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Analysis of Bolted Beam-Column Connections with Multiple Bolts  
per Row and Column Web Stiffeners

Undergraduate honors thesis submitted in partial  
fulfillment of the requirements for the degree of  
Bachelor of Science in Civil Engineering

by

Benjamin Clay Sutherland  
University of Arkansas, May 2015

# 1) Introduction

Bolted beam-column connections are a common connection used in steel buildings. The beam column connection shown below (left) is a typical beam-column connection geometry having an endplate attached to the beam end, allowing the beam to be bolted to the column flange [Figure 1]. As building functions change or as higher service loads are required, these connections often require strengthening. Strengthening of the connection can be achieved in many ways, including: using extended endplates [1], or adding stiffening members between the endplate and beam [2]. However, welding stiffening plates can be expensive, pose potential fire hazards to the existing structure, and be difficult to implement when a concrete slab is present.

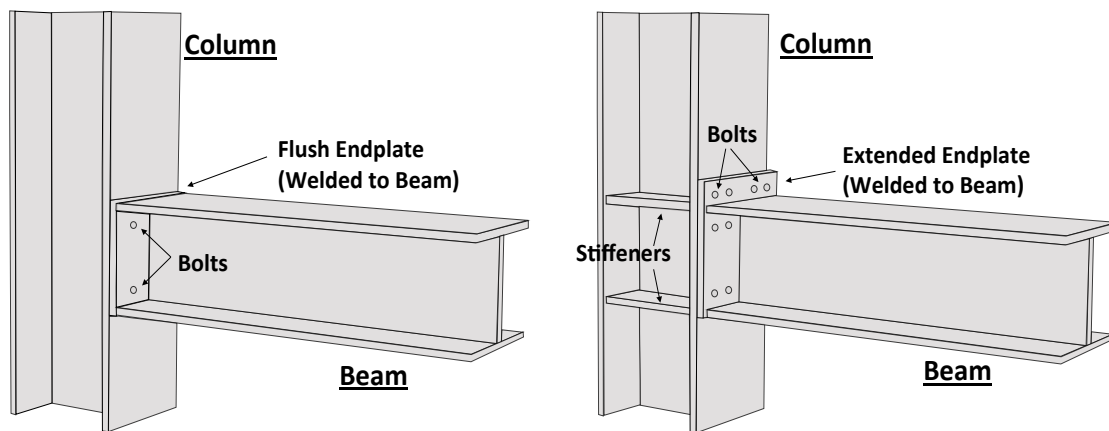


Figure 1. Standard bolted beam-column connection (left) with stiffeners and multiple bolts per row (right).

Simply adding additional bolts to the connection may offer a potential economical solution with little fire risk, as additional welding is not required. It is also possible that this solution could be useful for connection design. A recent study investigating benefits of adding bolts to bolted beam-column connections, demonstrated little improvement to connection strength [3]; however, all connections tested by Prinz did not include column web stiffeners (continuity plates). In the study, significant column flange deformations were observed, leading to early bolt fractures from increased bolt prying [3]. T-Stub tests having instrumented bolts [Figure 2] showed that the outer bolts of the multiple-bolt-per-row configurations contributed little to connection strength gain as flange deformations forced the applied loads into the inner bolts. It was determined that any component strength increase resulted from the inner bolts being closer to the column web. Because the position of the inner bolts would not be expected to change in a retrofitting/strengthening scenario, adding more bolts to configurations without column web stiffeners would not be expected to increase connection strength.

This study analytically investigates the performance of beam-column connection configurations having multiple-bolts-per-row and column web stiffeners (continuity plates) [Figure 1]. In this study, advanced finite element simulations are used to build upon the previous work [3], investigating both equal-column equal-beam and weak-column strong-beam configurations [Figure 3]. Relationships between component behavior and the resulting contribution to connection strength are investigated.

The paper begins by describing the various beam-column connection configurations investigated. Following, a description of the connection analysis is provided, including modeling techniques, boundary conditions, and loadings. Next, T-stub configurations and modeling methods are described. The goal of these T-stub analyses was to provide insight into beam-column connection component behavior, but the information recovered was not adequate for use in this research. Lastly, results from the beam-column analysis are presented and conclusions are made.

