy of the finite element model. The results from each analysis were recorded and tracked allowing for structured storage of the data which could easily be sorted, edited, and added to throughout the various cases represented.

When all values of plate bending stress and axial bolt tension stress were recorded for the stiffened and unstiffened case, a statistical analysis was performed. The main objective of the analysis was to compare the results under similar loading between the stiffened and unstiffened case. A percentage difference calculation was used to compare the results of the analysis. The basis of the experiment was to determine the effects that a stiffener has on the prying action forces in a bolted tension connection. Therefore, the results from the unstiffened case were considered to be the baseline for measuring the difference and the results from the stiffened case served as the differing value, giving a percent difference equation of

$$\%\ difference = \frac{(Unstiffened\ resultant)-(Stiffened\ resultant)}{(Case\ 1\ resultant)}, \tag{23}$$

where the resultants are the corresponding plate bending or bolt tension stress for each model. The results of this procedure were intended to show whether or not there is an increase in the amount of stress experienced by the plate and the bolt when a transverse stiffener is present.

Results and Discussion

The method of analysis for the FEA model consists of analyzing each model independently for values of bolt force and shell element stress. These individual analysis results are then compared to each other and to expected values, which are calculated by hand, to determine if there is an increase in prying action in the stiffened case. Both models were analyzed using the Version 1 and Version 2 mesh layouts. The Version 2 mesh was found to yield results of bolt force closer to the expected values than the Version 1 mesh. For this reason, the Version 2 mesh results are the exclusive focus of the results and discussion of this report. The results for the Version 1 mesh can be found in Appendix D.

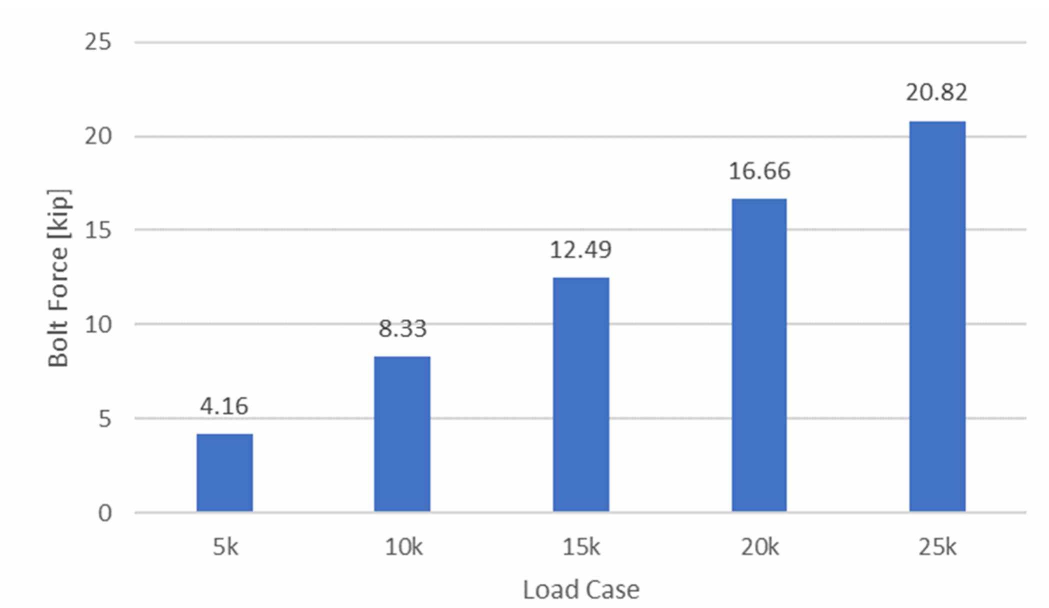
The results of the analysis under the initial presumed link stiffness values did not produce viable results. As a result, the stiffness values of the linear links representing the bolts was approximately doubled to 22,000 kips per inch. The stiffness of the gap links was likewise doubled from its original value to 44,000 kips per inch to maintain the established relationship between the two values.

Unstiffened Model

The results of the unstiffened model show a linear progression in the amount of force experienced per bolt, with bolt force values ranging from 4.16 kips to 20.82 kips (Figure 14).

Figure 14

Unstiffened Model Bolt Forces



The distribution of the stresses in the flanges and web of the beams was done by directly observing the Von Mises stresses (SVM) in the SAP2000 software visual output option. The results of the stress distributions at each load case show the development of stresses in the flanges and the accumulation of stress near the web-flange interface and the location of the linear link, which represents the bolts in the connection (Figures 15, 16, 17, 18, and 19).

Figure 15

Unstiffened Model SVM - 5k Load Case

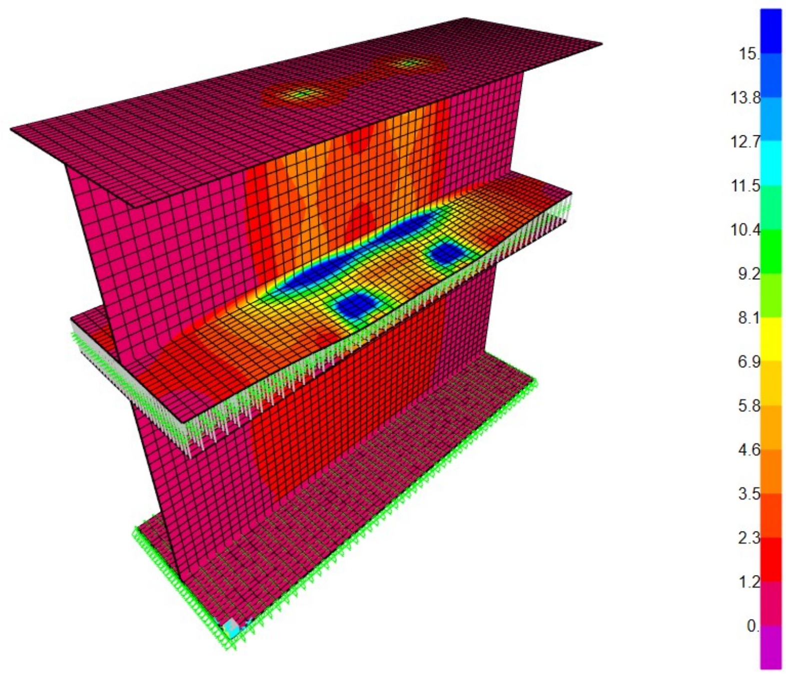


Figure 16

Unstiffened Model SVM - 10k Load Case

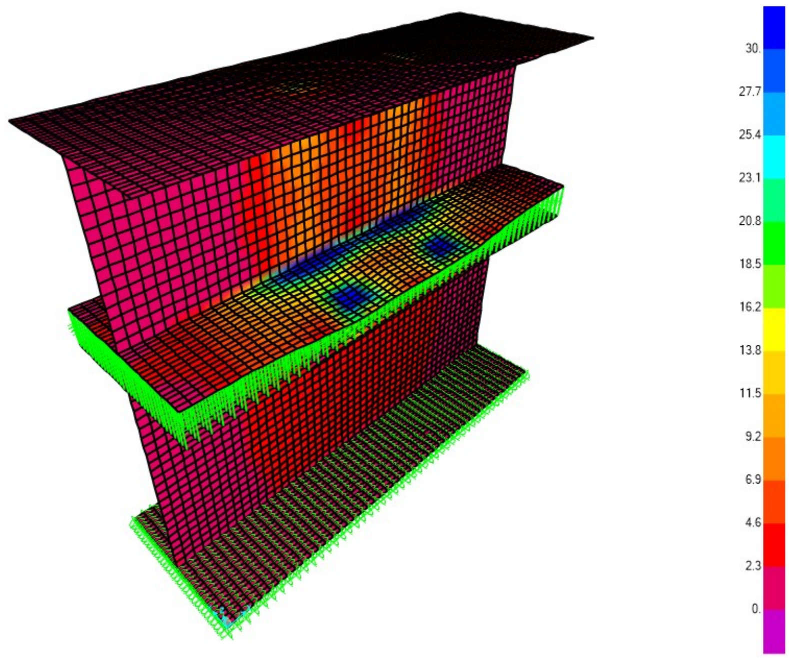


Figure 17

Unstiffened Model SVM - 15k Load Case

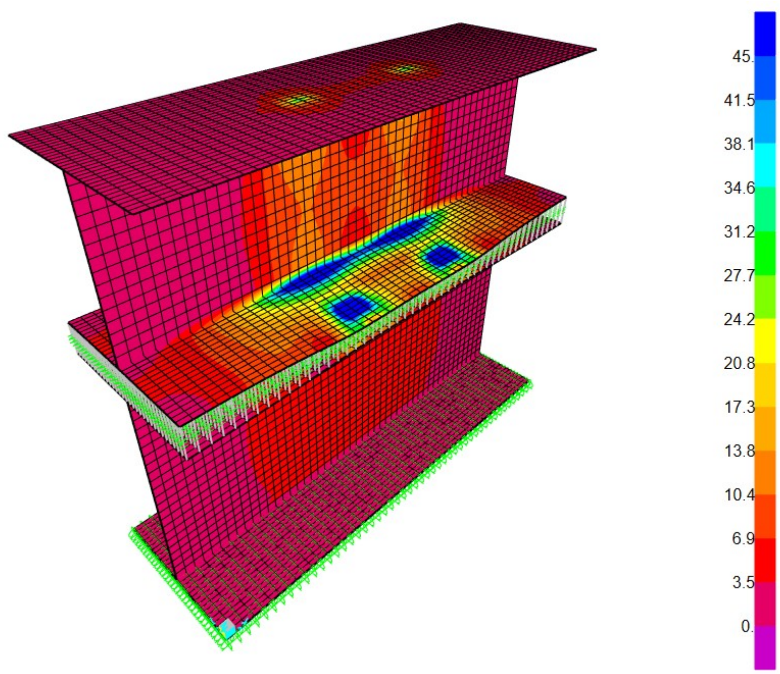


Figure 18

Unstiffened Model SVM - 20k Load Case

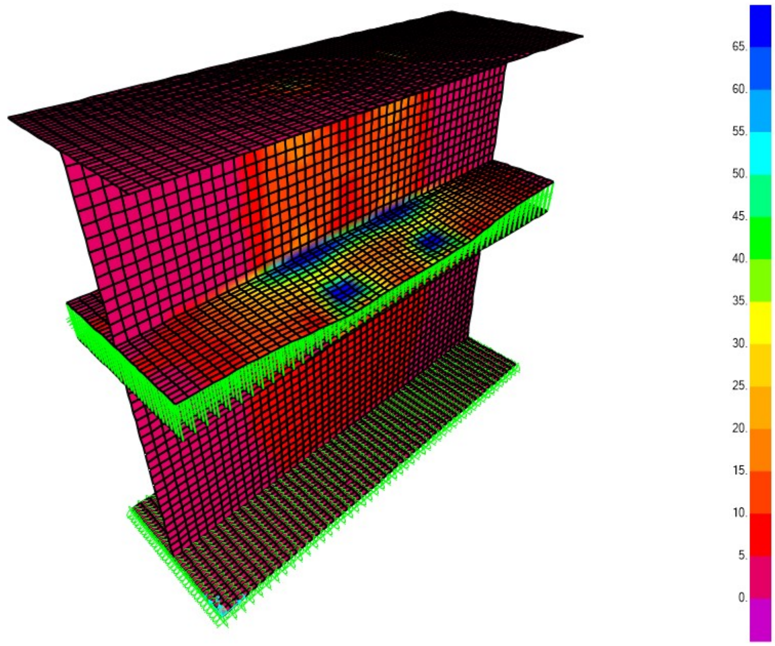
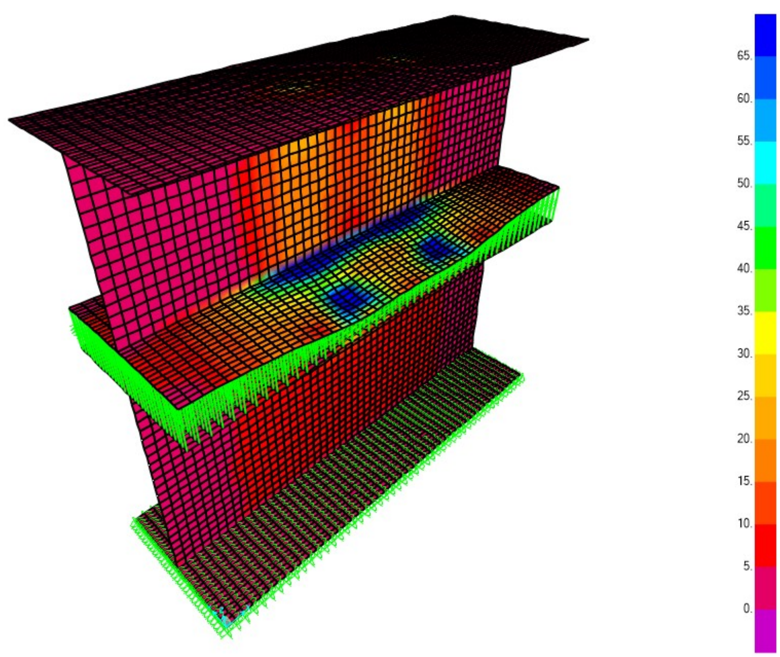


