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Detailed 3D Modeling and Simulation of Bolted Connections

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ABSTRACT: This study presents a detailed three-dimensional (3D) approach for the analysis of bolted connections. Nonlinear displacement-based finite element (FE) method with 3D continuum elements is used. Contact between all the components in the connection is explicitly recognized. Models with different parameters drawn from a previous experimental study are generated in order evaluate the effectiveness of this approach. FE analysis input parameters, such as friction, bolt pretension, and material parameters are selected from typical reported design values. Good prediction is shown by the 3D detailed models when compared with the experimental results. The proposed 3D modeling approach is general and allows for accurate modeling different types of connections. Different numerical investigations are presented.

Keywords: Bolted Connection; partially restrained; semi-rigid; pretension; bolt slip; three-dimensional; non-linear; finite element.

ÖZET: Bu çalışma bulonlu çelik kolon kiriş bağlantılarinin űç boyutlu bir modeleme yöntemini sunmaktadir. Lineer olmayan deplasman bazli űç boyutlu sonlu elemanlar kullanılmaktadir. Tűm bağlantı parçaları arasındaki temaslar tanımlanmıştır. Modeleme yöntemi deneysel verilerle karşılaştırılmakta. Sűrtűnme katsayısı, bulon öngerilmesi ile malzeme değişkenleri olağan tasarım değerlerinden seçilmekte. Model deneylerle karşilastırıldığında iyi neticeler alındıgı gözlenmektedir. Önerilen modelleme yöntemi genel olup değisik bulonlu bağlantılarına uygulanılabilir. Ayrıca bu model kullanılarak değişik nűmerik calışmalar da sunulmaktadır

Introduction

The failure of welded connections of steel frame structures in the Northridge and Kobe earthquakes has raised new interest in bolted connections. Such connections have the advantage of easy installation without skilled labor and consistent mechanical properties unlike welded connections. Studies conducted to investigate the seismic worthiness of various bolted connection configurations found desirable stiffness and ductility properties. (Astaneh-Asl 1998, Kasai 1998)

The effect of bolted partially-restrained (PR) connections on the behavior of steel frames and their potential economical benefits is also well recognized (Weynand 1998). However, many structural analysis and design approaches still consider connections as either fixed or pinned. This assumption is mainly due to convenience and the lack of common analysis and design approaches that address bolted connections. Despite many full-scale experimental studies that have been conducted to date, there is still a need for a better understanding of the mechanisms that effect the nonlinear behavior of bolted connections (Chen 1996).

Moment rotation functions can be useful for designers in practice. These usually include small number of parameters taken into account from limited test data. The lack of a large and parameterized experimental database does not allow for generating standardized functions. Thus, there is a need to be able to analytically generate a reliable moment-rotation response of bolted connections that can be used in analysis and design.

Detailed Modeling Approach

Displacement-based 3D finite element models are used to predict the behavior of bolted connections. The geometry and mesh is established through a parametric mesh generator program. The ABAQUS FE (1993) code is used to carry out the 3D finite element analysis. Different classes of structural shapes can be generated using the programming language of TrueGrid (1997). A program library of parametric structural shapes and bolts is generated. These programs are executed within TrueGrid to generate the specific components of the connection configuration and assemble these components to form the connection model. This versatility of this approach allows for a wide range of parametric studies to be conducted without time-consuming preprocessing.

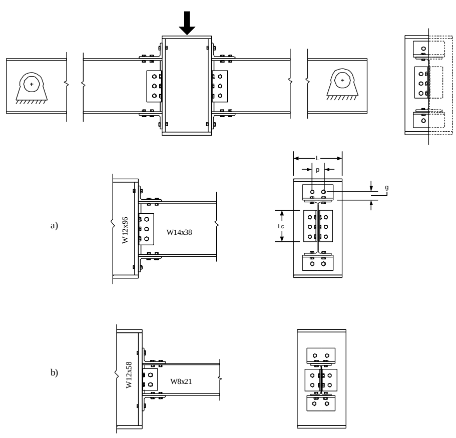

Figure 1. Schematic representation of the connection test set-up used by Azizinamini et. al. (1985,1989).

