Effect of bolt modeling [i.e. modelling] on initial stiffness of cleated connections

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Effect of Bolt Modeling on Initial Stiffness of Cleated Connections

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Summary

Finite element models of semirigid cleated connections are used to evaluate the contribution of the bolts to the connection initial stiffness. Two dimensional shell and one dimensional bar elements are used to construct the models and the three dimensional behavior of the connection is thereby approximated. Bolt to plate contact regions and bolt heads and nuts are included in the finite element models using local modeling details called *bolt models*. Results are compared with test results and analytical formulae in the literature.

1. Connection Models

Three types of cleated connections are investigated using finite element models, six *top and seat angle with double web angle* connections, and as their subassemblies with same geometrical and material properties, five *top and seat angle* and three *double web angle* connections. The dimensions of the modeled *top and seat with double web angle connections* are taken same as in the static test series performed by Azizinamini *et al.* (1989), Table 1.

1.1. Modeling Assumptions

Material is assumed to behave linear elastic, isotropic and homogeneous in the load range of interest. To enable direct comparison with the results of analytical formulae, Azizinamini *et al.* (1989) and Kishi *et al.* (1990), the contributions of the column flanges and web to the flexibility of the connection are neglected. Thus, the column flange is replaced with a *rigid boundary*. At the initial stage of the loading the applied forces on the connection are small compared to the applied bolt pretension force. Therefore, the effect of pretension in the vicinity of bolts is modeled using deformational constraints. Due to the symmetry of the above mentioned connection types only the half of the connections are modeled.

Table 1. Properties and Test Results of Azizinamini et al. (1985) Test Series.

(a) Top and Seat with Double Web Angle Connections

Test ID Number	**Bolt Diameter** ∅ *(mm.)*	**Average Nut thickness** H_a *(mm.)*	**Web angle thickness** t_{ww} *(mm.)*	**Top & seat thickness** t_{ts} *(mm.)*	**Test Results** $k_{i,exp}$ *[kN-m/rad]*
14S1	19.1	15.3	6.4	9.5	22035
14S2	19.1	15.3	6.4	12.7	33335
14S4	19.1	15.3	9.5	9.5	25075
14S5	22.2	17.9	6.4	9.5	27911
14S6	22.2	17.9	6.4	12.7	32318 *
14S8	22.2	17.9	6.4	15.9	65427

(b) Top & Seat Angle Connections

Model ID	**Bolt Diameter** ∅ [mm]	**Average Nut thickness** H_a [mm]	**Top & seat thickness** t_{ts} [mm]
TS1	19.1	15.3	9.5
TS2	19.1	15.3	12.7
TS5	22.2	17.9	9.5
TS6	22.2	17.9	12.7
TS8	22.2	17.9	15.9

(c) Double Web Angle Connections

Model ID	**Bolt Diameter** ∅ [mm]	**Average Nut thickness** H_a [mm]	**Web angle thickness** t_{ww} [mm]
DW1	19.1	15.3	6.4
DW4	19.1	15.3	9.5
DW5	22.2	17.9	6.4

* *Same configuration under the name 14S9 has* S_i*=29154 kN-m/rad, Azizinamini et al. (1985).*