Figure 19

Unstiffened Model SVM - 25k Load Case



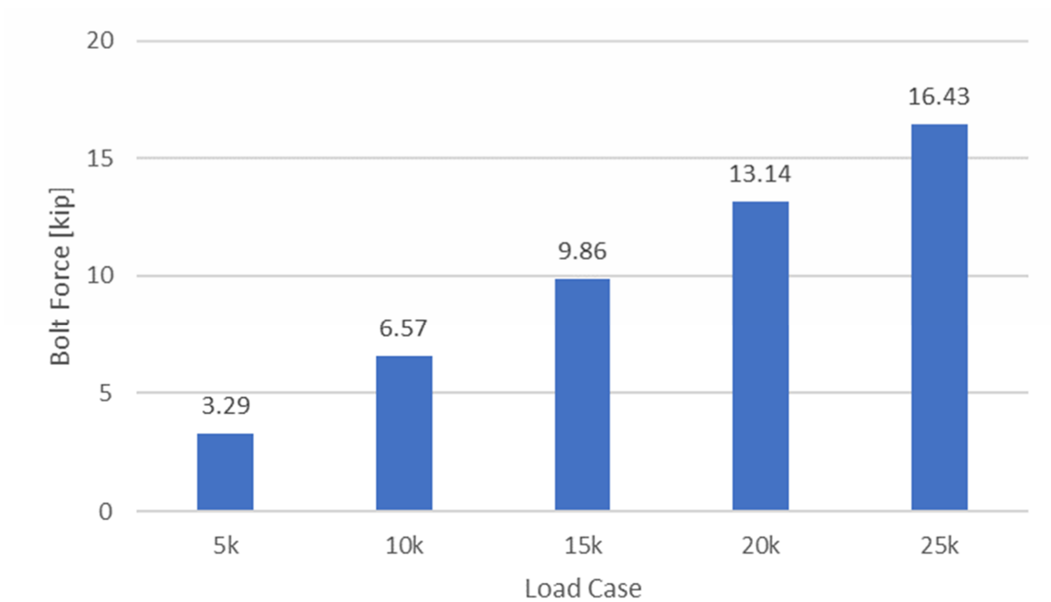
The load analysis indicates that yielding of the beam begins at the 15k load case and the beam exceeds its ultimate stress of 65 ksi at the 20k and 25k load cases. These results generally agree with the previously discussed models of prying and the current literature regarding the failure modes of prying action. The formation of a plastic hinge at the web-flange interface, followed by the locations of high SVM near the bolt holes agrees with prying failure Modes 2 and 3 as discussed in the background of the report.

Stiffened Model

The results of the stiffened model analysis for bolt forces show a linear relationship between the load case and bolt force. Values of bolt force range from 3.29 kips to 16.43 kips (Figure 20).

Figure 20

Stiffened Model Bolt Forces



The distribution of stresses in the flanges was similarly taken by visually observing the SVM visual output option in SAP 2000 (Figures 21, 22, 23, 24, and 25). The Von Mises stress distribution shows similar stress distribution as the unstiffened case at the interface of the beam flange and web. The stiffened beam flanges approach the beam's yield stress as a result of the 15k load case, with the area around the bolt link having the highest concentration of stress (Figure 23). The beam reaches its 65 ksi ultimate stress at the 20k and 25k load cases. The areas of highest stress concentration in these load cases occur at the bolt link, the web and flange interface directly adjacent to the bolt link, and the interface of the stiffener and the beam flange at the tip of the flange (Figures 24 and 25).

Figure 21

Stiffened Model SVM - 5k Load Case

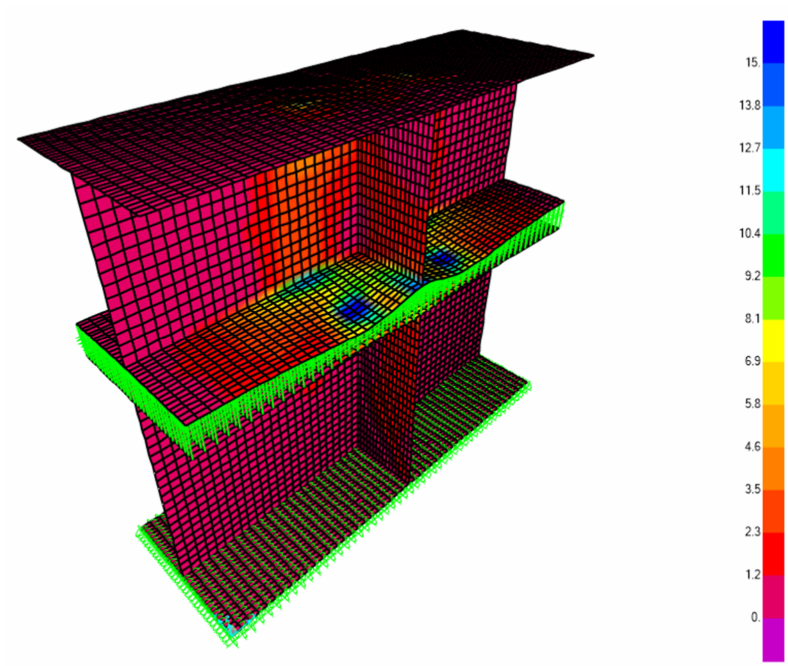


Figure 22

Stiffened Model SVM - 10k Load Case

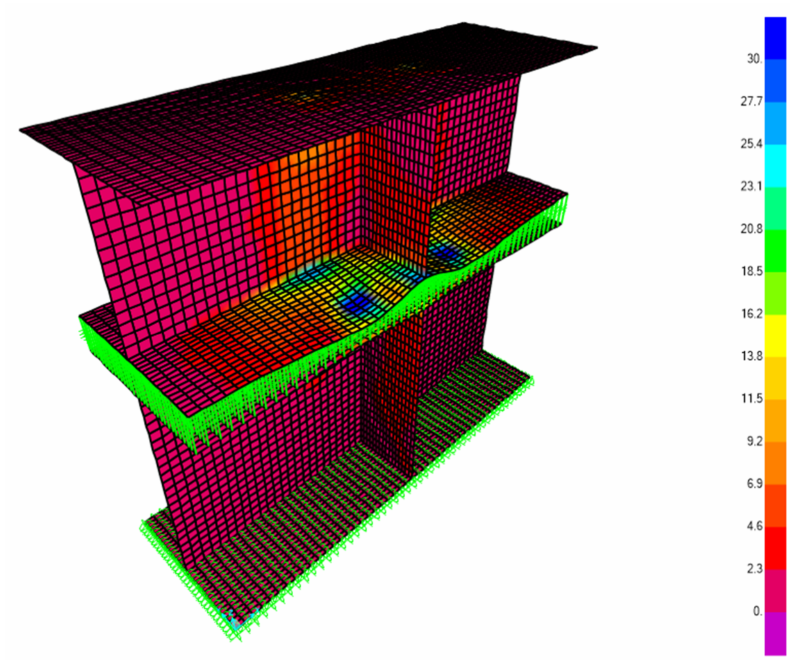


Figure 23

Stiffened Model SVM - 15k Load Case

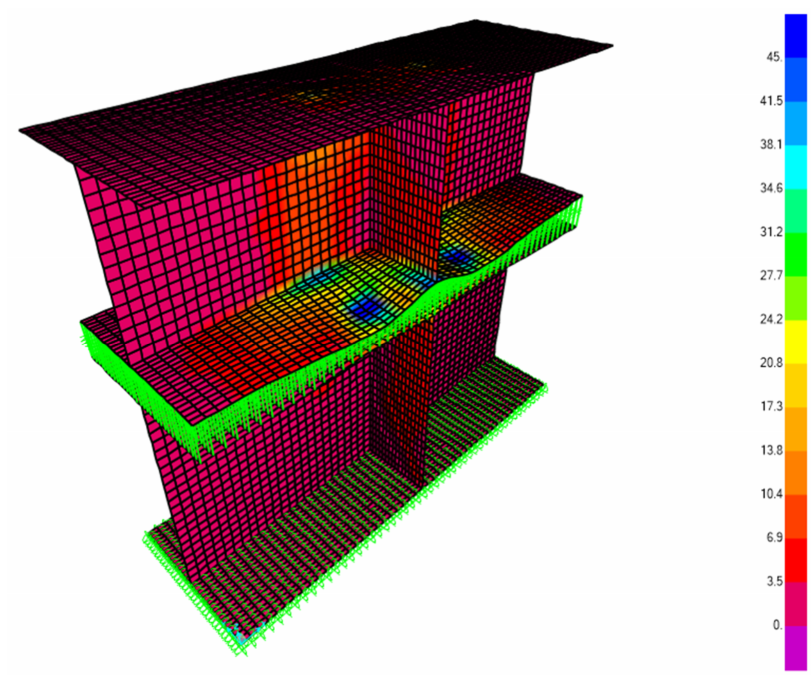


Figure 24

Stiffened Model SVM - 20k Load Case

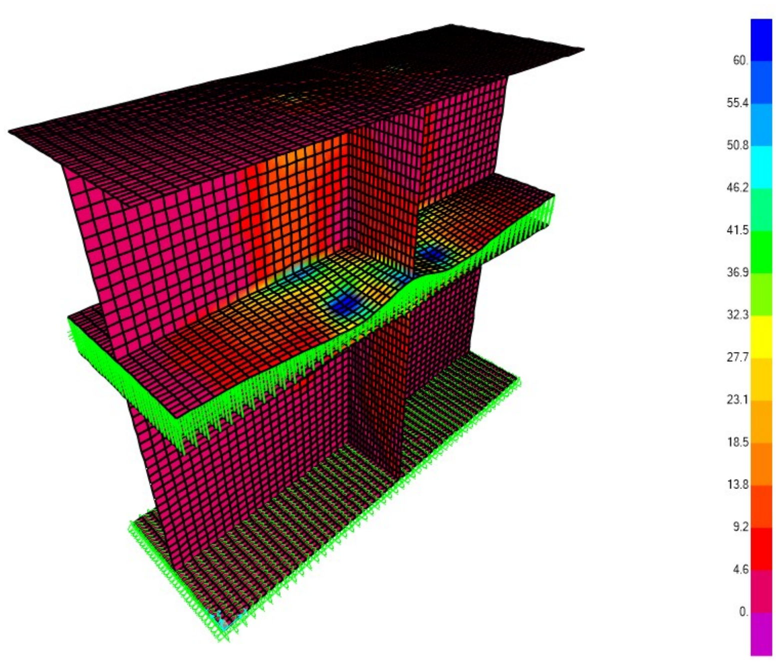
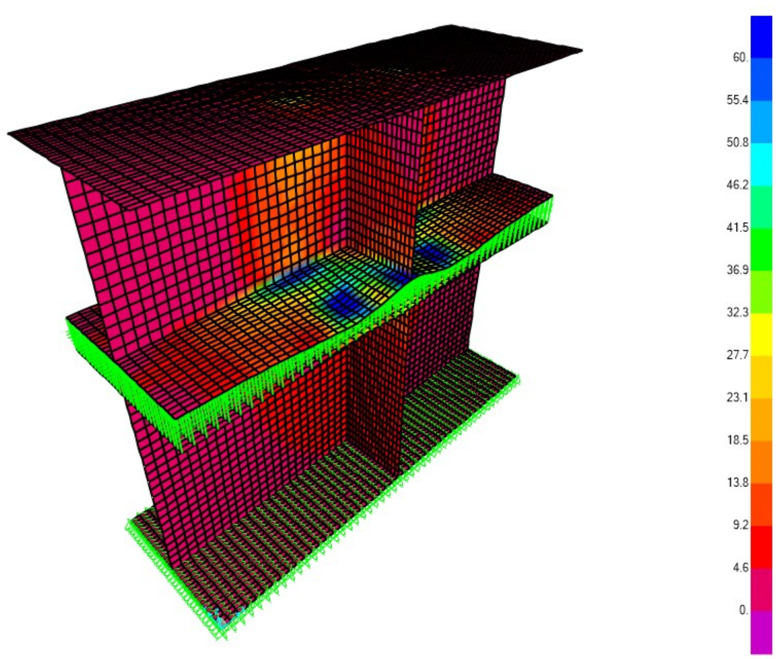