The experimental work and test results of Azizinamini (1982,1985,1989) are modeled in order to critically examine the ability of the proposed 3D models to capture the overall experimental response of the connections. The test setup of Azizinamini is illustrated in Fig. 1. It consists of a pair of beams connected to a central stub column via top and seat angles bolted to the flanges of the beam and column. The double web angles are bolted both to the beam web and column flanges. High strength bolts and nuts, ASTM A325 heavy hex, are used with A325 hardened washers. The ends of the beams are pinned while an actuator loads the central stub column. The parametric investigation demonstrates the capability of the finite element models to efficiently generate connection responses beyond experimental data

The connection model is discretized using C3D8I eight-node brick elements with full integration and incompatible modes. It has been seen that such elements give better results for bending-dominated problems with relatively small thickness (Bursi 1998). C3D6 six-node wedge elements are also used to model the core of the bolts. A representative 3D FE model of a top and bottom seat angle connection with double web angles is shown in Fig.2. Half of the connection is modeled by using symmetry about the plane of the web. Only the flange of the column is modeled assuming that it is a sufficiently rigid part due to the stiffeners used of the column. The hex bolt heads are modeled as cylinders, taking in to account the washers by averaging the diameter.

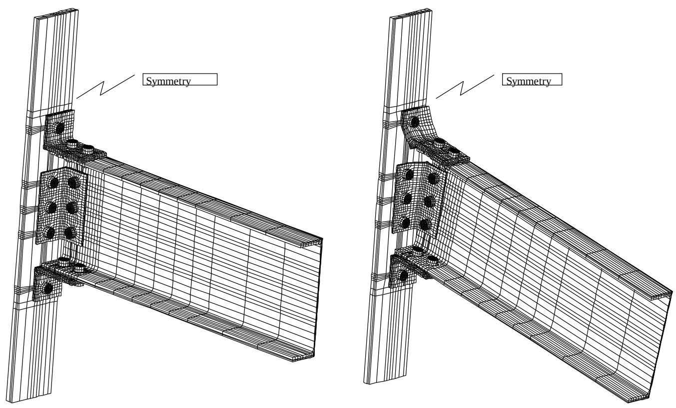

Figure 2. 3D finite element connection model, deformed and undeformed shape.

Contact between all parts is explicitly modeled. The general contact formulation used in ABAQUS involves a "master-slave" type algorithm (ABAQUS 1993). This formulation recognizes whether the surfaces are in contact, interpenetrate, or slip and imposes constraints on the nodes of the slave surface such that they do not penetrate the master surface.

The pretension of the bolts and friction are critical parameters in bolted connections. The forces are transferred through friction due to clamping between the members caused by the pretensioning of the bolts. A methodology to model the pretension of the bolts is described by Çıtıpıtıoğlu (2002). Approximate common design values are used for modeling the pretension: 133 kN (30 kips) for the 19.1 mm (3/4 in) and 178 kN (40 kips) for the 22.3 mm (7/8 in) diameter A325 bolts. The friction coefficient of 0.33 for Class A surfaces is used (AISC 1995).

The experimental data describing the uniaxial stress-strain response is taken from coupon tests performed by Azizinamini (1982) and is used to determine the material properties for the FE model. A trilinear stress-strain curve is used in the FE models having a modulus of elasticity of 207,218 MPa (30,000 ksi), 276.9 MPa (40.1 ksi) yield stress, and a Poisson's ratio of 0.3. The bolts are modeled as elastic components in order to ease convergence problems that are occasionally encountered due to severe localized plastic strain at the corners of the bolt heads. Little or no effect on the overall connection response is observed when compared to results from the models with elastic-plastic bolt material.

The end cross-section of the beam is constrained as a "rigid section". An external displacement is applied. This loading is consistent with what is transmitted to the end of the beam through the pins as shown in Fig. 1. The force-displacement response of the connection is converted to the moment-rotation response using simple relations: M = F.L, ø = arctan (Δ/L); where M, is the moment, ø is the rotation of the connection, F is the force, L is the length of the beam, and Δ is the tip displacement of the beam.