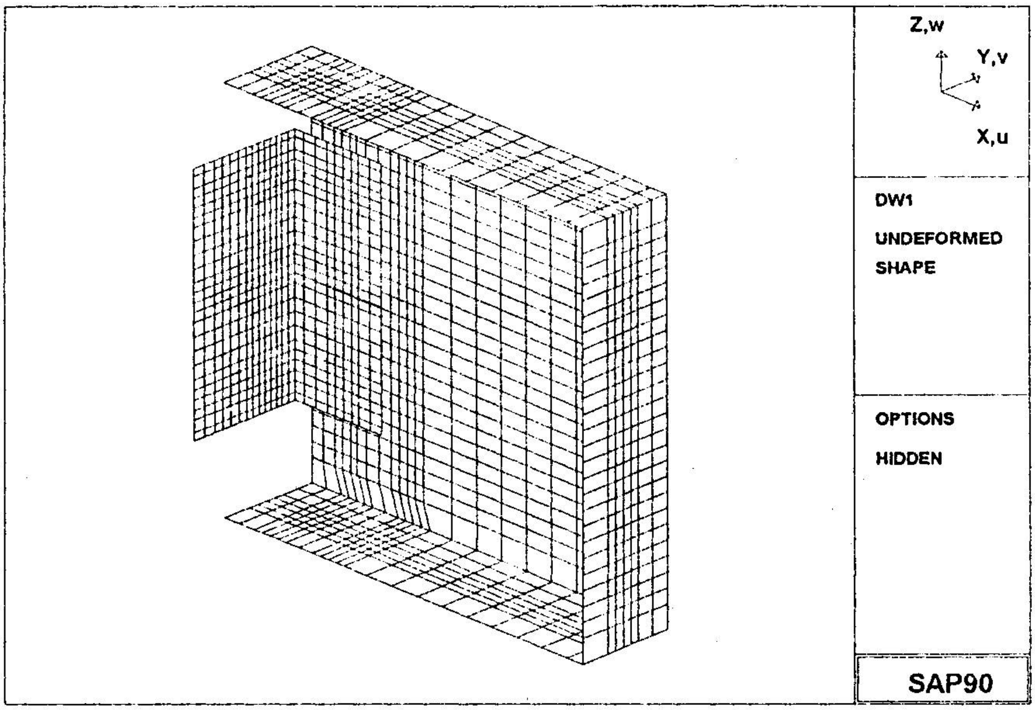

Figure 1. Sample Finite Element Mesh for Double Web Angle Connections.

1.2. The Model

Connection models include a portion of the beam of a length equal to the depth of the profile, and the other components such as the cleats, bolts and nuts. Moreover, a rigid plate is attached to the end of the beam portion. Loads are applied onto this plate to avoid stress concentrations on the finite elements forming the beam profile and connection components, Figure 1.

The portions of the cleats and connectors in contact with the column flanges are forming the *column boundary*. The portions of plates or cleats in the connection in contact with the beam are forming the *plate boundary*.

1.2.1. Discretization

Beam profile and cleats are discretized using four noded quadrilateral shell elements with plate bending and stretch capabilities. The shell element layers are located at the midheight of the web and flanges of the I-profile, and the legs of the cleats. The shell element layers are assigned the corresponding thickness of the modeled regions. Bolt shanks are formed using bar elements and the ends of the bars are connected to the shell element layers. The ends of the bar elements are released with respect to torsion.

Bolt heads and nuts are represented in the finite element models in two different ways. Either these portions are assumed to impose certain constraints on the deformation of the shell layers, and this is modeled with restraints and/or constraints, or an additional patch of shell elements is placed onto the shell layers that are already formed for cleat legs or I-profile plates. These sets of restraints and/or constraints, or element patches are named as *bolt models*. The *bolt models* are applied at each bolt location in the model.