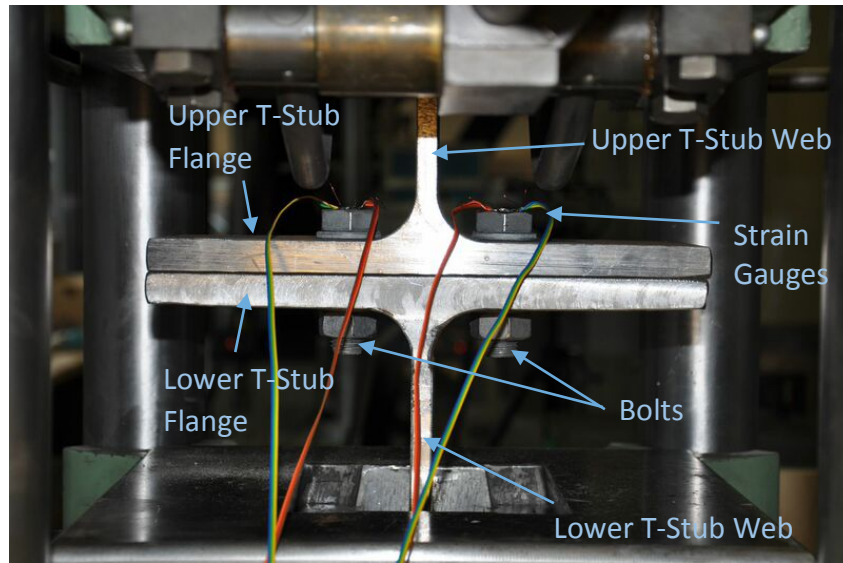


Figure 2. T-Stub Connection Test

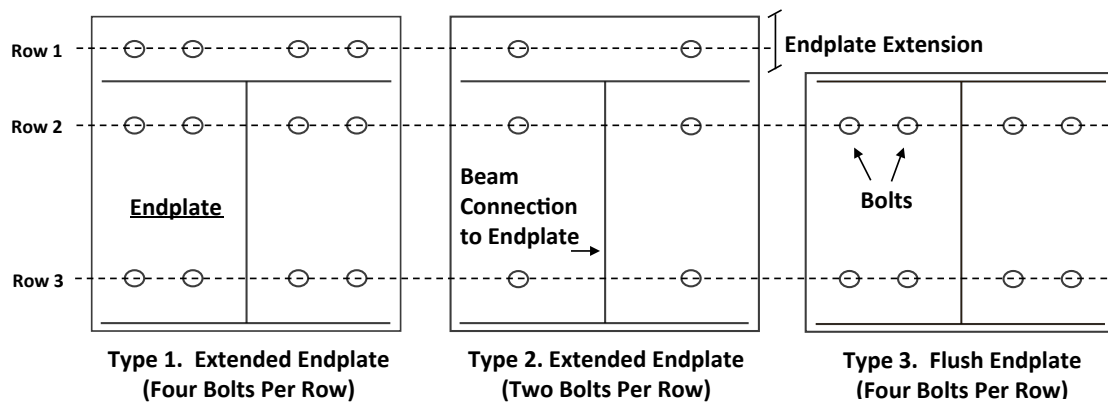


Figure 3. Endplate Configurations

## 2) Connection Analysis

### 2.1) Beam Column Connections Considered

Several connection configurations are investigated herein, having various combinations of features, including: column web stiffeners (continuity plates), flush or extended endplates, and endplates with additional bolts on each row. In total, 12 different beam column configurations are considered. A total of 12 different combinations of features were

considered for each beam-column connection, along with 6 configurations for T-stub component analyses [Figure 4]. See Figure 1 (above, right) for a depiction of a bolted beam-column connection configuration (model BCC 1A) having an extended endplate and multiple bolts-per-row [Figure 1].

Model	Material	Beam	Column	Stiffeners	Number of Bolts	Endplate
BCC 1A	s235, s355	HE 300B	HE 300A	-	12	Extended
BCC 1A (Stiffened)	s235, s355	HE 300B	HE 300A	Column Web	12	Extended
BCC 2A	s235, s355	HE 300B	HE 300A	-	6	Extended
BCC 2A (Stiffened)	s235, s355	HE 300B	HE 300A	Column Web	6	Extended
BCC 3A	s235, s355	HE 300B	HE 300A	-	8	Flush
BCC 3A (Stiffened)	s235, s355	HE 300B	HE 300A	Column Web	8	Flush
BCC 1B	s235, s355	HE 300B	HE 300B	-	12	Extended
BCC 1B (Stiffened)	s235, s355	HE 300B	HE 300B	Column Web	12	Extended
BCC 2B	s235, s355	HE 300B	HE 300B	-	6	Extended
BCC 2B (Stiffened)	s235, s355	HE 300B	HE 300B	Column Web	6	Extended
BCC 3B	s235, s355	HE 300B	HE 300B	-	8	Flush
BCC 3B (Stiffened)	s235, s355	HE 300B	HE 300B	Column Web	8	Flush
Tstub A	s235, s355	-	HE 300B	-	2	-
Tstub A (Stiffened)	s235, s355	-	HE 300B	Column Web	2	-
Tstub B	s235, s355	-	HE 300B	-	4	-
Tstub B (Stiffened)	s235, s355	-	HE 300B	Column Web	4	-
Tstub C	s235, s355	-	HE 300B	-	2	-
Tstub C (Stiffened)	s235, s355	-	HE 300B	Column Web	2	-