Figure 25

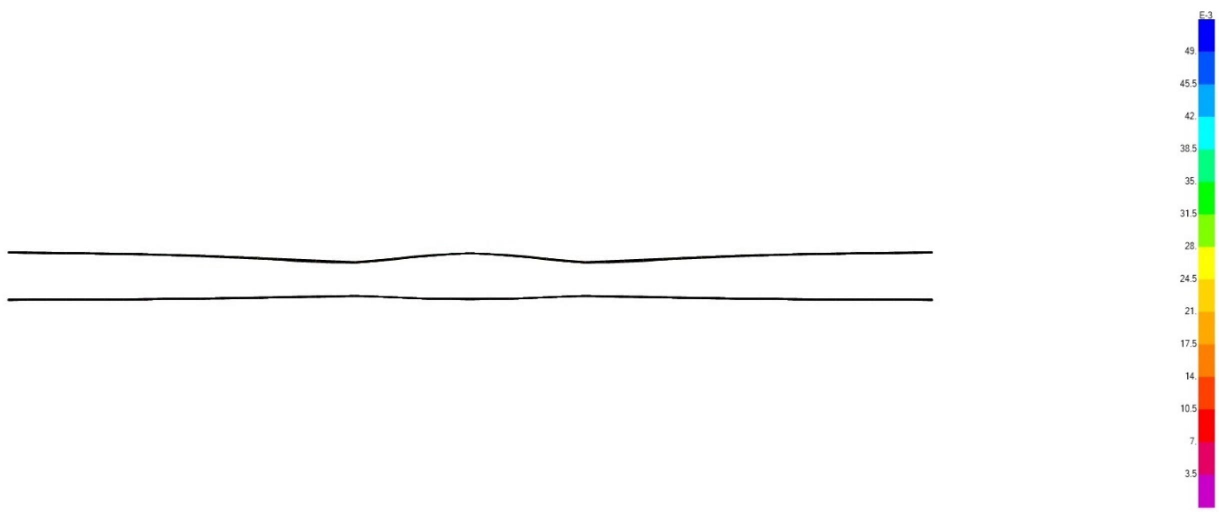
Stiffened Model SVM - 25k Load Case



The initial SVM visual results of the stiffened analysis indicate that prying action could occur in two different planes. The stress distribution about the stiffener appears similar to the stress distribution about the web at the 25k load case. Further investigation was performed on an isolated view of the beam curvature along its length in SAP (Figure 26).

Figure 26

Stiffened Model Beam Flange Deflection - 25k Load Case



The beam appears to behave along its length similarly to that of a beam experiencing typical prying action, especially at the area between the bolts. The bending that occurs at the stiffeners appears similar to the bending that occurs in typical prying action, which leads to the formation of plastic hinge, previously described as prying Mode 2. However, the beam does not appear to behave immediately beyond the bolt locations in a way which would impart a prying force on the bolt. Prying force is created by the additional bearing reaction created at the flange tips, so the lack of bearing beyond the bolt location indicates that there is no initiation of a prying force. This result is further analyzed in the comparison of the stiffened and unstiffened cases.

Comparison of Stiffened and Unstiffened

A comparison between the results of the stiffened and unstiffened models indicates whether or not the presence of a transverse stiffener causes an increase in the amount of force experienced by a bolt in the connection. If the stiffened case is found to produce a higher value for bolt force than the unstiffened case, two-way prying action potentially occurs and must be accounted for in design.

The comparison of bolt forces indicates that the unstiffened model produced higher values of bolt forces at every load case compared to the stiffened model. Table 1 shows the direct comparison of bolt force values with a percent difference calculation comparing the results of each load case.

Table 1

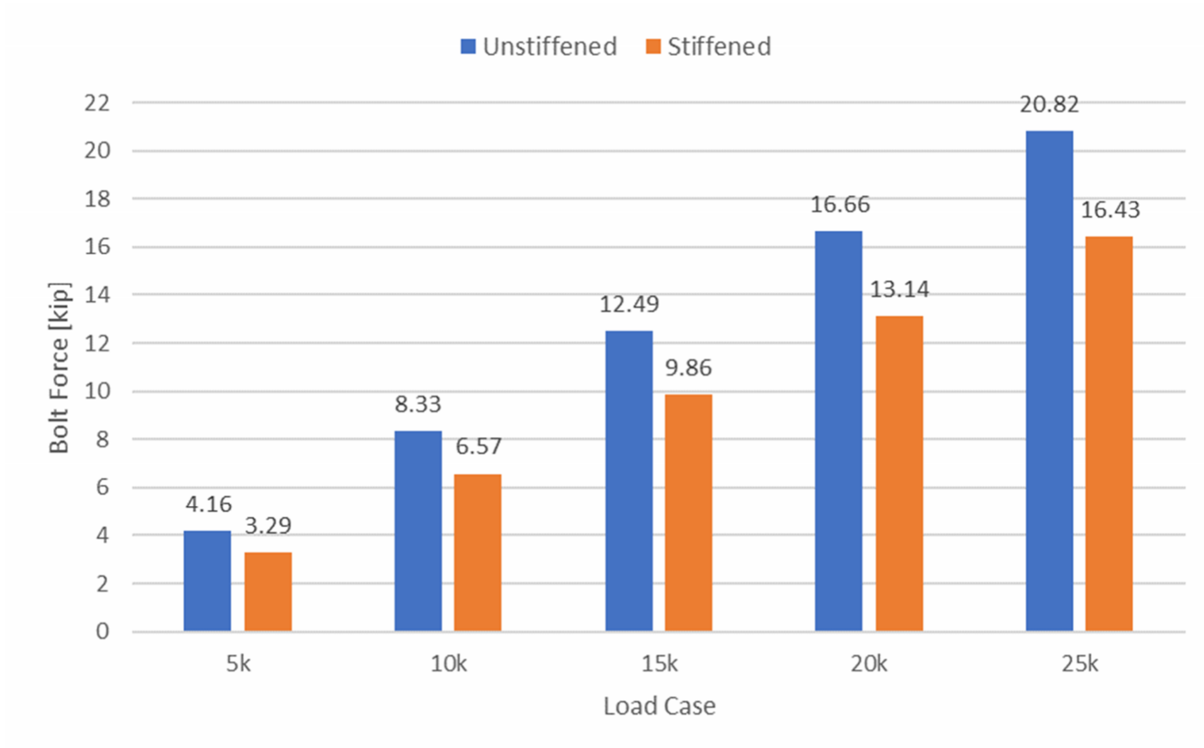
Comparison of Unstiffened and Stiffened Model Bolt Forces

	Unstiffened	**Stiffened**	**Comparison (% Difference)**
0	4.23	3.29	22.4%
5k	8.47	6.57	22.4%
10k	12.70	9.86	22.4%
15k	16.93	13.14	22.4%
20k	21.17	16.43	22.4%

Each load case displayed a linear progression in the values of bolt force as the load case increased. This is apparent in observing the constant percent difference value among all load cases. Figure 27 graphically present these data and illustrate this relationship further.

Figure 27

Comparison of Unstiffened and Stiffened Model Bolt Forces

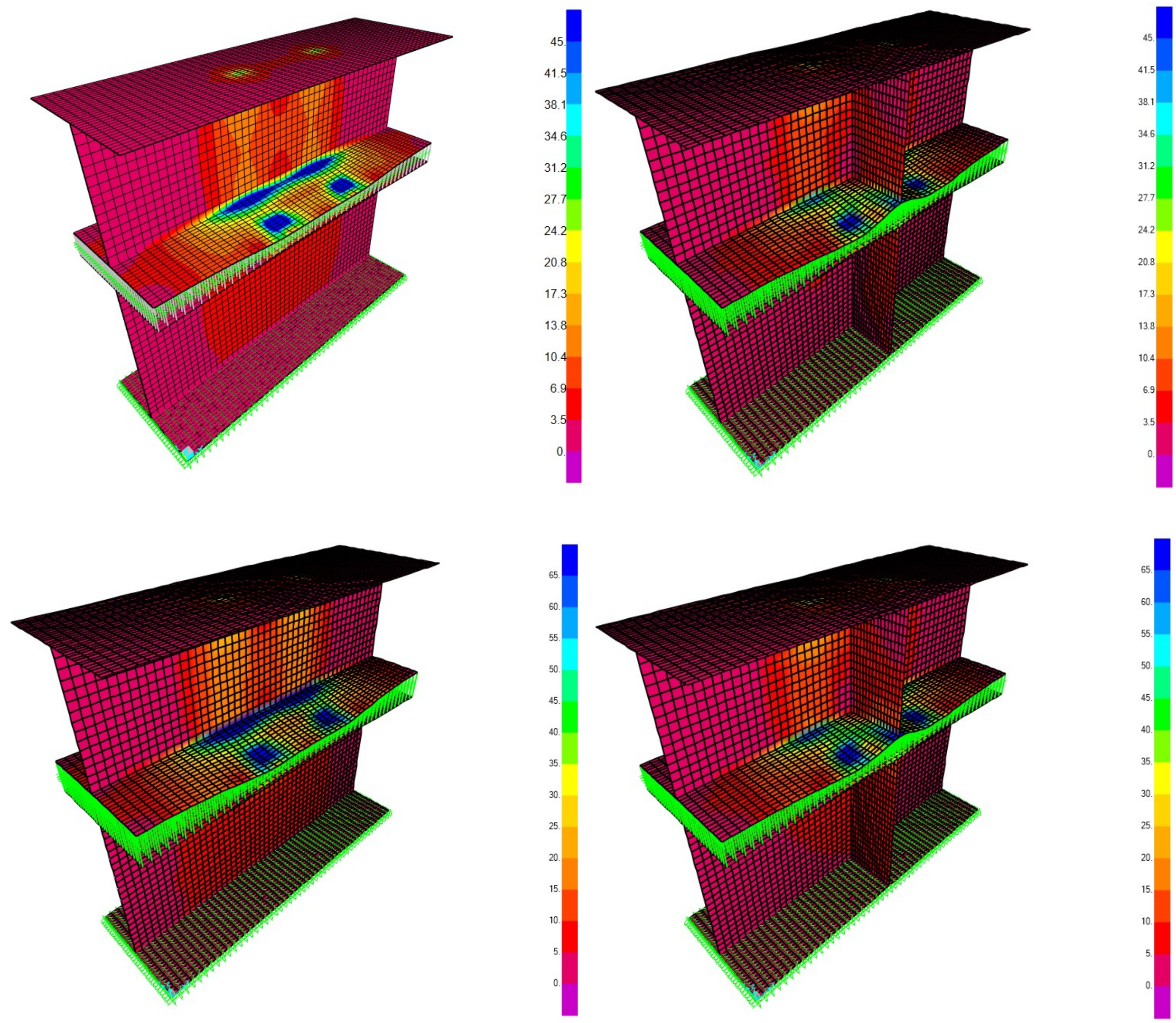


The results of the comparison indicate that the bolts did not experience any greater tension force in the stiffened model. Table 1 and Figure 27 indicate that an opposite effect occurs due to the addition of transverse stiffeners. The bolt force in the stiffened model is approximately 22% less than that of the unstiffened case at the same load case. The results indicate that a two-way prying scenario did not have any effect on the amount of bolt force experienced in a connection with a transverse stiffener.

The results of the analysis also give insight as to the distribution of stress in the flange of the beam. Figure 28 shows a comparison of the Von Mises stress distribution at the 15k and 25k load cases for the stiffened and unstiffened models.

Figure 28

Comparison of Flange Stresses at 15k and 25k Load Cases



The stress distribution in the unstiffened model occurs more prominently around the interface of the web and the flange of the beam, whereas the stiffened model exhibits far less stress at this location but accumlates more stress at the interface of the flange and the stiffener. The stiffener is effective in reducing the amount of stress at the web and flange interface. The stiffener also creates a more even distribution of the overall stress in the flange in comparison to the unstiffened model.