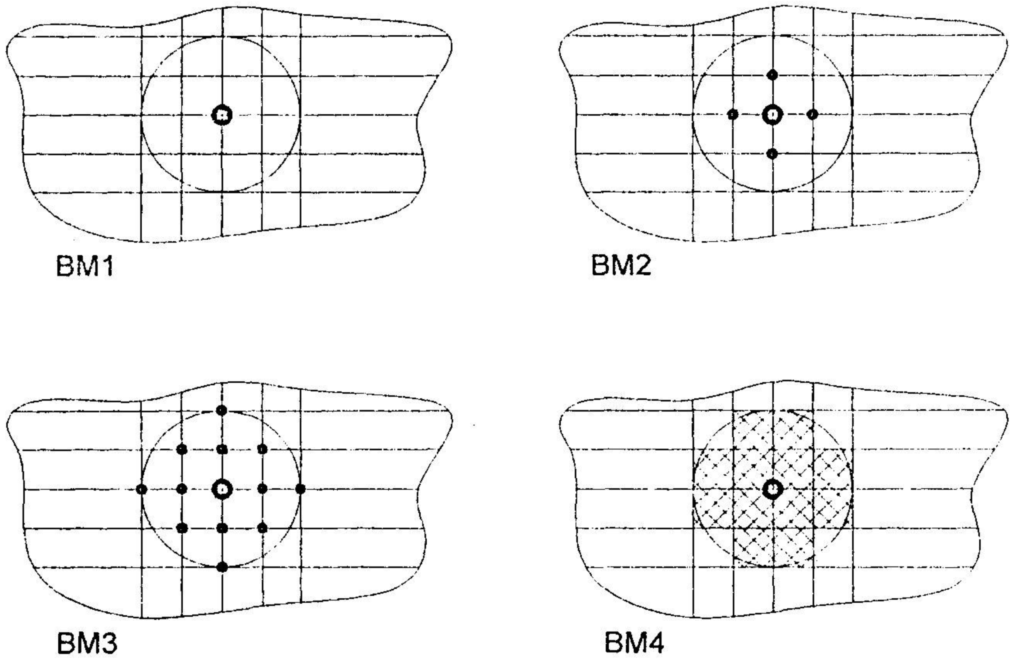

Figure 2. Bolt Models.

1.2.2. Bolt Models

There are four *bolt models*; BM1, BM2, BM3 and BM4. In Figure 2., the implications of the applied *bolt models* are indicated on corresponding sketches. Intersection points of the lines are the active nodes of the model. A bolt element end node is identified with a thick ring. The true diameter of the bolt head or nut is shown with a thin circle, and it is taken equal to the distance across flats of the bolt head. A heavy dot in these sketches stands for a constraint to be applied to the marked node. This constraint forces the marked node to translate equally with a node on another mesh layer that is adjacent to this node. For example, this case arises for the bolts connecting the cleats to the beam profile flanges. In this and similar regions, two mesh layers are adjacent to each other with same mesh density and they are formed so that the projection of their nodes onto the horizontal plane coincide.

The first three *bolt models* aim to define the radius of influence of the bolt heads and nuts. This is achieved by increasing the radius of the restrained and constrained region around the bolt element end nodes. Bolt model BM1 is a configuration where no stiffnening effect due to the presence of bolt head and nuts nor due to pretension is modeled. BM2 has the restraint and constraint sets applied at the first neighbourhood of the bolt end nodes only. Therefore, only the nodes on the shell layers that are belonging to the bolt shank are influenced. This corresponds to a better representation of the bolt shank. BM3 applies the maximum number of restraints, that is to all of the nodes inside the bolt head diameter. This results in the full restraint of the nodes in this region and models the presence of pretensioning.

Bolt model BM4 is using an additional shell element patch to model the stiffness of the bolt head and nut.

