ROTATION AND STRENGTH DEMANDS FOR SIMPLE CONNECTIONS TO SUPPORT LARGE VERTICAL DEFLECTIONS

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ABSTRACT

Structural collapse may be initiated by numerous hazards, including earthquakes, hurricanes and blasts. Steel gravity framing systems, present in virtually every steel building constructed in the United States, may be particularly susceptible to collapse, especially when a column suffers damage that compromises its ability to carry gravity loads. In order to assess the ability of current gravity framing systems to prevent collapse when column damage occurs, deformation and strength demands on connections must be evaluated in the context of overall system behavior, including the development of large vertical deformations. Once known, means to enhance the threat-independent robustness of gravity framing systems can be developed, preventing future collapses. This paper proceeds a parametric study developed to assess the behavior of typical steel gravity framing systems bearing various layouts, member sizes, and connection configurations under loading consistent with column loss scenarios. Connection rotation and displacement demands are examined for systems utilizing various connection types including i) single plate shear connections ii) bolted web angle connections, and iii) bolted top and seat angle connections, under typical gravity loading to assess the development of large vertical deformations.

KEYWORDS: Connection, Rotation, Demands, Analysis, Framework

1. INTRODUCTION

The integrity of steel framing systems subjected to unanticipated loadings is an important issue applicable to many hazards, and worthy of considerable investigation. In order to determine the ability of current gravity framing systems to withstand unanticipated loading, deformation and strength demands on connections must be assessed, and the ability of connections to withstand those demands evaluated.

Characterizing progressive collapse of steel structures is an ongoing research topic being investigated worldwide. Foley et al. (2006) performed nonlinear dynamic analyses on steel grillage models with elastic perfectly plastic connection models, in MASTAN. Khandelwal et al. (2008) perfomed dynamic analyses on systems with moment resisting connections subjected to column loss by modeling panel zone stiffness and strength using LS-DYNA. Izzuddin et al. (2007) considers a simplified framework for progressive collapse assessment of multi-story buildings and proposes a quantifiable measure of robustness. Izzuddin et al. (2007) also develops a finite element model of a longitudinal floor system beam, and represents the slab as a "concrete flange" connected via rigid links.

In conventional analysis of steel moment framing and gravity systems, moment resisting and simple shear connections are most often modeled as “perfectly fixed” or “perfectly flexible”, respectively; mathematical idealizations established to simplify analysis procedures. However, the partial rigidity of connections can be considered to more accurately assess the capacity of steel gravity framing systems, particularly when subjected to extreme loading conditions where considerable deformations are expected. The combined capacity of many partially rigid connections can contribute significantly to the overall collapse resistance of a system.

Evaluations of overall system response with partially rigid connections typically involve complex finite element analyses employing commercially liscensed softwares. Though these analyses provide useful and accurate results, implementation is often prohibitively timely and involved. More streamlined analyses in which connection and system configurations can be varied rapidly are necessary to study the impact of various parameters on system performance, and develop recommendations for steel gravity framing systems to ensure structural integrity in the event of column damage.

Component models for welded single plate shear connections and bolted angle connections have been adopted from Rex and Easterling (2003), and Shen and Astaneh-Asl (2000), respectively. Simplified component models are assembled into fiber models representing individual connections, capable of capturing the interaction between tensile and flexural behaviors.

In order to assess the overall behavior of floor framing systems under column loss scenarios, a floor framing system analysis framework developed in Matlab is implemented. Fiber models representing specific connections are integrated into the analysis framework which considers nonlinear geometry and material properties. Capable of tracking the behavior of connections and framing members independently, the analysis framework can determine displacement and rotation demands on each connection in an arbitrarily sized and configured system. Furthermore, the effects of various connection parameters on system behavior will be explored in an effort to offer preliminary recommendations for enhancing the multihazard robustness of steel gravity framing systems.