Finite Element Results

Typical comparisons of the connection response from experimental data to the FE simulation are shown in Fig. 4. Having such a tool several studies is possible:

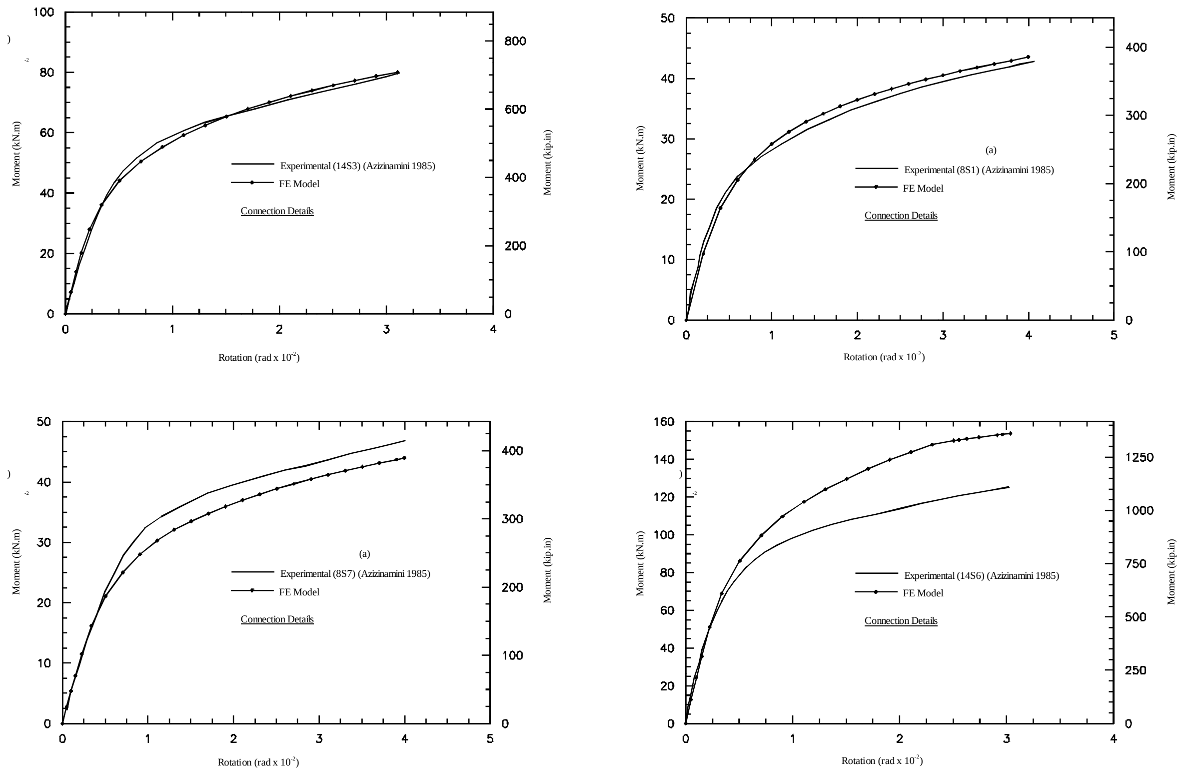

Figure 3. Typical comparisons of connection response from experimental data and FE model.

Effect of Friction and Bolt Pretension

The effect of friction and bolt pretension on the response of the connection is studied. In Fig 4a the change in response of a connection is shown with the friction coefficient varied from 0.25 to 0.5 while keeping the bolt pretension value fixed at 133kN (30 kips).

The pretension value of the bolts has a similar effect, as friction, on the response of the connections. Figure 4b. shows the result of a parametric study where the pretension value of the bolts vary from 111 kN (25 kips) to 178 kN (40 kips). The friction coefficient is kept fixed at 0.33. Upto 20 percent change in the connection response is observed in these studies.

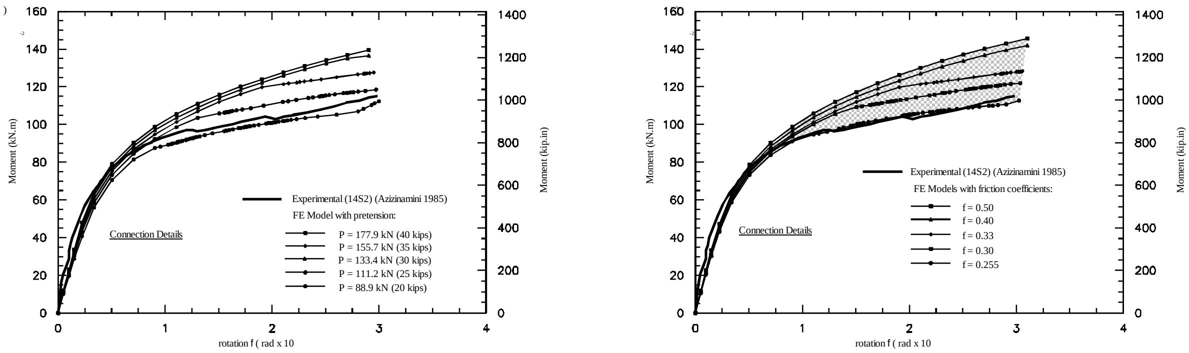

Figure 4. Connection response with varying pretension values(a); and varying friction coefficients (b).