Figure 4. Analysis Matrix

## 2.2) Finite Element Analysis:

Each configuration is analyzed using the finite element method. Finite element analysis is a useful and economical tool to gain valuable information prior to expensive large-scale experimental testing [Figure 4]. Advanced finite element simulations using multi-dimension elements allow accurate representation of connection geometry and localized connection performance, including any local instabilities and plasticity. The commercial finite element software ABAQUS [4] will be used for all analyses in this study.

Many studies have used finite element simulations to model beam-column connections in steel structures. Shi analyzed extended endplate connections with physical testing and theoretical analysis of components, showing reasonable predictions compared to the theoretical analysis [5]. Prinz conducted research on beam-column connections using physical testing, the component analysis method, and finite element modeling [3]. Results showed that finite element analysis using shell elements was a reasonably accurate method for predicting

connection strength, capturing local instabilities (i.e. local buckling), and identifying localized yielding.

### **2.2.1) Model Configuration and Loading:**

Each beam-column connection was created using shell elements to model the beam, column, and endplate. Each shell element is located at the centerline of each member section (flange, web, or endplate). The welded connection between the endplate and the beam is assumed to be fixed. Each end of the column section being modeled is connected to a pin with a rigid body constraint on the face of the column. This causes the end of the column to remain planar, eliminating localized deformations and column end warping [Figure 5].

Each bolt was discretely modeled using three nonlinear springs. The tensile springs were given force displacement values based on testing results [5], and were made to be infinitely stiff in compression representing contact. Bolt stresses are evenly distributed over an area (equal to bolt cross-sectional area) on both the endplate and column flange using a rigid body constraint [Figure 5]. To provide contact between the endplate and column flange, multiple connectors having infinite stiffness are added near the compression region of the endplate.

All simulations represent a displacement controlled loading situation, where an applied displacement to the beam tip results in connection rotations. To determine moment-rotation behavior from the applied displacement, a moment arm between location of applied displacement and the surface of the column flange is combined with the beam-tip reaction force. Connection rotation is taken as the applied displacement divided this moment arm distance (1m for all connection models).

Mesh size can affect the accuracy of analysis, with smaller mesh sizes typically resulting in more accurate analysis results. In regions of interest, near the bolt (spring-to-shell regions), a mesh sensitivity study was conducted to ensure adequate mesh size, without high computational time expense. Three levels of mesh refinement were used near the bolt partition region [Figure 6]. From the sensitivity study, a mesh size of approximately 0.5 mm was chosen for the area near the bolt diameter partition. A mesh size of 2 mm was used everywhere else for computational efficiency.

### **2.2.2) Bolt Stress:**

The circular partition around the bolt face in the column flange was used to calculate an equivalent bolt stresses, including bearing stresses. Von Mises stress values for each element that borders the bolt were recorded and used to identify tensile behavior and prying tendencies of the bolts.