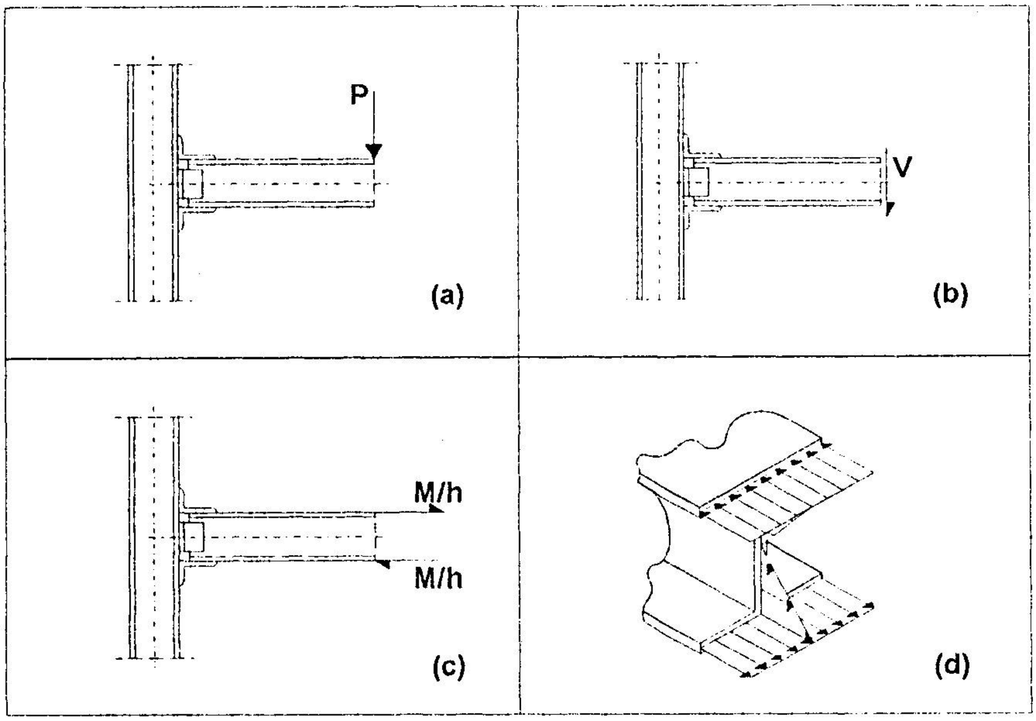

Figure 3. Possible Loading Cases.

1.3. Loading

As a part of a frame, connections may be subjected to direct shear, eccentric shear, which produces a combination of direct shear and a twisting moment, direct tension, moment and combinations of these cases. Possible loading cases of finite element models are shown in Figure 3. Without the load application plate all loading cases except (d) cause stress concentrations and improper stress boundary conditions for the beam free end. Loading case (d) represents linear stress distribution throughout the cross section implying pure bending of the member, Krishnamurthy *et al.*, 1976, and Sherbourne *et al.*, 1994.

The connection specimens subject to testing are often statically determinate subassemblies, tested under point loading. With the dimension information of the subassembly provided, the moment, shear and axial force values at the location of the load application plate can be calculated and applied as statically equivalent concentrated loads acting on the load application plate. Thus a combined loading made of shear and moment that is representative of the loading during testing is obtained, case (b) and (c).

1.4. Computational Methodology

The finite element program, SAP90 is verified for convergence performance by solving benchmark plate bending and stretch problems with different mesh densities. The results indicate that the calculated nodal displacement values are uniformly converging to the exact solutions of the posed benchmark problems. With increase in the number of nodes and elements used in the model the deformations increase and approach the exact value asymptotically. Therefore, convergence of the finite element analysis results is provided with the refinement of the finite element model mesh.

A connection is first analyzed with the only constraint applied by the bolts connected at the *column* and *plate boundaries*. This analysis results in incompatibility at all the contact regions. As an example, cleats on the *column boundary* penetrate into the column flanges. *Rigid boundary* to element mesh contact locations are defined applying a sequence of analysis and control of boundary violation. Incompatibilities at the boundaries are detected and the locations of these penetrations are listed and sorted regarding the magnitude of deformation. These penetrations are prevented applying restraints to the relevant deformational degrees of freedom of the nodes. For restraining purposes, groups of nodes of maximum violation are selected so that the first and last selected nodes do not significantly differ in the magnitude of their deformation. A maximum number of 20 nodes is used in restraining. Analysis and control are continued until no violation in the contact boundaries are left. Five to seven iterations are needed to achieve convergence of boundary contact conditions.

For the initial stiffness calculation the output of only two nodes is used. These are the nodes that are at the beam end and at the mid height of the flanges. Moreover, the difference between the Y- and Z- displacements, Δv and Δw, are not included in the calculation of rotation, Krishnamurthy *et al.*, (1976). Thus, the angle θ is obtained by dividing the difference of the X-displacements, Δu, of the flange centroids by the distance between these points. Inverse of this value multiplied by the applied moment, M_t, yields the required initial stiffness. Errors in prediction of initial stiffness results are evaluated taking the test results and analytical models reported in references as basis.