Pull Test Approximation

The ability of a simple pull test to approximate the response of a top and bottom seat angle connection is investigated (Fig. 5). Two cases are modeled using angle thicknesses of 0.953 cm. (3/8 in) and 1.27 cm. (1/2 in.). The force-displacement response of the pull tests are converted to approximate the moment-rotation response of the connection using the relations: $M = F.d$; $ø = \arctan(\Delta/d)$; where M is the moment, ø is the rotation of the connection, F is the force, d is the depth of the beam, and Δ is the displacement of the plate representing the beam flange. It can be seen that the pull test model is successful in predicting the initial stiffness of the connection up to a certain point where it begins to diverge from the full connection response. The initial stiffness of the connection is shown to be governed by the geometry of the top seat angle

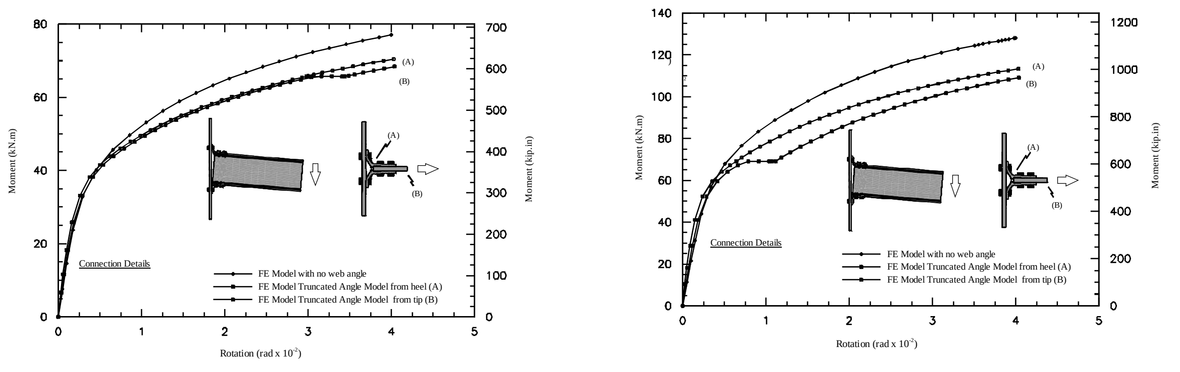

Figure 5.Comparison of full connection to pull test approximation for angle thin (a) and thick (b) angle.

The displacements in the pull tests are monitored at both the heel of the angle (A - Figs. 5a & 5b) and the tip of the plate pulled (B – Figs. 5a & 5b). The two curves (A and B) demonstrate the effect of the slip between the angle and the plate. Comparing the two cases, similar to the previous parametric friction study, the slip is more pronounced when the connecting members are thicker (stiffer). The pull tests consistently show a softer response compared to the full model response, especially for higher rotation values.

Connection Component Interaction

In the design of top and bottom seat angle connections with web angles, it is generally assumed that the top and bottom angles work in resisting the moment forces, while the web angles (shear tabs) simply carry the shear load. The interaction of the various components for the connection response is investigated. Three connection configurations are compared: a top and bottom seat angle connection, a web angle connection and a full top and bottom seat angle connection with web angles. When the response of decoupled component responses are added directly and compared to the full connection, it can be seen that the behavior differs (Fig. 6). This indeed indicates an interaction between the components when assembled together in the full connection, which results in an increased response.