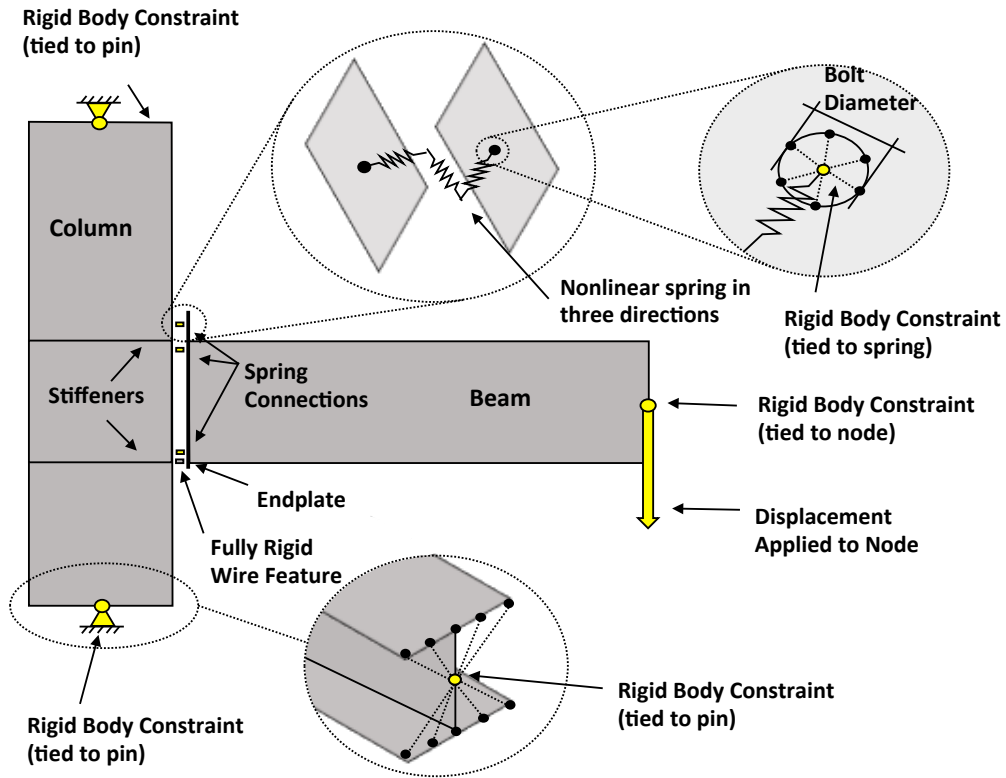


Figure 5. Connection Schematic for Finite Element Analysis Model

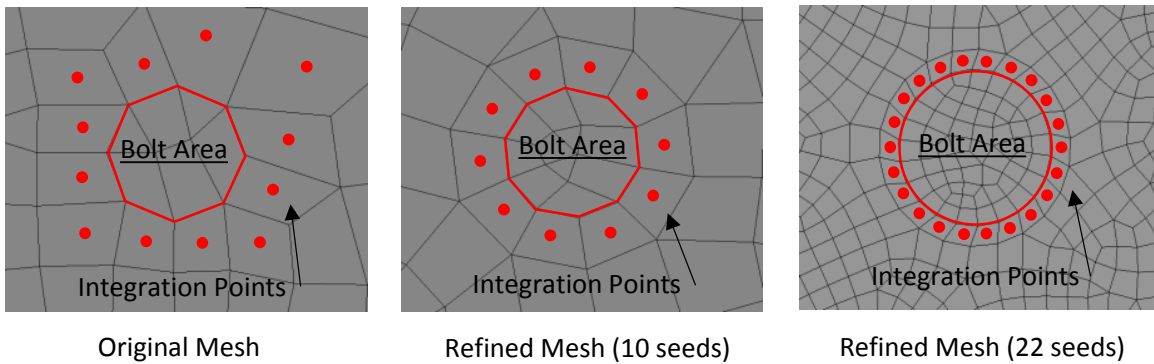


Figure 6. Refinement of Bolt Mesh

### 3) T-stub Connections

#### 3.1) Background/Purpose:

For bolted endplate beam-column connections, bolt participation can be modeled using bolted T-stub connections. These T-Stub connections consist of the flange of a beam being bolted to the flange of another beam. For ease of testing, only 50% of the web is used above and below the bolted connection. Based on Eurocode 3 [7], there are multiple failure modes for T-stub connections, including bolt failure with and without flange yielding. The most common failure mode is bolt failure resulting from flange only yielding within the bolted area, but other failure modes are possible based on strength of different components. For example,

with extremely thick endplates and weaker bolts, the bolts may fail before the flange has even begun to yield.

T-stub connections are very useful for physical modeling of bolted connection strength and can be modeled using finite element analysis. Certain T-stub connections have been introduced as benchmarks for validating finite element models [6]. For this project, validation of finite element analysis techniques will be based on physical T-stub testing results [3].

### 3.2) Model Configuration:

The T-stub models for this project were created to directly model the tensile region of the beam-column connections. The T-stubs were created using shell element geometry in ABAQUS. Similar to techniques used for the beam-column configurations, rigid bodies and nonlinear springs were used to model the bolts and bolt-to-endplate interaction. To simulate contact, wire features having infinite compressive stiffness were added to the ends of the T-stubs [Figure 7]. Additional work was required to refine the mesh for more precise stress readings around the bolts.