2. COMPONENT MODELS

In order to determine the moment-rotation and force-displacement response of a single plate shear or bolted angle connection, each connection is divided into several fibers. Each fiber physically represents an individual component in the connection and is governed by a component model. For single plate shear connections, an individual component is characterized by a single bolt and a tributary width of plate. Alternatively, for bolted angle connections, a single component is characterized by two bolts and a tributary width of angle. Visual representation of web angle components and fibers can be seen in Figures 1 and 2.

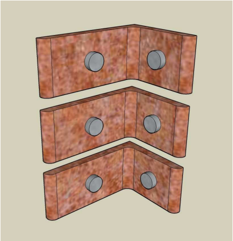

Figure 1: Component Model

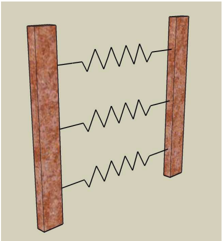

Figure 2: Fiber Model

2.1. *Welded Single Plate Shear Connections*

The component model for single plates shear connections used in this study is adapted from Rex and Easterling (2003) who employed a nonlinear expression originally developed by Richard and Elsalti (1991):

$$R(\Delta) = \frac{\Delta K_1}{[1+(\frac{\Delta K_1}{R_o})^n]^{\frac{1}{n}}} + \Delta K_p \tag{1}$$

where

$$\begin{array}{lcl} n & = & \frac{-ln(2)}{ln(\frac{R_1}{R_o} - \frac{K_p}{K-K_p})} = \mathit{Curvature\ Parameter} \\ \Delta & = & \mathit{Deformation} \\ K & = & \mathit{Initial\ (Elastic)\ Stiffness} \\ K_p & = & \mathit{Plastic\ Stiffness} \\ K_1 & = & K - K_p \\ R_o & = & \mathit{Reference\ Load} \quad . \end{array}$$

By substituting normalized values determined from nonlinear regression of experimental data and nonlinear finite element results, the expression was modified by Rex and Easterling to represent the behavior of a single bolt bearing against a single plate such that

$$\frac{R}{R_n} = \frac{1.74\bar{\Delta}}{(1+\bar{\Delta}^{0.5})^2} - 0.009\bar{\Delta} \tag{2}$$

where

$$\begin{array}{lcl} R & = & \mathit{Plate\ Load} \\ R_n & = & \mathit{Nominal\ Strength} = L_e t_p F_u \leq 2.4 d_b t_p F_u \\ \bar{\Delta} & = & \mathit{Normalized\ Deformation} = \Delta\beta\frac{K_i}{R_n} \\ \Delta & = & \mathit{Hole\ Elongation} \\ \beta & = & \mathit{Correction\ Factor} = 1.0\ \mathit{(for\ typ.\ steels)} \\ K_i & = & \mathit{Initial\ Stiffness} = \frac{1}{\frac{1}{K_{br}}+\frac{1}{K_b}+\frac{1}{K_b}} \end{array}$$

and where K_i is defined as a function of

$$\begin{array}{lcl} K_{br} & = & \mathit{Bearing\ Stiffness} = 120 F_y t_p d_b^{(\frac{4}{5})} \\ K_b & = & \mathit{Bending\ Stiffness} = 32 E t_p (\frac{L_e}{d_b} - \frac{1}{2})^3 \\ K_v & = & \mathit{Shearing\ Stiffness} = 6.67 G t_p (\frac{L_e}{d_b} - \frac{1}{2}) \ . \end{array}$$

Equation (2) is employed as the force-deformation relationship representing the behavior of individual fibers for single plate shear connections in this study.

2.2. *Bolted Angle Connections*

A piecewise linear component model developed by Shen and Astaneh-Asl (2000) to represent the force-displacement behavior of a characteristic width of angle displaced in tension is adapted to the present problem. The model is initially dependent on the stiffness of the angle toe in flexure. After the onset of yielding, two distinct behavior patterns dominate. In the first pattern, plastic zones are located mainly in the outstanding legs, and in the second, plastic deformation is shared by the angle fillet and bolts. An expression for the ultimate deformation of the component is also established.