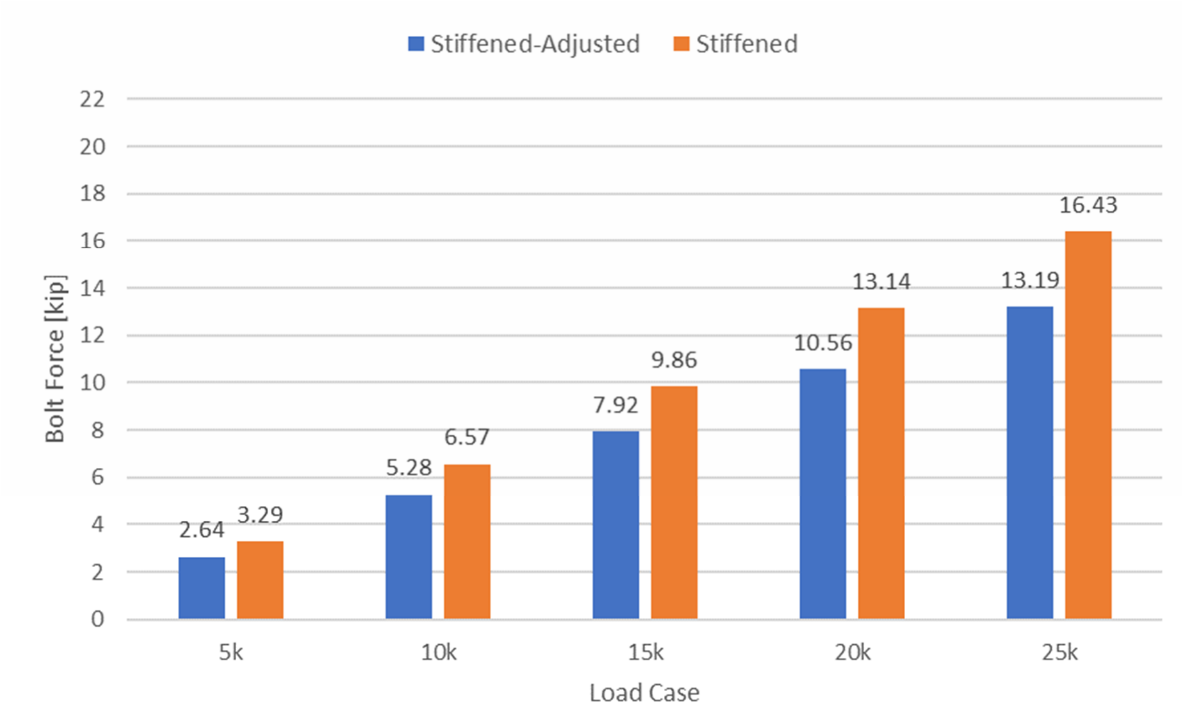
Adjusted Stiffened Case Comparison

Based on the results of the initial unstiffened and stiffened models, there was no increase in bolt force found to occur resulting from the presence of a transverse stiffener. This outcome was considered in conjunction with the deformation of the beam along its length (Figure 26) and the idea was proposed to create a secondary model with an adjusted bolt spacing. This model moved the bolts closer to the stiffener to determine if the distance from the stiffener had any impact on the amount of bolt force in the connection. This model was called the "adjusted stiffened" model. For this procedure, the stiffened model was modified so that the linear links representing the bolts in the connection were moved one inch closer to the stiffener. This resulted in a bolting geometry that remained centered about the beam and the transverse stiffener at a gage of 5-1/2-inches, but now had a spacing along the length of the beam of four inches, two inches in each direction from the center of the stiffener, along the beam's lengths.

The analysis for the adjusted stiffened model followed the same procedure as previously described for the stiffened model. The values of bolt force were obtained and compared to the stiffened model to determine if the bolt distance from the stiffener had any effect on the resulting bolt force (Figure 29).

Figure 29

Comparison of Stiffened and Adjusted Stiffened Model Bolt Forces



The adjusted stiffened model showed no increase in the values of bolt force in comparison to the stiffened model. In fact, the values of bolt force decreased as the bolts were moved closer to the transverse stiffener. This secondary model analysis indicated that moving the bolts closer to the stiffener did not result in a higher bolt force, but rather caused the bolt force to decrease.

Hand Calculation Validation

As is common with all computer models, a validation of the software's output should be validated with hand calculations to verify the accuracy and the viability of the computer model. The hand calculation of the bolt force for the unstiffened model was done using Equation (10). The focus of the calculated value comparison was the 25-kip load case, but the full calculations for all load cases can be found in Appendix A. The values of bolt force for the unstiffened model at the 25k load case were found to have a 13.7% difference from the calculated value (Table 2). The model was not tested for load cases higher than the 25-kip load case and therefore no validation of such load cases is provided.

Table 2

Comparison of Unstiffened Model and Hand Calculated Bolt Forces

Load Case	Unstiffened Model	Hand Calculation	% Difference
25k	20.82	18.32	13.7%

Validation of the stiffened model bolt forces was done by combining a two-way bending analysis and prying action calculation. Each bolt was analyzed for bending about the web and the stiffener in a two-way bending analysis. This procedure provides the values of expected bolt force from bending in each direction. Then a prying action analysis was performed using the values of bolt force from the bending analysis and Equation (10) to determine the expected prying force about the web and stiffener respectively. The bolt force from the bending analysis was combined with the prying force from prying about both the web and stiffener to give the total expected bolt force. The results of the hand calculations indicated that no prying would occur during the tested load cases; therefore, the expected bolt force values would be that of pure tension behavior within the connection. One analysis was performed on the model at a higher load case of 50 kips. At this load case, the hand calculations indicated that prying was expected to occur about the web and the stiffener and therefore the bolt force would be larger than the results of pure tension behavior in the connection. When the SAP model was run at the same 50-kip load case, it produced bolt force values which varied from the expected value in the hand calculation by roughly 9%. However, this percent difference was not similar to the percent difference in the typical load cases. For this reason, the validation of the stiffened model bolt force values must be investigated further. Full hand calculations for the bolt forces in the stiffened model under the typical load cases can be found in Appendix B.

Conclusions and Recommendations

The results of this project, which are based on the comparison of two finite element models, provide sufficient evidence that there is no increase in bolt force due to two-way prying about a transverse stiffener. The amount of tension force experienced by the bolts in the tested configuration was shown to decrease with the addition of a transverse stiffener, which can be employed to validate the finding that two-way prying did not occur. Further, the results indicated that the stiffener was effective in reducing the concentration of the stress in the flange at the location of the flange and web interface and distributed the stress more evenly throughout the beam flange, specifically at the interface of the stiffener and the flange, between the bolt locations.

Limitations

Although this project was supported by sufficient scholarly evidence, there were noteworthy factors which limited the experiment. The first is that the setup of the model's initial conditions was performed with a considerable amount of anticipation towards future physical testing of the model to be performed in the Milwaukee School of Engineering beam testing apparatus. The location of the bottom beam restraints in the model, the location of the applied point loads, and the size of the testing members were all factors that were decided based on the configuration of the beam testing apparatus. This was done so that any physical testing performed in the future would be directly comparable to the results of the FEA.

The FEA model is also limited based on a few considerations. The first limitation is the size of the FEA model mesh. The model was created with only two different mesh variations, whose resultant bolt force varied by 2%. Typical FEA includes the process of reducing the size of the mesh elements incrementally until a converging value is met. It can be assumed that values from an increasingly finer mesh variation would continue to trend in the same direction until ultimately converging upon a value which could be taken as the experimental bolt force value. The FEA also neglects to consider the bolt hole in the flanges of the beams, along with any potential clamping force or moments incurred in the flange at the bolt location due to a nut or fastener restraint. The final limitation of the FEA is the simplified modelling of the stiffener connection to the beam. In a typical fit-up the stiffener attachment to the beam would be specified through weld lengths that typically include a corner clip at the fillet of the beam. This factor was not accounted for in this project due to time constraints.

Improvements and Further Research

It is important to consider areas of improvement in order for this project to obtain the most accurate results relating to two-way prying action. Improvements that could be made to develop better results include refining the FEA mesh until a convergence is verified and modifying the boundary conditions to illustrate different restraint scenarios. It is also recommended that the model's elastic material behavior is verified before future data are collected. Lastly, the modelling of the bolts should be modelled more thoroughly in order to accurately illustrate prying action. This includes physically modelling the bolts in the connection and accounting for the presence of bolts, washers, and any other associated contact elements in order to create a more all-encompassing bolt model that more closely imitates expected bolt behavior.

It is recommended that further research be performed to validate the model and confirm the results of the FEA. Specifically, it is recommended that physical testing be performed on the setup in which the FEA model was created to replicate. The values of bolt force obtained from physical testing should be compared to the results of this analysis. Likewise, it is recommended that a more refined FEA model is created to validate the conclusions of this report and provide a more accurate understanding of two-way prying as it occurs in bolted steel connections.

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Appendix A - Hand Calculations for Unstiffened Model Bolt Force

Prying Action Calculation for W8x31

W8x31: $t_w := 0.285\ in$ $b_f := 8\ in$ $t_f := 0.435\ in$ $G := 5.5\ in$ $F_u := 65\ ksi$

3/4 DIA A325 bolt: $d_b := .75\ in$ $d' := \frac{13}{16}\ in = 0.813\ in$ *(AISC 15th - Table J3.3)*

$B_c := 90\ ksi \cdot \left(\frac{\pi \cdot d_b^2}{4}\right) = 39.76\ kip$ *Tensile Stress Fu in AISC Table J3.2*

CALCS Point Loads, $P := 5\ kip$ $T_r := \frac{2\ P}{4} = 2.5\ kip$ $T_a := T_r = 2.5\ kip$

$s := 6\ in$ $b := \frac{G}{2} - \frac{t_w}{2} = 2.608\ in$ $a := \frac{b_f - G}{2} = 1.25\ in$

$b' := b - \frac{d_b}{2} = 2.233\ in$

$a' := min\left(a + \frac{d_b}{2}, (1.25 \cdot b) + \frac{d_b}{2}\right) = 1.625\ in$

$p := min((3.5 \cdot b), s) = 6\ in$

$\delta := 1 - \frac{d'}{p} = 0.865$ $\rho := \frac{b'}{a'} = 1.374$ $\beta := \frac{1}{\rho} \cdot \left(\frac{B_c}{T_r} - 1\right) = 10.849$

$\alpha' :=$ if $\beta \geq 1$
  1.0
else
  $min\left(1, \frac{1}{\delta} \cdot \left(\frac{\beta}{1 - \beta}\right)\right)$
$= 1$

$3.5\ b = 9.126\ in$

$T_{prying} := \frac{t_f^2 \cdot p \cdot F_u}{4\ b'} = 8.264\ kip$

$2\ T_{prying} = 16.53\ kip$ *Point Load at which prying will occur (Eq. 9-17 solved for T)*

$t_c := \sqrt{\frac{4\ B_c \cdot b'}{p \cdot F_u}} = 0.954\ in$

Eq. (9-26)

if $t_f > t_c$
  "Bolts Developed"
else
  "Bolts Not Developed"
= "Bolts Not Developed"

$t_{np} := \sqrt{\frac{4\ T_a \cdot b'}{p \cdot F_u}} = 0.239\ in$

Eq. (9-17)

if $t_f > t_{np}$
  "No Prying"
else
  "Prying Occurs"
= "No Prying"

$t_{min} := \sqrt{\frac{4\ T_a \cdot b'}{p \cdot F_u \cdot (1 + (\delta \cdot \alpha'))}} = 0.175\ in$

Eq. (9-19)

if $t_f > t_{min}$
  "Combined Strength OK"
else
  "NG"
= "Combined Strength OK"

$$\alpha_{det} := \frac{1}{\delta} \cdot \left(\frac{T_r}{B_c} \cdot \left(\frac{t_c}{t_f} \right)^2 - 1 \right) = -0.807$$

Eq. (9-25)

$$\alpha := \text{if } 0 < \alpha_{det} < 1 \;\; \| \; \alpha_{det} \;\; \text{else if } \alpha_{det} \le 0 \;\; \| \; 0 \;\; \text{else if } \alpha_{det} \ge 1 \;\; \| \; 1 \quad = 0$$

$$q_r := B_c \cdot \left(\delta \cdot \alpha \cdot \rho \cdot \left(\left(\frac{t_f}{t_c} \right)^2 \right) \right) = 0 \; \mathbf{kip}$$