2. Finite Element and Analytical Modeling Results of Cleated Connections

For the modeling study of cleated connections, a well documented and frequently referred test series is selected as reference (Azizinamini *et al.*, 1989). Specimens of the test series consist of two beam sections attached to a stub column that is positioned between these two beams and connected to them by *top and seat angle with double web angle connections*. The specimens are simply supported at the beam free ends and loaded through the column by an applied point load to a plate attached to the top of the column. The described configuration is statically determinate. Therefore, simple statics may be used to determine the moment and shear composition at any distance away from the column face to determine the actual loading composition that was present during early stages of the test.

2.1. Finite Element Model Results

Figure 4. summarizes the results for the modeled six *top and seat angle with double web angle connections*. In the test series results of two specimens with identical properties, numbered as 14S6 and 14S9, have been reported, only the test and finite element modeling results of specimen 14S6 are reported herein.

For the investigation of *double web angle* (DW), and *top and seat angle connection* (TS) behavior, the specimens of the above mentioned test series are separated into connections having the same cleats and gages used in the test series with only top and seat angles or web angles.

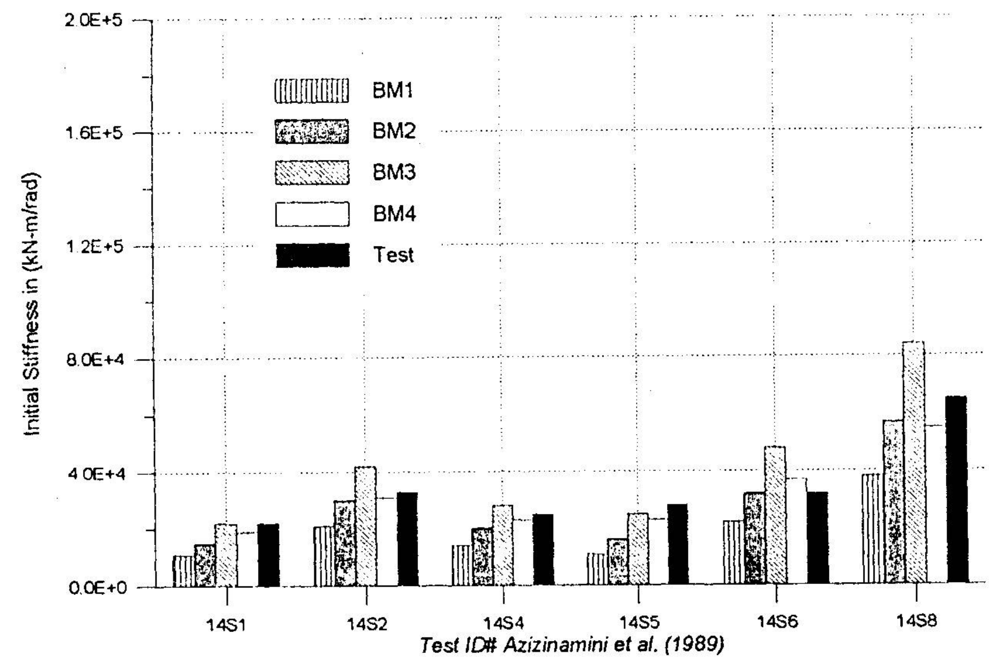

Figure 4. Finite Element and Test Results for Top and Seat with Double Web Angle Connections.

2.2. Analytical Model Results

Analytical models for the initial stiffness of cleated connections have been presented by Kishi *et al.* (1990 and 1993), assuming that the center of rotation is located at the heel of the seat angle bearing to the column. This model implies the superposition of the models separately derived for *top and seat angle connections*, and *double web angle connections.*

In the study by Azizinamini *et al.*, the tension flange and web angles are modeled as assemblies of "beam" segments and their individual contribution to the total stiffness of the connection are calculated. This model is calibrated with the deformation pattern observed during the tests. Two sets of expressions for the initial stiffness of *top and seat angle with double web angle connections* are presented with and without shear deformations of the "beam" segments.