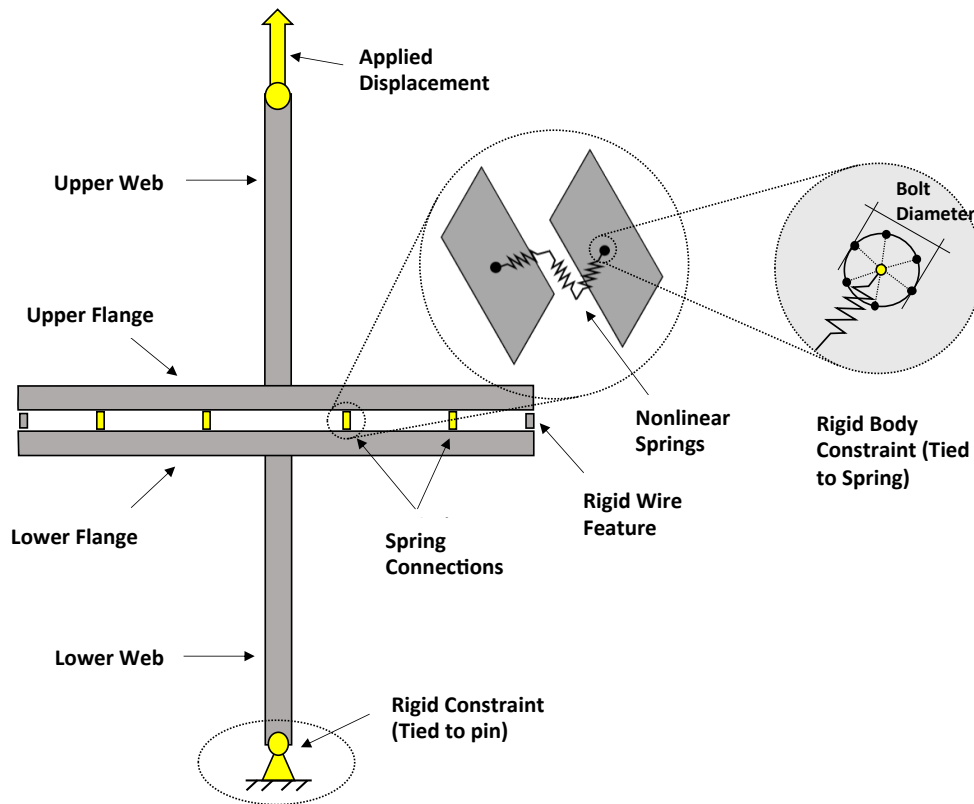


Figure 7. T-Stub Model Schematic

T-stub connections were validated using T-stubs in two configurations. T-stub tests having 2 bolts spaced 80mm from the web centerline, and tests having 4 bolts spaced at 45mm were used for the validation. Following the validation study, additional modeling of T-stubs having column web stiffeners was performed.