2.3. ***Modifications to Component Models***

2.3.1. *Softening*

The component model for bolted angle connections developed by Shen and Astaneh-Asl (2000) has been modified to allow additional softening at large rotations. This allows the model to more closely resemble experimental data obtained by Azizinamini and Radziminski (1989).

2.3.2. *Unload*

As a single plate shear or bolted angle connection transitions from flexure- to tension-dominated behavior, the neutral axis of the connection must migrate to maintain equilibrium. As the neutral axis travels, certain fibers will necessarily unload while others continue loading. Consequently, it is necessary to establish unload criteria for each component model.

The aforementioned component models were modified such that any component is allowed to unload at its own initial stiffness until a zero-force value is obtained. The component then exhibits negligible stiffness in the opposite direction until sufficient deformation is sustained to activate the initial stiffness. This behavior represents the effect of hole elongation and is somewhat analogous to the cyclic behavior of a tension-only bracing system.

2.3.3. *Bolt Shear*

In a physical bolted connection, if the deformation of a particular bolt reaches a critical value, the bolt will shear, and the connection will lose capacity. Components in a fiber model must be allowed to exhibit similar behavior. Therefore, if a bolt deformation limit is exceeded, a fiber is allowed to lose capacity at its own individual initial stiffness until it contributes no additional capacity. After reaching a zero-capacity, the "sheared" component is permanently deactivated.

3. CONNECTION MODEL

Understanding individual connection response to applied displacements is integral to understanding system response at large deformations. Under gravity loading, simple shear connections predominately experience an applied shear force and any applied moment is relatively negligible because of inherently small connection flexural stiffness. However, when a column is compromised, the span lengths are essentially doubled. Vertical loading at a large eccentricity initiates (nearly) pure rotation on the connection, applying primarily horizontal deformations to each connection component.

However, as a connection continues to rotate, translational deformations become significant. Intuitively, this can be inferred from the decomposition of vertical gravity forces into perpendicular components (causing pure rotation) and parallel components (causing pure tension) on the beam in the deformed configuration. Figure 3 schematically shows horizontal framing in both undeformed and deformed configurations with respect to the applied loading, and Figure 4 decomposes the vertical loading into rotational and translational components for each fiber.

Ideally during analysis, both rotational and translational displacements should be applied simultaneously. However, this is very difficult to implement computationally. Rather, incremental displacements applied during each step in analysis are further discretized into an arbitrary number of substeps and equilibrium is

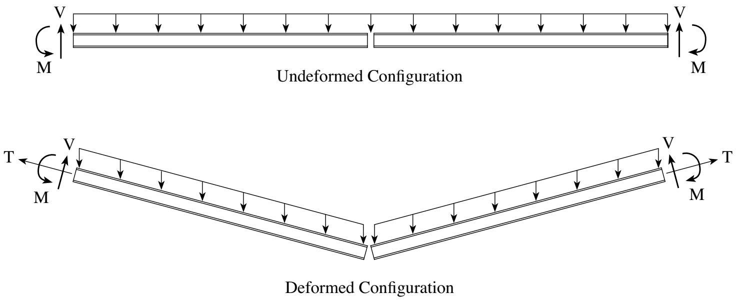

Figure 3: Undeformed and Deformed Beam Configurations

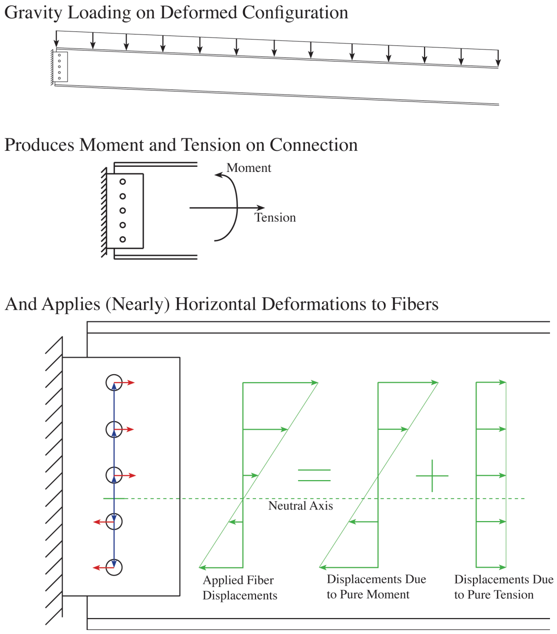

Figure 4: Decomposition of Gravity Loading on Fibers

enforced at each, simulating simultaneous application.