Prying Force in each bolt

$$Bolt\_Force := q_r + T_r = 2.5 \; \mathbf{kip}$$

$$Bolt\_Force = 2.5 \; \mathbf{kip}$$

CALCS Point Loads, $P := 10\ kip$ $T_r := \frac{2P}{4} = 5\ kip$ $T_a := T_r = 5\ kip$

$s := 6\ in$ $b := \frac{G}{2} - \frac{t_w}{2} = 2.608\ in$ $a := \frac{b_f - G}{2} = 1.25\ in$

$b' := b - \frac{d_b}{2} = 2.233\ in$

$a' := min\left(a + \frac{d_b}{2}, (1.25 \cdot b) + \frac{d_b}{2}\right) = 1.625\ in$

$p := min((3.5 \cdot b), s) = 6\ in$

$\delta := 1 - \frac{d'}{p} = 0.865$ $\rho := \frac{b'}{a'} = 1.374$ $\beta := \frac{1}{\rho} \cdot \left(\frac{B_c}{T_r} - 1\right) = 5.06$

$\alpha' :=$ if $\beta \geq 1$
‖ 1.0
else
‖ $min\left(1, \frac{1}{\delta} \cdot \left(\frac{\beta}{1-\beta}\right)\right)$
$= 1$

$3.5\ b = 9.126\ in$

$T_{prying} := \frac{t_f^2 \cdot p \cdot F_u}{4\ b'} = 8.264\ kip$

$2\ T_{prying} = 16.53\ kip$ *Point Load at which prying will occur (Eq. 9-17 solved for T)*

$t_c := \sqrt{\frac{4\ B_c \cdot b'}{p \cdot F_u}} = 0.954\ in$

Eq. (9-26)

if $t_f > t_c$
‖ "Bolts Developed"
else
‖ "Bolts Not Developed"
= "Bolts Not Developed"

$t_{np} := \sqrt{\frac{4\ T_a \cdot b'}{p \cdot F_u}} = 0.338\ in$

Eq. (9-17)

if $t_f > t_{np}$
‖ "No Prying"
else
‖ "Prying Occurs"
= "No Prying"

$t_{min} := \sqrt{\frac{4\ T_a \cdot b'}{p \cdot F_u \cdot (1 + (\delta \cdot \alpha'))}} = 0.248\ in$

Eq. (9-19)

if $t_f > t_{min}$
‖ "Combined Strength OK"
else
‖ "NG"
= "Combined Strength OK"

$\alpha_{det} := \frac{1}{\delta} \cdot \left(\frac{T_r}{B_c} \cdot \left(\frac{t_c}{t_f}\right)^2 - 1\right) = -0.457$

Eq. (9-25)

$\alpha :=$ if $0 < \alpha_{det} < 1$
‖ α_{det}
else if $\alpha_{det} \leq 0$
‖ 0
else if $\alpha_{det} \geq 1$
‖ 1
$= 0$

$q_r := B_c \cdot \left(\delta \cdot \alpha \cdot \rho \cdot \left(\left(\frac{t_f}{t_c}\right)^2\right)\right) = 0\ kip$ *Prying Force in each bolt*

$Bolt\_Force := q_r + T_r = 5\ kip$ $Bolt\_Force = 5\ kip$

CALCS Point Loads, $P := 15\ kip$

$T_r := \frac{2\ P}{4} = 7.5\ kip$ $T_a := T_r = 7.5\ kip$

$s := 6\ in$

$b := \frac{G}{2} - \frac{t_w}{2} = 2.608\ in$ $a := \frac{b_f - G}{2} = 1.25\ in$

$b' := b - \frac{d_b}{2} = 2.233\ in$

$a' := min\left(a + \frac{d_b}{2}, (1.25 \cdot b) + \frac{d_b}{2}\right) = 1.625\ in$

$p := min((3.5 \cdot b), s) = 6\ in$

$\delta := 1 - \frac{d'}{p} = 0.865$ $\rho := \frac{b'}{a'} = 1.374$ $\beta := \frac{1}{\rho} \cdot \left(\frac{B_c}{T_r} - 1\right) = 3.131$

$\alpha' :=$ if $\beta \geq 1$
  1.0
else
  $min\left(1, \frac{1}{\delta} \cdot \left(\frac{\beta}{1-\beta}\right)\right)$
$= 1$

$3.5\ b = 9.126\ in$

$T_{prying} := \frac{t_f^2 \cdot p \cdot F_u}{4\ b'} = 8.264\ kip$

$2\ T_{prying} = 16.53\ kip$ *Point Load at which prying will occur (Eq. 9-17 solved for T)*

$t_c := \sqrt{\frac{4\ B_c \cdot b'}{p \cdot F_u}} = 0.954\ in$

Eq. (9-26)

if $t_f > t_c$
  "Bolts Developed"
else
  "Bolts Not Developed"
= "Bolts Not Developed"

$t_{np} := \sqrt{\frac{4\ T_a \cdot b'}{p \cdot F_u}} = 0.414\ in$

Eq. (9-17)

if $t_f > t_{np}$
  "No Prying"
else
  "Prying Occurs"
= "No Prying"

$t_{min} := \sqrt{\frac{4\ T_a \cdot b'}{p \cdot F_u \cdot (1 + (\delta \cdot \alpha'))}} = 0.303\ in$

Eq. (9-19)

if $t_f > t_{min}$
  "Combined Strength OK"
else
  "NG"
= "Combined Strength OK"

$\alpha_{det} := \frac{1}{\delta} \cdot \left(\frac{T_r}{B_c} \cdot \left(\frac{t_c}{t_f}\right)^2 - 1\right) = -0.107$

Eq. (9-25)

$\alpha :=$ if $0 < \alpha_{det} < 1$
  α_{det}
else if $\alpha_{det} \leq 0$
  0
else if $\alpha_{det} \geq 1$
  1
$= 0$

$q_r := B_c \cdot \left(\delta \cdot \alpha \cdot \rho \cdot \left(\left(\frac{t_f}{t_c}\right)^2\right)\right) = 0\ kip$ *Prying Force in each bolt*

$Bolt\_Force := q_r + T_r = 7.5\ kip$ $Bolt\_Force = 7.5\ kip$

CALCS Point Loads, $P := 20\ kip$ $T_r := \frac{2\ P}{4} = 10\ kip$ $T_a := T_r = 10\ kip$

$s := 6\ in$ $b := \frac{G}{2} - \frac{t_w}{2} = 2.608\ in$ $a := \frac{b_f - G}{2} = 1.25\ in$

$b' := b - \frac{d_b}{2} = 2.233\ in$ $a' := min\left(a + \frac{d_b}{2}, (1.25 \cdot b) + \frac{d_b}{2}\right) = 1.625\ in$

$p := min((3.5 \cdot b), s) = 6\ in$

$\delta := 1 - \frac{d'}{p} = 0.865$ $\rho := \frac{b'}{a'} = 1.374$ $\beta := \frac{1}{\rho} \cdot \left(\frac{B_c}{T_r} - 1\right) = 2.166$

$\alpha' :=$ if $\beta \geq 1$ | 1.0 | else | $min\left(1, \frac{1}{\delta} \cdot \left(\frac{\beta}{1-\beta}\right)\right)$ $= 1$

$3.5\ b = 9.126\ in$

$T_{prying} := \frac{t_f^2 \cdot p \cdot F_u}{4\ b'} = 8.264\ kip$

$2\ T_{prying} = 16.53\ kip$ *Point Load at which prying will occur (Eq. 9-17 solved for T)*

$t_c := \sqrt{\frac{4\ B_c \cdot b'}{p \cdot F_u}} = 0.954\ in$

Eq. (9-26)

if $t_f > t_c$ | "Bolts Developed" | else | "Bolts Not Developed" = "Bolts Not Developed"

$t_{np} := \sqrt{\frac{4\ T_a \cdot b'}{p \cdot F_u}} = 0.479\ in$

Eq. (9-17)

if $t_f > t_{np}$ | "No Prying" | else | "Prying Occurs" = "Prying Occurs"

$t_{min} := \sqrt{\frac{4\ T_a \cdot b'}{p \cdot F_u \cdot (1 + (\delta \cdot \alpha'))}} = 0.35\ in$

Eq. (9-19)

if $t_f > t_{min}$ | "Combined Strength OK" | else | "NG" = "Combined Strength OK"

$\alpha_{det} := \frac{1}{\delta} \cdot \left(\frac{T_r}{B_c} \cdot \left(\frac{t_c}{t_f}\right)^2 - 1\right) = 0.243$

Eq. (9-25)

$\alpha :=$ if $0 < \alpha_{det} < 1$ | α_{det} | else if $\alpha_{det} \leq 0$ | 0 | else if $\alpha_{det} \geq 1$ | 1 $= 0.243$

$q_r := B_c \cdot \left(\delta \cdot \alpha \cdot \rho \cdot \left(\left(\frac{t_f}{t_c}\right)^2\right)\right) = 2.385\ kip$ *Prying Force in each bolt*

$Bolt\_Force := q_r + T_r = 12.385\ kip$ $Bolt\_Force = 12.38\ kip$

CALCS Point Loads, $P := 25\ kip$

$T_r := \frac{2\ P}{4} = 12.5\ kip$ $\quad T_a := T_r = 12.5\ kip$

$s := 6\ in$ $\quad b := \frac{G}{2} - \frac{t_w}{2} = 2.608\ in$ $\quad a := \frac{b_f - G}{2} = 1.25\ in$

$b' := b - \frac{d_b}{2} = 2.233\ in$ $\quad a' := min\left(a + \frac{d_b}{2}, (1.25 \cdot b) + \frac{d_b}{2}\right) = 1.625\ in$

$p := min((3.5 \cdot b), s) = 6\ in$

$\delta := 1 - \frac{d'}{p} = 0.865$ $\quad \rho := \frac{b'}{a'} = 1.374$ $\quad \beta := \frac{1}{\rho} \cdot \left(\frac{B_c}{T_r} - 1\right) = 1.587$

$\alpha' :=$ if $\beta \ge 1$ then 1.0, else $min\left(1, \frac{1}{\delta} \cdot \left(\frac{\beta}{1-\beta}\right)\right)$ $= 1$

$3.5\ b = 9.126\ in$

$T_{prying} := \frac{t_f^2 \cdot p \cdot F_u}{4\ b'} = 8.264\ kip$

$2\ T_{prying} = 16.53\ kip$ *Point Load at which prying will occur (Eq. 9-17 solved for T)*

$t_c := \sqrt{\frac{4\ B_c \cdot b'}{p \cdot F_u}} = 0.954\ in$

Eq. (9-26)

if $t_f > t_c$ "Bolts Developed" else "Bolts Not Developed" = "Bolts Not Developed"

$t_{np} := \sqrt{\frac{4\ T_a \cdot b'}{p \cdot F_u}} = 0.535\ in$

Eq. (9-17)

if $t_f > t_{np}$ "No Prying" else "Prying Occurs" = "Prying Occurs"

$t_{min} := \sqrt{\frac{4\ T_a \cdot b'}{p \cdot F_u \cdot (1 + (\delta \cdot \alpha'))}} = 0.392\ in$

Eq. (9-19)

if $t_f > t_{min}$ "Combined Strength OK" else "NG" = "Combined Strength OK

$\alpha_{det} := \frac{1}{\delta} \cdot \left(\frac{T_r}{B_c} \cdot \left(\frac{t_c}{t_f}\right)^2 - 1\right) = 0.593$

Eq. (9-25)

$\alpha :=$ if $0 < \alpha_{det} < 1$ then α_{det}, else if $\alpha_{det} \le 0$ then 0, else if $\alpha_{det} \ge 1$ then 1 $= 0.593$

$q_r := B_c \cdot \left(\delta \cdot \alpha \cdot \rho \cdot \left(\left(\frac{t_f}{t_c}\right)^2\right)\right) = 5.82\ kip$ *Prying Force in each bolt*

$Bolt\_Force := q_r + T_r = 18.32\ kip$ $\quad Bolt\_Force = 18.32\ kip$

Appendix B – Hand Calculations for Stiffened Model Bolt Forces

Two-Way Bending Calculation for W8x31

W8x31: $t_w := 0.285\ in$ $b_f := 8\ in$ $t_f := 0.435\ in$ $G := 5.5\ in$ $F_u := 65\ ksi$