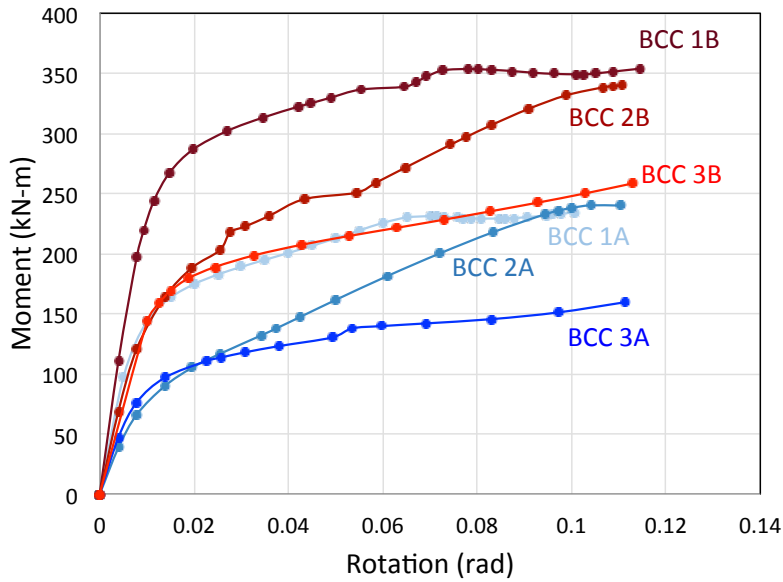


Figure 9. Moment Rotation Data: Unstiffened Connections

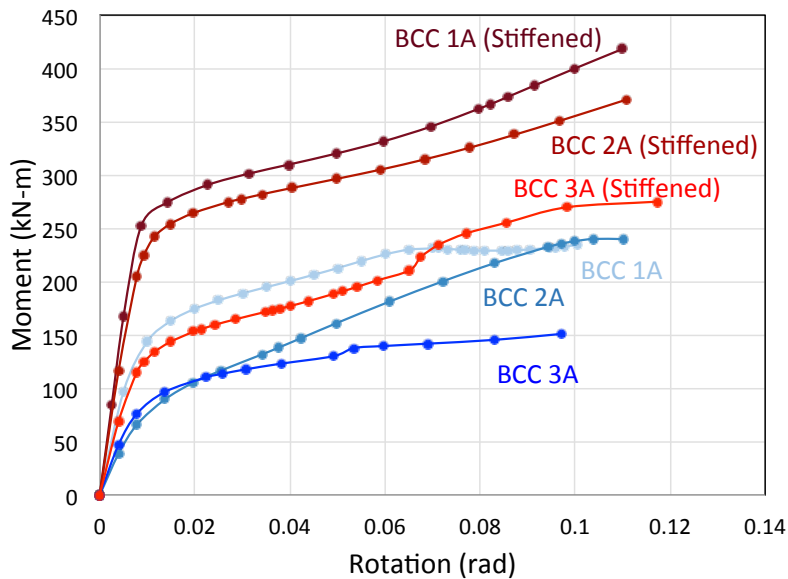


Figure 10. Moment Rotation Data: Weak-Beam Strong-Column Connections

The column web stiffeners had the most varied effects on the different configurations. Based on bolt stress data taken from the output files, the stiffeners helped to engage the outside bolts in configurations 1 and 3. However, the stiffeners had the greatest effect on configuration 2. This is likely because the innermost bolts still carry the majority of the moment, and they are further from the column web with this connection, so column flange deformation had the greatest effect on their moment capacity.

## 4.2) Bolt Bearing Capacity:

Figure 11 and Figure 12 illustrate the bearing stresses within the connection bolts during beam loading. The connection with multiple bolts per row and a standard endplate, BCC 3B, showed a 5% increase in the axial stress in the outer bolts when stiffeners were used [Figure 11]. With BCC 1B, the outer bolts in beneath the beam flange had significantly lower stress values (approximately 30% of the inner bolt stress). When column web stiffeners were used, the outer bolts carried an amount of stress nearly equal to the inner bolts. As you can see in Figure 12, the left and right side of the bolt was under less stress, suggesting that the column flange was held rigid, and the majority of stress was due to connection rotation.