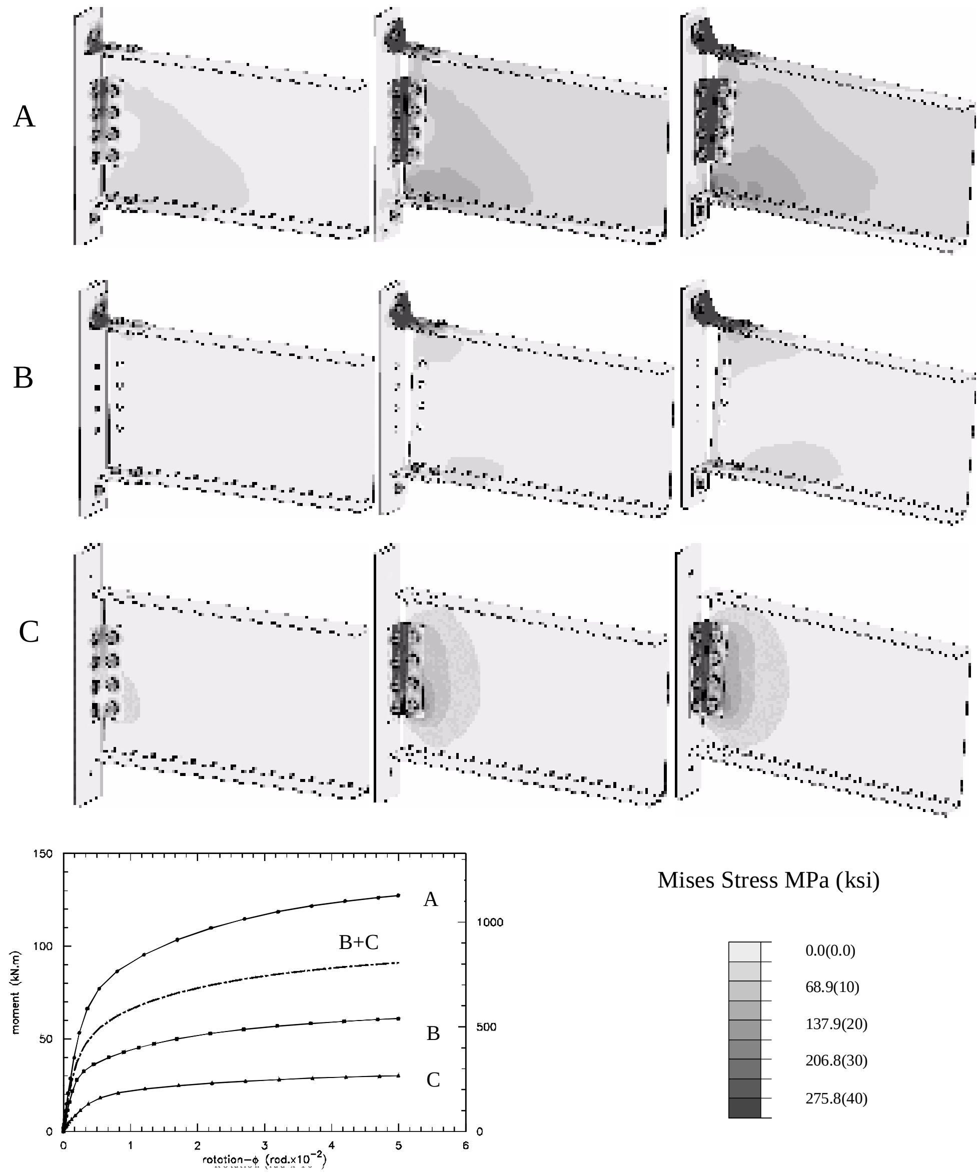

Figure 6. Comparison of the behavior and mechanism of a full connection to decoupled component connections.

Conclusion

A methodology for modeling the moment-rotation response of bolted connections is described. Detailed 3D finite element models are generated using a parametric library of structural steel shapes. The methodology is efficiently applied for several connections. Contact conditions including slip between all the connection components are explicitly recognized. A nonlinear incremental plasticity model is used for the steel material. The effectiveness of this modeling approach is extensively demonstrated by comparison with a series of experimental results from a previous study. The inclusion of friction and slip in the model along with the simplicity of changing mesh geometry makes it a general approach for modeling a wide variety of bolted connections.

Having established confidence in the proposed modeling approach by verification with previous experimental work, parametric studies are used to investigate the effect of friction and pretension of the bolts on the connection response. A pronounced effect of friction and slip between the connection components, especially with thicker (stiffer) seat angles, is demonstrated. The approximation of the overall moment-rotation response for top and bottom seat angle connections using pull tests is also investigated. Finally the interaction of individual connection component mechanisms is displayed.

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