3/4 DIA A325 bolt: $d_b := .75\ in$ $d' := \frac{13}{16}\ in = 0.81\ in$ *(AISC 15th - Table J3.3)*

$B_c := 90\ ksi \cdot \left(\frac{\pi \cdot d_b^2}{4}\right) = 39.76\ kip$ *Tensile Stress Fu in AISC Table J3.2*

Stiffener: $t_s := \frac{3}{8}\ in$ $s := 6\ in$

CALCS Point Loads, $P := 5\ kip$ $T_r := \frac{2\ P}{4} = 2.5\ kip$ *(Pure tension load per bolt)*

$e_w := \frac{G - t_w}{2} = 2.61\ in$ $b_{eff\_w} := 2 \cdot e_w = 5.22\ in$

$e_s := \frac{s - t_s}{2} = 2.81\ in$ $b_{eff\_s} := min\left(\left(\frac{b_f - t_w}{2}\right), (2 \cdot e_s)\right) = 3.86\ in$ *(Limited by bolt hole edge distance)*

$z := \left(\frac{e_w^3}{b_{eff\_w}}\right) \cdot \frac{b_{eff\_s}}{e_s^3} = 0.58945$ $M := \begin{bmatrix} z & -1 \\ 1 & 1 \end{bmatrix}$ $v := \begin{bmatrix} 0 \\ T_r \end{bmatrix}$ $S := \text{lsolve}(M, v) = \begin{bmatrix} 1.573 \\ 0.927 \end{bmatrix}\ kip$

(Top Value: Bending about web Bottom Value: Bending about stiffener)

$P_w := S_0 = 1.573\ kip$ $P_s := S_1 = 0.927\ kip$ $P_T := P_w + P_s = 2.5\ kip$

Prying About Web

$b := \frac{G}{2} - \frac{t_w}{2} = 2.61\ in$ $b' := b - \frac{d_b}{2} = 2.23\ in$

$a := \frac{b_f - G}{2} = 1.25\ in$ $a' := min\left(a + \frac{d_b}{2}, (1.25 \cdot b) + \frac{d_b}{2}\right) = 1.63\ in$

$p := min((3.5 \cdot b), s) = 6.00\ in$

$\delta := 1 - \frac{d'}{p} = 0.86$ $\rho := \frac{b'}{a'} = 1.37$ $\beta := \frac{1}{\rho} \cdot \left(\frac{B_c}{P_w} - 1\right) = 17.67$

$t_c := \sqrt{\frac{4\ B_c \cdot b'}{p \cdot F_u}} = 0.95\ in$

Eq. (9-26)

try
  if $t_f > t_c$
    "Bolts Developed"
  else
    "Bolts Not Developed"
on error

= "Bolts Not Developed"

$\alpha_{det} := \frac{1}{\delta} \cdot \left(\frac{P_w}{B_c} \cdot \left(\frac{t_c}{t_f}\right)^2 - 1\right) = -0.94$

Eq. (9-25)

$\alpha :=$ if $0 < \alpha_{det} < 1$
  α_{det}
else if $\alpha_{det} \le 0$
  0
else if $\alpha_{det} \ge 1$
  1

$= 0.00$

$q_{r\_web} := B_c \cdot \left(\delta \cdot \alpha \cdot \rho \cdot \left(\left(\frac{t_f}{t_c}\right)^2\right)\right) = 0.00\ kip$ *Prying Force about web in each bolt*

$\text{clear}(b, a, b', a', p, \delta, \rho, \beta, t_c, \alpha_{det}, \alpha, q_r, Bolt\_Force)$

Prying About Stiffener

$b := \frac{s}{2} - \frac{t_s}{2} = 2.81\ in$

$b' := b - \frac{d_b}{2} = 2.44\ in$

$p := min((3.5 \cdot b), s) = 6.00\ in$

$a' := (1.25\ b) + \frac{d_b}{2} = 3.89\ in$

$\delta := 1 - \frac{d'}{p} = 0.86$

$\rho := \frac{b'}{a'} = 0.63$

$\beta := \frac{1}{\rho} \cdot \left(\frac{B_c}{P_s} - 1\right) = 66.86$

$t_c := \sqrt{\frac{4\ B_c \cdot b'}{p \cdot F_u}} = 1.00\ in$

Eq. (9-26)

if $t_f > t_c$
  "Bolts Developed"
else
  "Bolts Not Developed"
= "Bolts Not Developed"

$\alpha_{det} := \frac{1}{\delta} \cdot \left(\frac{P_s}{B_c} \cdot \left(\frac{t_c}{t_f}\right)^2 - 1\right) = -1.01$

Eq. (9-25)

$\alpha :=$ if $0 < \alpha_{det} < 1$
  α_{det}
else if $\alpha_{det} \le 0$
  0
else if $\alpha_{det} \ge 1$
  1
$= 0.00$

$q_{r\_stiffener} := B_c \cdot \left(\delta \cdot \alpha \cdot \rho \cdot \left(\left(\frac{t_f}{t_c}\right)^2\right)\right) = 0.00\ kip$

Prying Force about stiffener in each bolt

$Total\_Bolt\_Force := q_{r\_web} + q_{r\_stiffener} + T_r = 2.50\ kip$

$Total\_Bolt\_Force = 2.5\ kip$

Two-Way Bending Calculation for W8x31

W8x31: $t_w := 0.285\ in$ $b_f := 8\ in$ $t_f := 0.435\ in$ $G := 5.5\ in$ $F_u := 65\ ksi$

3/4 DIA A325 bolt: $d_b := .75\ in$ $d' := \frac{13}{16}\ in = 0.81\ in$ *(AISC 15th - Table J3.3)*

$B_c := 90\ ksi \cdot \left(\frac{\pi \cdot d_b^2}{4}\right) = 39.76\ kip$ *Tensile Stress Fu in AISC Table J3.2*

Stiffener: $t_s := \frac{3}{8}\ in$ $s := 6\ in$

CALCS Point Loads, $P := 10\ kip$ $T_r := \frac{2\ P}{4} = 5.0\ kip$ *(Pure tension load per bolt)*

$e_w := \frac{G - t_w}{2} = 2.61\ in$ $b_{eff\_w} := 2 \cdot e_w = 5.22\ in$

$e_s := \frac{s - t_s}{2} = 2.81\ in$ $b_{eff\_s} := min\left(\left(\frac{b_f - t_w}{2}\right), (2 \cdot e_s)\right) = 3.86\ in$ *(Limited by bolt hole edge distance)*

$z := \left(\frac{e_w^3}{b_{eff\_w}}\right) \cdot \frac{b_{eff\_s}}{e_s^3} = 0.58945$ $M := \begin{bmatrix} z & -1 \\ 1 & 1 \end{bmatrix}$ $v := \begin{bmatrix} 0 \\ T_r \end{bmatrix}$ $S := \text{lsolve}(M, v) = \begin{bmatrix} 3.146 \\ 1.854 \end{bmatrix} kip$

$P_w := S_0 = 3.146\ kip$ $P_s := S_1 = 1.854\ kip$ *(Top Value: Bending about web Bottom Value: Bending about stiffener)*

$P_T := P_w + P_s = 5.0\ kip$

Prying About Web

$b := \frac{G}{2} - \frac{t_w}{2} = 2.61\ in$ $b' := b - \frac{d_b}{2} = 2.23\ in$

$a := \frac{b_f - G}{2} = 1.25\ in$

$a' := min\left(a + \frac{d_b}{2}, (1.25 \cdot b) + \frac{d_b}{2}\right) = 1.63\ in$

$p := min((3.5 \cdot b), s) = 6.00\ in$

$\delta := 1 - \frac{d'}{p} = 0.86$ $\rho := \frac{b'}{a'} = 1.37$ $\beta := \frac{1}{\rho} \cdot \left(\frac{B_c}{P_w} - 1\right) = 8.47$

$t_c := \sqrt{\frac{4\ B_c \cdot b'}{p \cdot F_u}} = 0.95\ in$

Eq. (9-26)

```
try
  ‖ if t_f > t_c
  ‖   ‖ "Bolts Developed"
  ‖ else
  ‖   ‖ "Bolts Not Developed"
on error
  ‖
= "Bolts Not Developed"
```

$\alpha_{det} := \frac{1}{\delta} \cdot \left(\frac{P_w}{B_c} \cdot \left(\frac{t_c}{t_f}\right)^2 - 1\right) = -0.72$

Eq. (9-25)

```
α := if 0 < α_det < 1
       ‖ α_det
     else if α_det ≤ 0
       ‖ 0
     else if α_det ≥ 1
       ‖ 1
= 0.00
```

$q_{r\_web} := B_c \cdot \left(\delta \cdot \alpha \cdot \rho \cdot \left(\left(\frac{t_f}{t_c}\right)^2\right)\right) = 0.00\ kip$ *Prying Force about web in each bolt*

$\text{clear}(b, a, b', a', p, \delta, \rho, \beta, t_c, \alpha_{det}, \alpha, q_r, Bolt\_Force)$

Prying About Stiffener

$b := \frac{s}{2} - \frac{t_s}{2} = 2.81\ in$

$b' := b - \frac{d_b}{2} = 2.44\ in$

$p := min((3.5 \cdot b), s) = 6.00\ in$

$a' := (1.25\ b) + \frac{d_b}{2} = 3.89\ in$

$\delta := 1 - \frac{d'}{p} = 0.86$

$\rho := \frac{b'}{a'} = 0.63$

$\beta := \frac{1}{\rho} \cdot \left(\frac{B_c}{P_s} - 1\right) = 32.63$

$t_c := \sqrt{\frac{4\ B_c \cdot b'}{p \cdot F_u}} = 1.00\ in$

Eq. (9-26)

if $t_f > t_c$
  "Bolts Developed"
else
  "Bolts Not Developed"
= "Bolts Not Developed"

$\alpha_{det} := \frac{1}{\delta} \cdot \left(\frac{P_s}{B_c} \cdot \left(\frac{t_c}{t_f}\right)^2 - 1\right) = -0.87$

Eq. (9-25)

$\alpha :=$ if $0 < \alpha_{det} < 1$
  α_{det}
else if $\alpha_{det} \le 0$
  0
else if $\alpha_{det} \ge 1$
  1
$= 0.00$

$q_{r\_stiffener} := B_c \cdot \left(\delta \cdot \alpha \cdot \rho \cdot \left(\left(\frac{t_f}{t_c}\right)^2\right)\right) = 0.00\ kip$

Prying Force about stiffener in each bolt

$Total\_Bolt\_Force := q_{r\_web} + q_{r\_stiffener} + T_r = 5.00\ kip$

$Total\_Bolt\_Force = 5\ kip$

Two-Way Bending Calculation for W8x31

W8x31: $t_w := 0.285\ in$ $b_f := 8\ in$ $t_f := 0.435\ in$ $G := 5.5\ in$ $F_u := 65\ ksi$

3/4 DIA A325 bolt: $d_b := .75\ in$ $d' := \frac{13}{16}\ in = 0.81\ in$ *(AISC 15th - Table J3.3)*

$B_c := 90\ ksi \cdot \left(\frac{\pi \cdot d_b^2}{4}\right) = 39.76\ kip$ *Tensile Stress Fu in AISC Table J3.2*

Stiffener: $t_s := \frac{3}{8}\ in$ $s := 6\ in$

CALCS Point Loads, $P := 15\ kip$ $T_r := \frac{2\ P}{4} = 7.5\ kip$ *(Pure tension load per bolt)*

$e_w := \frac{G - t_w}{2} = 2.61\ in$ $b_{eff\_w} := 2 \cdot e_w = 5.22\ in$

$e_s := \frac{s - t_s}{2} = 2.81\ in$ $b_{eff\_s} := min\left(\left(\frac{b_f - t_w}{2}\right), (2 \cdot e_s)\right) = 3.86\ in$ *(Limited by bolt hole edge distance)*

$z := \left(\frac{e_w^3}{b_{eff\_w}}\right) \cdot \frac{b_{eff\_s}}{e_s^3} = 0.58945$ $M := \begin{bmatrix} z & -1 \\ 1 & 1 \end{bmatrix}$ $v := \begin{bmatrix} 0 \\ T_r \end{bmatrix}$ $S := \text{lsolve}(M, v) = \begin{bmatrix} 4.719 \\ 2.781 \end{bmatrix} kip$

(Top Value: Bending about web Bottom Value: Bending about stiffener)

$P_w := S_0 = 4.719\ kip$ $P_s := S_1 = 2.781\ kip$ $P_T := P_w + P_s = 7.5\ kip$