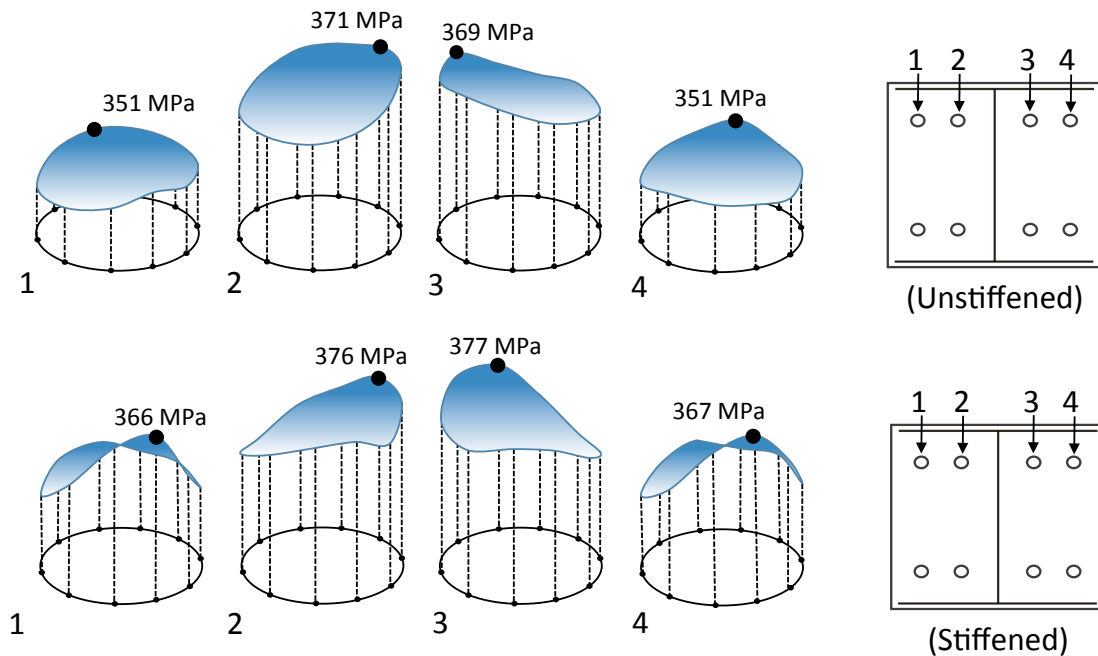


Figure 11. Bolt Stresses for BCC 3B (Stiffened and Unstiffened)

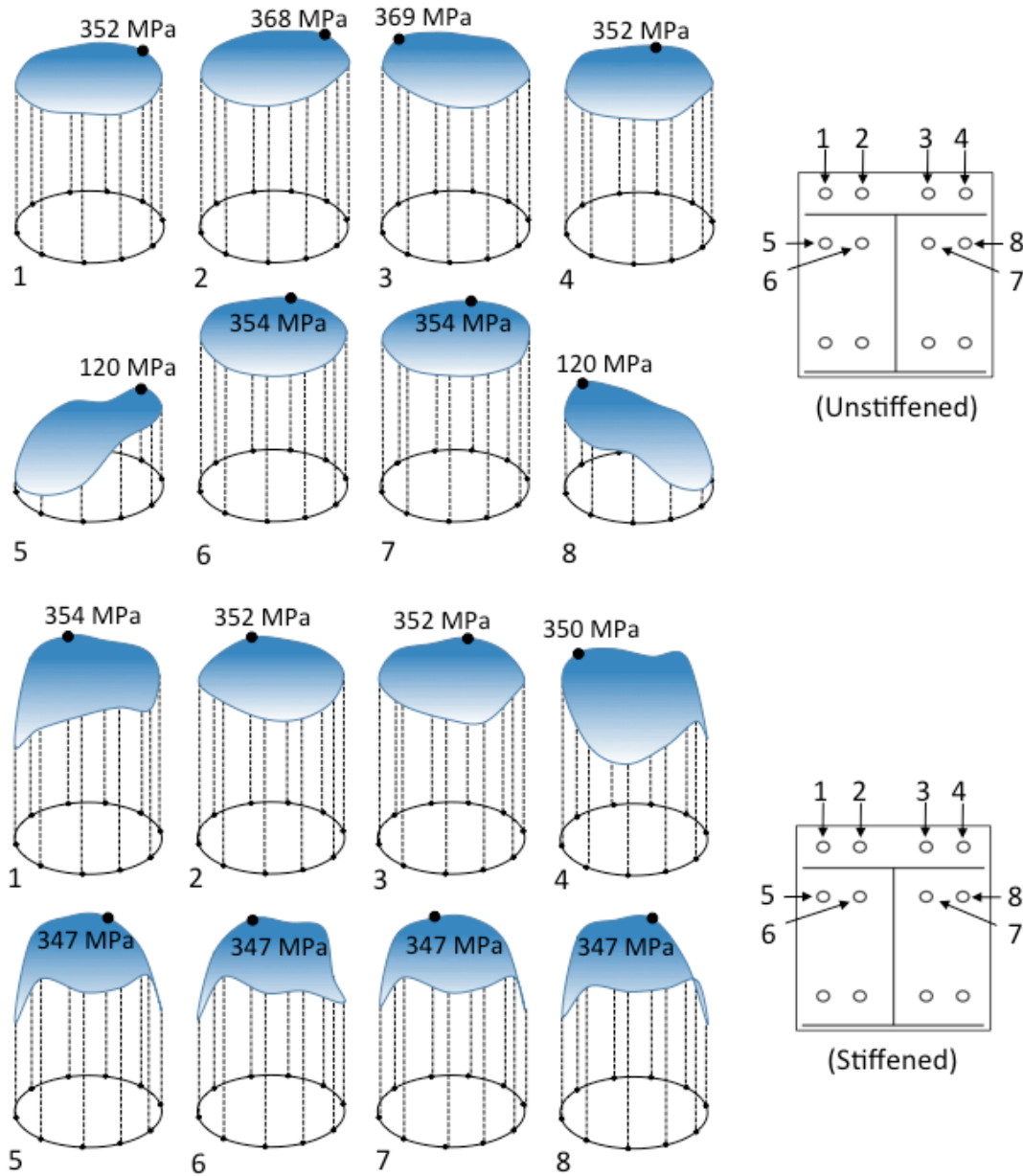


Figure 12. Bolt Stresses for BCC 1B (Unstiffened and Stiffened)