In addition to characterizing single plate shear and bolted angle fibers, a fiber characterizing the concrete floor slab, present in most steel framing gravity systems, is implemented. The fiber has an assumed characteristic width and effective length, and is placed at the center of gravity of concrete. The Modified Hognestad concrete compressive stress-strain relationship (MacGregor and Wight) is assumed and the strength of the concrete fiber in tension is negligible.

4. ANALYSIS FRAMEWORK

A comprehensive analysis framework is constructed using Matlab in order to incorporate partially rigid connection fiber models into an overall finite element analysis construct. A typical analysis consists of four bays comprised of two longitudinal girders, an arbitrary number of intermediate floor beams, and fixed boundary conditions around the perimeter. A typical analysis configuration is shown in Figure 5.

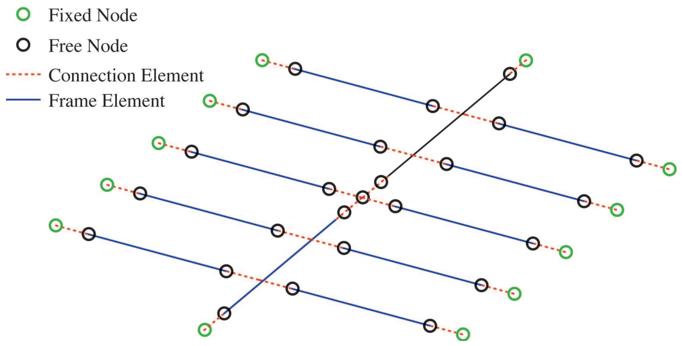

Figure 5: Typical Floor System Configuration

Each horizontal framing member is meshed into two "connection elements" of length $\frac{L}{n}$, and a frame member of length $\frac{n-2}{n}L$; where L is the length of the overall frame member and n is a relatively large number (≥ 25). "Connection elements" are necessary to isolate connection rotation and translation from the total rotation and translation of the overall frame member.

The analysis framework supports nonlinear frame geometric properties and nonlinear connection reactions. Within the framework, an overall system is iterated to equilibrium using a displacement-controlled *Newton-Raphson* solver. Moreover, an additional displacement-controlled *Newton-Raphson* solver enforces equilibrium on each connection for every step and substep during analysis.

4.1. *Parametric Study*

The advantages of the analysis framework become apparent when conducting multiple analyses. Connection and system parameters can be interchanged quickly and easily, facilitating a large parametric study. Results from the parametric study will be used to gain valuable insight into the dependency of system response on connection behavior, and the dependency of connection demands on system parameters. In addition, results will be used to develop a loading protocol for use in future hybrid testing of connection subassemblages.

5. VALIDATION

5.1. *Component Models*

Some experimental data for the moment-rotation response of single plate shear connections exists to validate and calibrate experimental models. Liu and Astaneh (1999) conducted cyclic testing of single plate shear connections with and without a composite concrete floor slab at the University of Calfornia, Berkeley. In addition, Crocker and Chambers (2004) tested 3-, 4-, and 6-bolt single plate shear connections with relatively stiff shear plates. Figures 6 and 7 compare the moment-rotation response of fiber models to bare steel test data provided by Liu and Astaneh and Crocker and Chambers, respectively.

Fiber models constructed for all connections compare fairly well with available experimental data. Bolt shear occurs somewhat prematurely compared to tests performed by Liu and Astaneh; likely because the fiber models use a bolt deformation limit developed by Crocker and Chambers in which relatively thick shear plates were used, more exclusively isolating deformation to the bolts. Liu and Astaneh used significantly thinner plates for the same bolt diameters, adding a degree of flexibility to the connections.