The initial stiffness values calculated or reproduced using the above stated references are given in the Figure 5-7. These figures include a comparison made using the finite element model results of BM4. The test results for *top and seat with double web angle connections* are also included in Figure 5.

2.3. Comparison of Finite Element and Analytical Model Results

The analytical models use a simplified distribution of applied loads and assume a single contact condition that is assumed to be valid for all possible gage and thickness configurations. Furthermore, superposition principle is used to form the more complex connection geometries using the subconnection deformations and stiffnesses. Therefore, where one of the above given simplifying assumptions are not applicable, the results tend to deviate from the test results. This

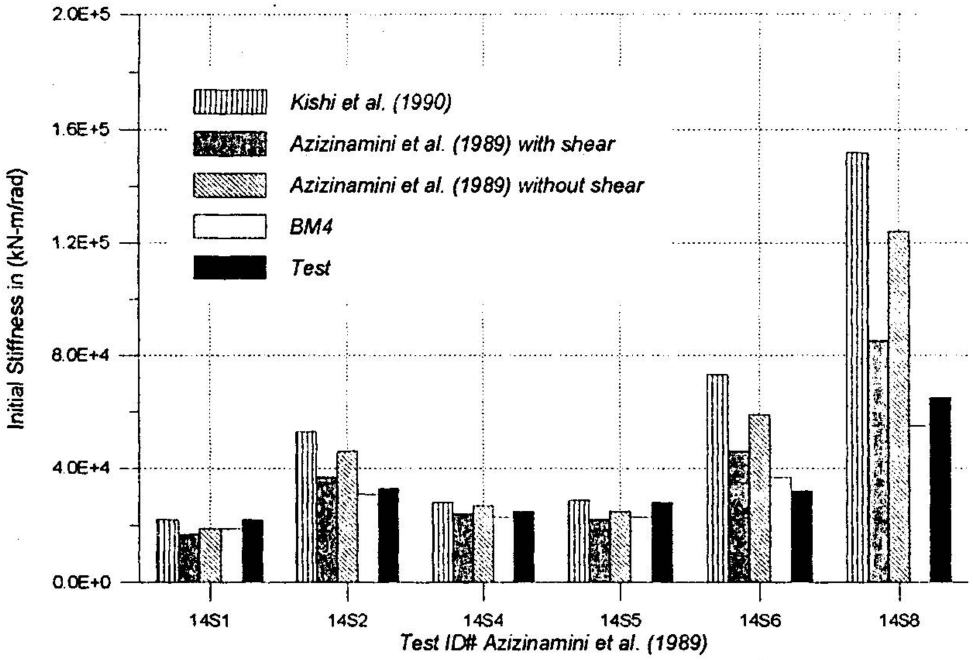

Figure 5. Initial Stiffness Results for Top and Seat with Double Web Angle Connections.

is particulary obvious for *top and seat with double web angle connection* configurations with thick top and seat angles where the analytical formulae over estimate the connection stiffness.

With reference to the test results, the finite element models have produced satisfactory results. Finite element results are obtained using a standardized procedure to provide repeatability and are, therefore, applicable to all connection geometries. In finite element modeling, the loading is made to resemble to the actual loading applied during testing and the contact conditions are defined using iterative schemes.

3. Conclusions

Connections modeled in this study cover a wide range of cleated semirigid connection types. Modeled portion of the connection includes a portion of the connected beam that is of one beam depth length and all of the connectors and secondary elements. Column flange and web are not modeled. This allowed direct comparison of finite element modeling performance with analytical models that exclude the column flange and web stiffness, and tests that are performed using stiff columns. Moreover, the behavior of the connectors and secondary elements can be observed more closely this way.The finite element models are constructed and analyzed using a unified modeling approach. Two and one dimensional finite elements are used to approximate the three dimensional behavior of the connections. Thereby, saving on computation time is achieved. The assumptions made in the modeling of connections are supported by the observed behavior reported by the researchers working in this field. Initial attempts on modeling indicated that there are three major sources of stiffness contribution other than the stiffness of secondary elements in the connection. These are local effects such as, stiffening effect of bolt heads and nuts, friction between the connected components and pretensioning of bolts. These conclusions resulted in the development of *bolt models*.