#### 4.3) T-Stub Connections:

The T-Stub model results are shown in Figure 13. From Figure 13, the T-stub models show similar yield points as the experimental testing; however, the strain-load curve in the models increases linearly while the experiment strain-load curve remains fairly flat until significant prying. One possible explanation is that in the physical testing, the bolts were under a constant pre-strain until the load reached about 300 kN, when the strain in tensile bolts increased exponentially. This pre-strain behavior was not captured in the simulation [Figure 13]. T-Stub modeling can be useful to determine how additional bolts participate in a variety of

scenarios and therefore in future research, the spring elements representing the bolts should be modified to model the pre-strain.

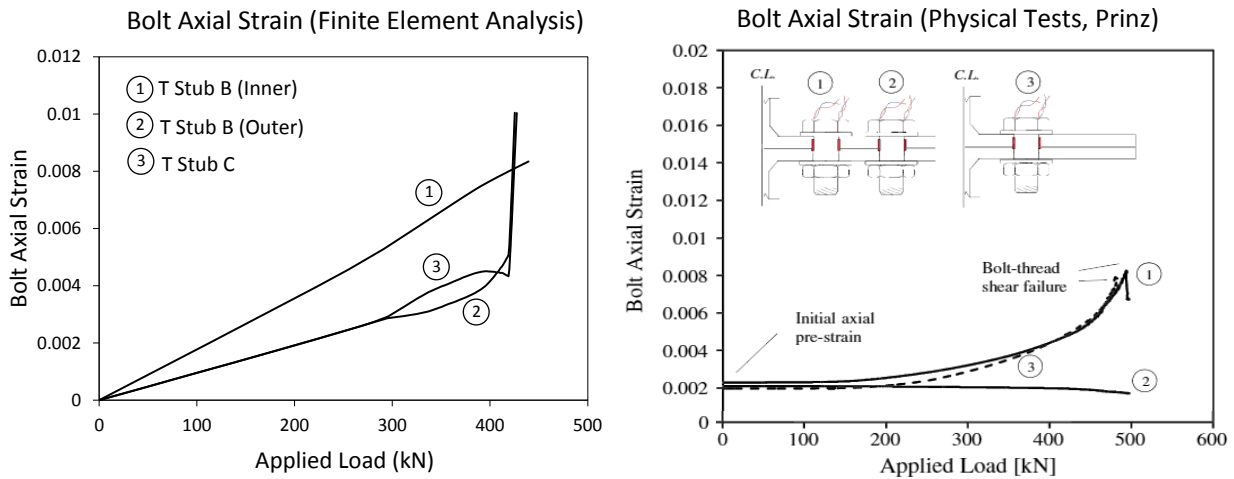


Figure 13. T-Stub Bolt Axial Strain (Finite Element Analysis and Physical Tests from Prinz et al. 2013)

## 5) Conclusion and Discussion

In this study, 12 beam-column configurations were analyzed using validated finite element techniques, to investigate the effects on performance of adding bolts to beam-column connections having column web stiffeners and thick endplates. Additional T-stub analyses investigated component behavior for comparison with existing component based analysis approaches. The following conclusions are based on the results from the beam-column and T-stub analyses.

1. Finite Element Analysis using shell elements, springs, and wire features as described can be used to reasonably model beam-column connection performance.
2. The innermost bolt of each row experiences the highest demands, even when column web stiffeners are included (due to column flange distortions); however, the addition of column web stiffeners reduces column web distortions and helps engage outer bolts (evidenced by increased outer bolt stresses during loading).
3. For extremely large connections or connections with very thick endplates, there could be greater potential for the outer bolts to be engaged due to flange stiffness.
4. Additional bolts or stiffeners have the same effect on weak-column strong-beam and strong-column-beam connections, indicating the component performance can be used for either connection type.
5. The addition of outer bolts increases the moment capacity of the beam-column connections, but this was mainly due to the innermost bolts being closer to the column web. The greatest increase in moment capacity was achieved by using extended endplates and column web stiffeners.

## 6) References

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