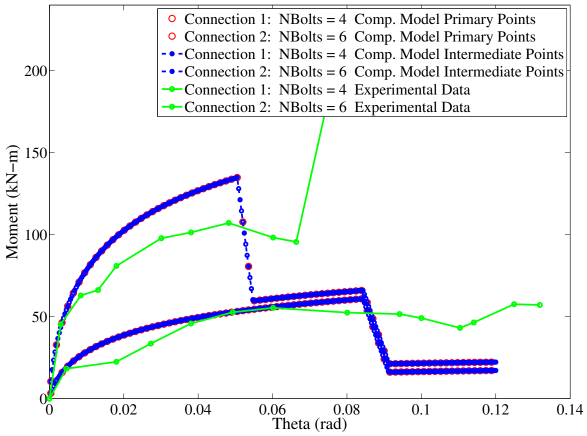

Figure 6: Comparison of Fiber Model to Liu and Astaneh (1999)

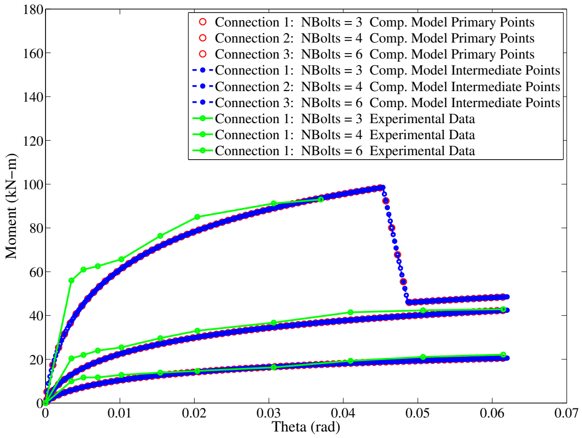

Figure 7: Comparison of Fiber Model to Crocker and Chambers (2004)

Fiber models are also compared to connections with the presence of a concrete floor slab. Figure 8 compares the moment-rotation response of fiber models with a slab to experimental data published by Liu and Astaneh-Asl (1999).

5.2. *Analysis Framework*

Validation of the analysis framework was conducted at an intermediate step in development. Analysis of a specific configuration in the framework was compared to identical systems constructed in SAP and MSC Marc, with fully fixed connections throughout. Comparison confirmed nearly identical results, as expected.

Validation of the analysis framework with partially rigid connections has yet to be performed. Several configurations will be constructed in the framework and OpenSees, respectively, for comparison.

6. SUMMARY

An analysis framework supporting nonlinear frame properties and fiber models characterizing partially rigid connections has been developed in Matlab for analysis of steel gravity framing systems subjected to loading consistent with column loss. Fiber model representations of connections have been validated against available experimental data. In an analysis framework, connection and frame properties, as well as spans and configurations can be cycled rapidly; and the behavior of connections and framing members tracked independently. The effects of various connection parameters on system behavior can be studied by performing numerous analyses in a rapid parametric study.

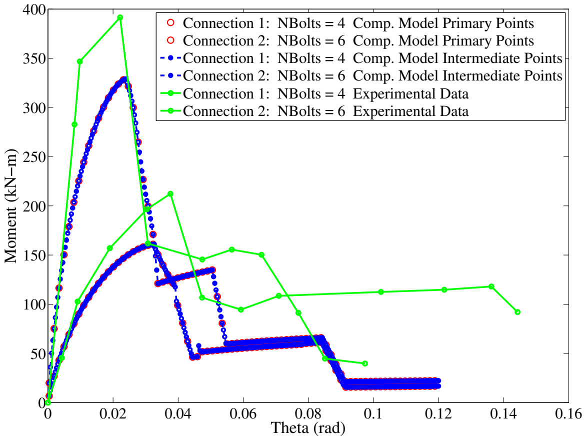

Figure 8: Comparison of Fiber Model (with slab) to Liu and Astaneh (1999)

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