Prying About Web

$b := \frac{G}{2} - \frac{t_w}{2} = 2.61\ in$ $b' := b - \frac{d_b}{2} = 2.23\ in$

$a := \frac{b_f - G}{2} = 1.25\ in$

$a' := min\left(a + \frac{d_b}{2}, (1.25 \cdot b) + \frac{d_b}{2}\right) = 1.63\ in$

$p := min((3.5 \cdot b), s) = 6.00\ in$

$\delta := 1 - \frac{d'}{p} = 0.86$ $\rho := \frac{b'}{a'} = 1.37$ $\beta := \frac{1}{\rho} \cdot \left(\frac{B_c}{P_w} - 1\right) = 5.41$

$t_c := \sqrt{\frac{4\ B_c \cdot b'}{p \cdot F_u}} = 0.95\ in$

Eq. (9-26)

try
 if $t_f > t_c$
  "Bolts Developed"
 else
  "Bolts Not Developed"
on error
= "Bolts Not Developed"

$\alpha_{det} := \frac{1}{\delta} \cdot \left(\frac{P_w}{B_c} \cdot \left(\frac{t_c}{t_f}\right)^2 - 1\right) = -0.50$

Eq. (9-25)

$\alpha :=$ if $0 < \alpha_{det} < 1$
 α_{det}
else if $\alpha_{det} \le 0$
 0
else if $\alpha_{det} \ge 1$
 1
$= 0.00$

$q_{r\_web} := B_c \cdot \left(\delta \cdot \alpha \cdot \rho \cdot \left(\left(\frac{t_f}{t_c}\right)^2\right)\right) = 0.00\ kip$ *Prying Force about web in each bolt*

$$\text{clear}\left(b, a, b', a', p, \delta, \rho, \beta, t_c, \alpha_{det}, \alpha, q_r, Bolt\_Force\right)$$

<u>Prying About Stiffener</u>

$$b := \frac{s}{2} - \frac{t_s}{2} = 2.81\ in \qquad b' := b - \frac{d_b}{2} = 2.44\ in$$

$$p := min\left(\left(3.5 \cdot b\right), s\right) = 6.00\ in \qquad a' := \left(1.25\ b\right) + \frac{d_b}{2} = 3.89\ in$$

$$\delta := 1 - \frac{d'}{p} = 0.86 \qquad \rho := \frac{b'}{a'} = 0.63 \qquad \beta := \frac{1}{\rho} \cdot \left(\frac{B_c}{P_s} - 1\right) = 21.22$$

$$t_c := \sqrt{\frac{4\ B_c \cdot b'}{p \cdot F_u}} = 1.00\ in$$

Eq. (9-26)

if $t_f > t_c$
  "Bolts Developed"
else
  "Bolts Not Developed"
= "Bolts Not Developed"

$$\alpha_{det} := \frac{1}{\delta} \cdot \left(\frac{P_s}{B_c} \cdot \left(\frac{t_c}{t_f}\right)^2 - 1\right) = -0.73$$

Eq. (9-25)

$\alpha :=$ if $0 < \alpha_{det} < 1$
  α_{det}
else if $\alpha_{det} \le 0$
  0
else if $\alpha_{det} \ge 1$
  1
$= 0.00$

$$q_{r\_stiffener} := B_c \cdot \left(\delta \cdot \alpha \cdot \rho \cdot \left(\left(\frac{t_f}{t_c}\right)^2\right)\right) = 0.00\ kip$$

Prying Force about stiffener in each bolt

$$Total\_Bolt\_Force := q_{r\_web} + q_{r\_stiffener} + T_r = 7.50\ kip$$

$$Total\_Bolt\_Force = 7.5\ kip$$

Two-Way Bending Calculation for W8x31

W8x31: $t_w := 0.285\ in$ $b_f := 8\ in$ $t_f := 0.435\ in$ $G := 5.5\ in$ $F_u := 65\ ksi$

3/4 DIA A325 bolt: $d_b := .75\ in$ $d' := \frac{13}{16}\ in = 0.81\ in$ *(AISC 15th - Table J3.3)*

$B_c := 90\ ksi \cdot \left(\frac{\pi \cdot d_b^2}{4}\right) = 39.76\ kip$ *Tensile Stress Fu in AISC Table J3.2*

Stiffener: $t_s := \frac{3}{8}\ in$ $s := 6\ in$

CALCS Point Loads, $P := 20\ kip$ $T_r := \frac{2\ P}{4} = 10.0\ kip$ *(Pure tension load per bolt)*

$e_w := \frac{G - t_w}{2} = 2.61\ in$ $b_{eff\_w} := 2 \cdot e_w = 5.22\ in$

$e_s := \frac{s - t_s}{2} = 2.81\ in$ $b_{eff\_s} := min\left(\left(\frac{b_f - t_w}{2}\right), (2 \cdot e_s)\right) = 3.86\ in$ *(Limited by bolt hole edge distance)*

$z := \left(\frac{e_w^3}{b_{eff\_w}}\right) \cdot \frac{b_{eff\_s}}{e_s^3} = 0.58945$ $M := \begin{bmatrix} z & -1 \\ 1 & 1 \end{bmatrix}$ $v := \begin{bmatrix} 0 \\ T_r \end{bmatrix}$ $S := \text{lsolve}(M, v) = \begin{bmatrix} 6.291 \\ 3.709 \end{bmatrix} kip$

(Top Value: Bending about web Bottom Value: Bending about stiffener)

$P_w := S_0 = 6.291\ kip$ $P_s := S_1 = 3.709\ kip$

$P_T := P_w + P_s = 10.0\ kip$

Prying About Web

$b := \frac{G}{2} - \frac{t_w}{2} = 2.61\ in$ $b' := b - \frac{d_b}{2} = 2.23\ in$

$a := \frac{b_f - G}{2} = 1.25\ in$

$a' := min\left(a + \frac{d_b}{2}, (1.25 \cdot b) + \frac{d_b}{2}\right) = 1.63\ in$

$p := min((3.5 \cdot b), s) = 6.00\ in$

$\delta := 1 - \frac{d'}{p} = 0.86$ $\rho := \frac{b'}{a'} = 1.37$ $\beta := \frac{1}{\rho} \cdot \left(\frac{B_c}{P_w} - 1\right) = 3.87$

$t_c := \sqrt{\frac{4\ B_c \cdot b'}{p \cdot F_u}} = 0.95\ in$

Eq. (9-26)

```
try
  if t_f > t_c
    "Bolts Developed"
  else
    "Bolts Not Developed"
on error
                                    = "Bolts Not Developed"
```

$\alpha_{det} := \frac{1}{\delta} \cdot \left(\frac{P_w}{B_c} \cdot \left(\frac{t_c}{t_f}\right)^2 - 1\right) = -0.28$

Eq. (9-25)

```
α := if 0 < α_det < 1
       α_det
     else if α_det ≤ 0
       0
     else if α_det ≥ 1
       1
                          = 0.00
```

$q_{r\_web} := B_c \cdot \left(\delta \cdot \alpha \cdot \rho \cdot \left(\left(\frac{t_f}{t_c}\right)^2\right)\right) = 0.00\ kip$ *Prying Force about web in each bolt*

$$\text{clear}(b, a, b', a', p, \delta, \rho, \beta, t_c, \alpha_{det}, \alpha, q_r, Bolt\_Force)$$

Prying About Stiffener

$$b := \frac{s}{2} - \frac{t_s}{2} = 2.81\ in \qquad b' := b - \frac{d_b}{2} = 2.44\ in$$

$$p := min((3.5 \cdot b), s) = 6.00\ in \qquad a' := (1.25\ b) + \frac{d_b}{2} = 3.89\ in$$

$$\delta := 1 - \frac{d'}{p} = 0.86 \qquad \rho := \frac{b'}{a'} = 0.63 \qquad \beta := \frac{1}{\rho} \cdot \left(\frac{B_c}{P_s} - 1\right) = 15.52$$

$$t_c := \sqrt{\frac{4\ B_c \cdot b'}{p \cdot F_u}} = 1.00\ in$$

Eq. (9-26)

if $t_f > t_c$ "Bolts Developed" else "Bolts Not Developed" = "Bolts Not Developed"

$$\alpha_{det} := \frac{1}{\delta} \cdot \left(\frac{P_s}{B_c} \cdot \left(\frac{t_c}{t_f}\right)^2 - 1\right) = -0.59$$

Eq. (9-25)

$\alpha :=$ if $0 < \alpha_{det} < 1$ ‖ α_{det} else if $\alpha_{det} \leq 0$ ‖ 0 else if $\alpha_{det} \geq 1$ ‖ 1 $= 0.00$

$$q_{r\_stiffener} := B_c \cdot \left(\delta \cdot \alpha \cdot \rho \cdot \left(\left(\frac{t_f}{t_c}\right)^2\right)\right) = 0.00\ kip$$

Prying Force about stiffener in each bolt

$$Total\_Bolt\_Force := q_{r\_web} + q_{r\_stiffener} + T_r = 10.00\ kip$$

$$Total\_Bolt\_Force = 10\ kip$$

Two-Way Bending Calculation for W8x31

W8x31: $t_w := 0.285\ in$ $b_f := 8\ in$ $t_f := 0.435\ in$ $G := 5.5\ in$ $F_u := 65\ ksi$

3/4 DIA A325 bolt: $d_b := .75\ in$ $d' := \frac{13}{16}\ in = 0.81\ in$ *(AISC 15th - Table J3.3)*

$B_c := 90\ ksi \cdot \left(\frac{\pi \cdot d_b^2}{4}\right) = 39.76\ kip$ *Tensile Stress Fu in AISC Table J3.2*

Stiffener: $t_s := \frac{3}{8}\ in$ $s := 6\ in$

CALCS Point Loads, $P := 25\ kip$ $T_r := \frac{2\ P}{4} = 12.5\ kip$ *(Pure tension load per bolt)*

$e_w := \frac{G - t_w}{2} = 2.61\ in$ $b_{eff\_w} := 2 \cdot e_w = 5.22\ in$

$e_s := \frac{s - t_s}{2} = 2.81\ in$ $b_{eff\_s} := min\left(\left(\frac{b_f - t_w}{2}\right), (2 \cdot e_s)\right) = 3.86\ in$ *(Limited by bolt hole edge distance)*

$z := \left(\frac{e_w^3}{b_{eff\_w}}\right) \cdot \frac{b_{eff\_s}}{e_s^3} = 0.58945$ $M := \begin{bmatrix} z & -1 \\ 1 & 1 \end{bmatrix}$ $v := \begin{bmatrix} 0 \\ T_r \end{bmatrix}$ $S := \text{lsolve}(M, v) = \begin{bmatrix} 7.864 \\ 4.636 \end{bmatrix} kip$

(Top Value: Bending about web Bottom Value: Bending about stiffener)

$P_w := S_0 = 7.864\ kip$ $P_s := S_1 = 4.636\ kip$

$P_T := P_w + P_s = 12.5\ kip$

Prying About Web $b := \frac{G}{2} - \frac{t_w}{2} = 2.61\ in$ $b' := b - \frac{d_b}{2} = 2.23\ in$

$a := \frac{b_f - G}{2} = 1.25\ in$

$a' := min\left(a + \frac{d_b}{2}, (1.25 \cdot b) + \frac{d_b}{2}\right) = 1.63\ in$

$p := min((3.5 \cdot b), s) = 6.00\ in$

$\delta := 1 - \frac{d'}{p} = 0.86$ $\rho := \frac{b'}{a'} = 1.37$ $\beta := \frac{1}{\rho} \cdot \left(\frac{B_c}{P_w} - 1\right) = 2.95$

$t_c := \sqrt{\frac{4\ B_c \cdot b'}{p \cdot F_u}} = 0.95\ in$

Eq. (9-26)

```
try
  if t_f > t_c
    "Bolts Developed"
  else
    "Bolts Not Developed"
on error
= "Bolts Not Developed"
```

$\alpha_{det} := \frac{1}{\delta} \cdot \left(\frac{P_w}{B_c} \cdot \left(\frac{t_c}{t_f}\right)^2 - 1\right) = -0.06$

Eq. (9-25)

```
α := if 0 < α_det < 1
       α_det
     else if α_det ≤ 0
       0
     else if α_det ≥ 1
       1
= 0.00
```

$q_{r\_web} := B_c \cdot \left(\delta \cdot \alpha \cdot \rho \cdot \left(\left(\frac{t_f}{t_c}\right)^2\right)\right) = 0.00\ kip$ *Prying Force about web in each bolt*

$\text{clear}(b, a, b', a', p, \delta, \rho, \beta, t_c, \alpha_{det}, \alpha, q_r, Bolt\_Force)$

Prying About Stiffener

$b := \frac{s}{2} - \frac{t_s}{2} = 2.81\ in$

$b' := b - \frac{d_b}{2} = 2.44\ in$

$p := min((3.5 \cdot b), s) = 6.00\ in$

$a' := (1.25\ b) + \frac{d_b}{2} = 3.89\ in$

$\delta := 1 - \frac{d'}{p} = 0.86$

$\rho := \frac{b'}{a'} = 0.63$

$\beta := \frac{1}{\rho} \cdot \left(\frac{B_c}{P_s} - 1\right) = 12.09$

$t_c := \sqrt{\frac{4\ B_c \cdot b'}{p \cdot F_u}} = 1.00\ in$

Eq. (9-26)

if $t_f > t_c$
  "Bolts Developed"
else
  "Bolts Not Developed"
= "Bolts Not Developed"

$\alpha_{det} := \frac{1}{\delta} \cdot \left(\frac{P_s}{B_c} \cdot \left(\frac{t_c}{t_f}\right)^2 - 1\right) = -0.45$

Eq. (9-25)

$\alpha :=$ if $0 < \alpha_{det} < 1$
  α_{det}
else if $\alpha_{det} \le 0$
  0
else if $\alpha_{det} \ge 1$
  1
$= 0.00$

$q_{r\_stiffener} := B_c \cdot \left(\delta \cdot \alpha \cdot \rho \cdot \left(\left(\frac{t_f}{t_c}\right)^2\right)\right) = 0.00\ kip$

Prying Force about stiffener in each bolt

$Total\_Bolt\_Force := q_{r\_web} + q_{r\_stiffener} + T_r = 12.50\ kip$

$Total\_Bolt\_Force = 12.5\ kip$

Appendix C – Shell Layer Division Calculations

W8x31

t_f = 0.435 in

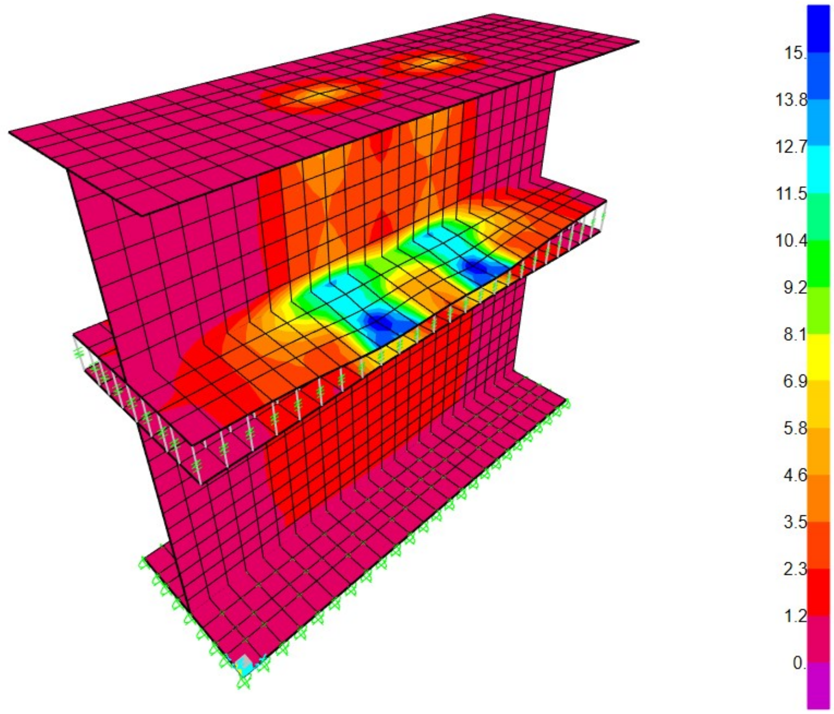
Layer	Location	Thickness
1	0	0.10875
2	0.10875	0.10875
3	0.2175	0.10875
4	0.32625	0.10875
	Total	0.435

W12x50

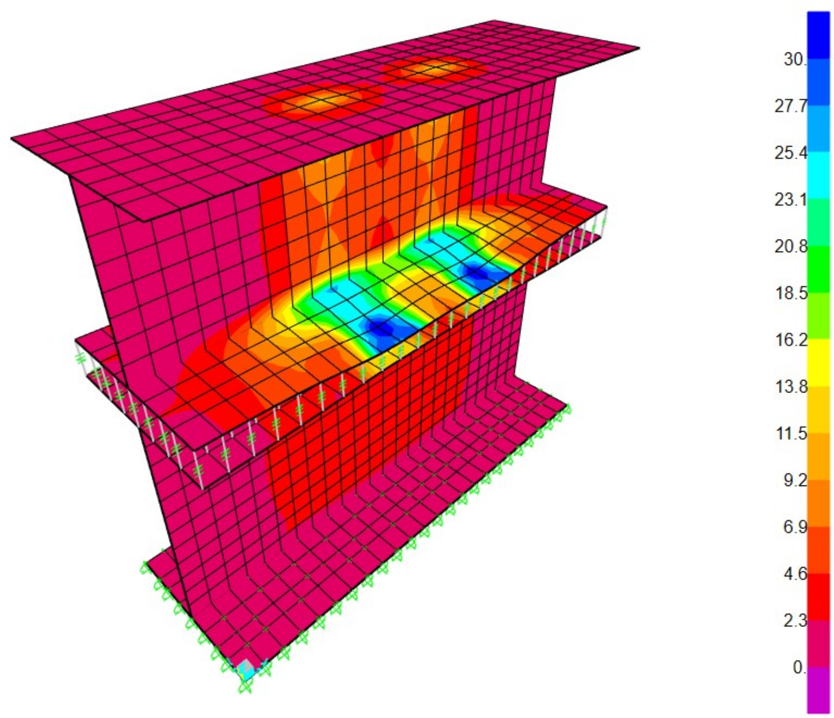
t_f = 0.64 in

Layers	Location	Thickness
1	0	0.16
2	0.16	0.16
3	0.32	0.16
4	0.48	0.16
	Total	0.64

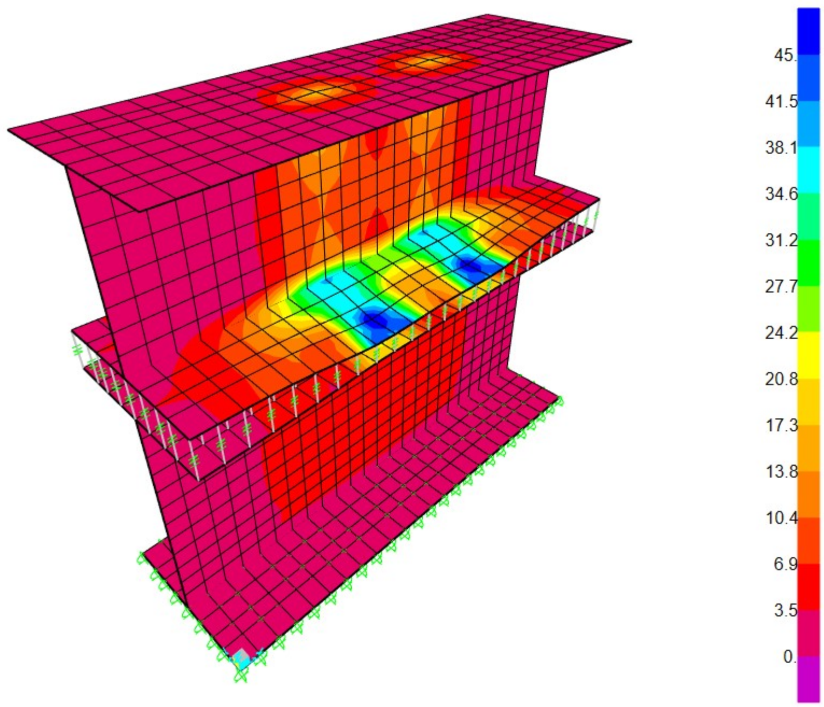
Appendix D – Version 1 Mesh Figures



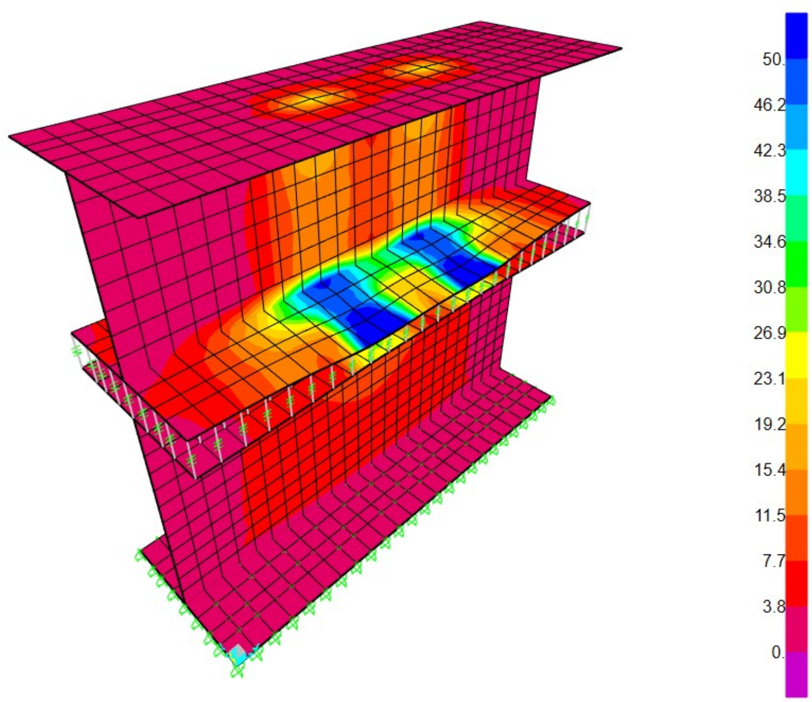
Note. By Author, 5k Load Case



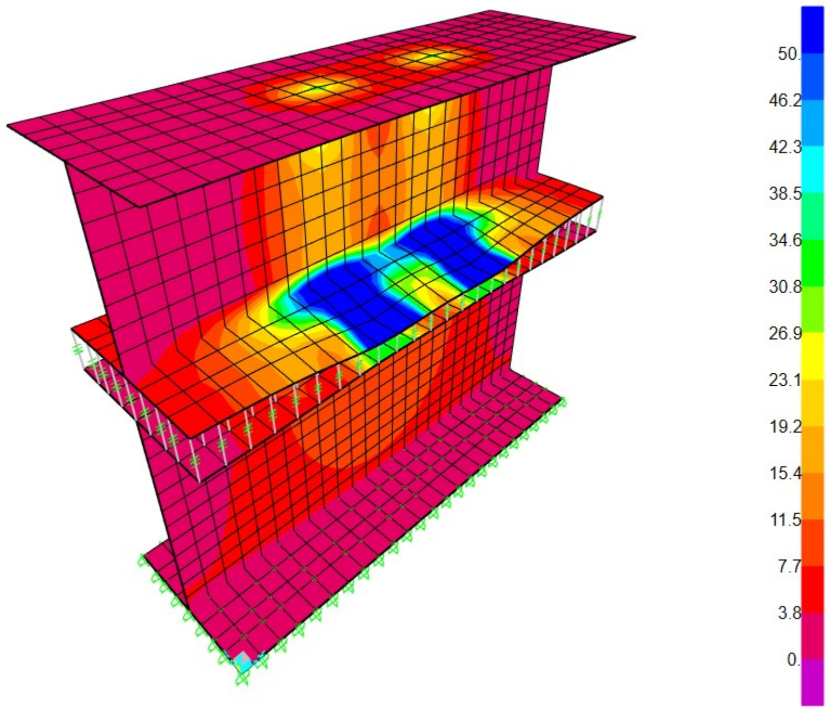
Note. By Author, 10k Load Case



Note. By Author, 15k Load Case



Note. By Author, 20k Load Case



Note. By Author, 25k Load Case

Architectural Engineering

Capstone Report Approval Form

Master of Science in Architectural Engineering – MSAE

Milwaukee School of Engineering

This capstone report, entitled "A Study of the Effects of Two-Way Prying Action in Bolted Connections" submitted by the student Cobey A. Alderden, has been approved by the following committee:

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