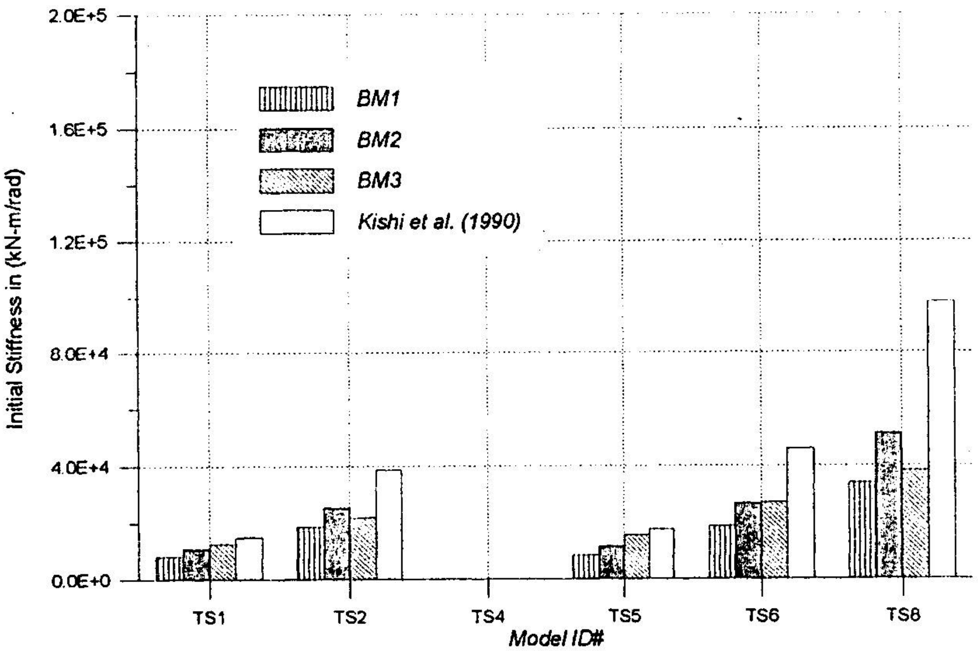

Figure 6. Initial Stiffness Results for Top and Seat Angle Connections.

The *bolt models* (BM) comprise of restraint and constraint patterns that model the influence of the pretension and account for the presence of the bolt heads and nuts. With the *bolt models*, it is possible to represent, non-pretensioned bolted connections accounting for the presence of bolt heads and nuts (BM4), and different levels of pretension (BM2 and BM3). Also a lower bound for the connection stiffness is established (BM1) with no allowance made for the presence of bolt heads and nuts nor fot pretensioning forces.

For cleated connections the mechanism of deformation is related to the deformation of the cleats rather than the local deformations of the secondary connection elements. The presence of bolt heads and nuts are equally important as the application of the pretensioning forces. The element patches used in BM4 produce the same effect as the sets of restraints, except in cases of thick angles where BM4 performs better. This suggests that there is a relation between the bolt head thickness and the thickness of the connected angle. For thin angles the bolts heads fully dominate the behavior and this is evident of the closeness of the results of BM3 and BM4. However, if the angle thickness increases, the bolt heads cannot force the angles to remain in contact as in the other case. This is seen in over estimation of the BM3 and is supported by the proper prediction of BM4.

Finite element modeling results indicate the importance of correct modeling of the stiffness sources and contact conditions. This can be seen in the difference of the results among *bolt models*. Analytical models presented in the literature involve assumptions that are not justified by the observed behavior of the connections. This results in erroneous initial stiffness prediction. The assumptions that are of major importance are those related to contact boundary conditions. Therefore, any other assumption violating these conditions is also invalid.

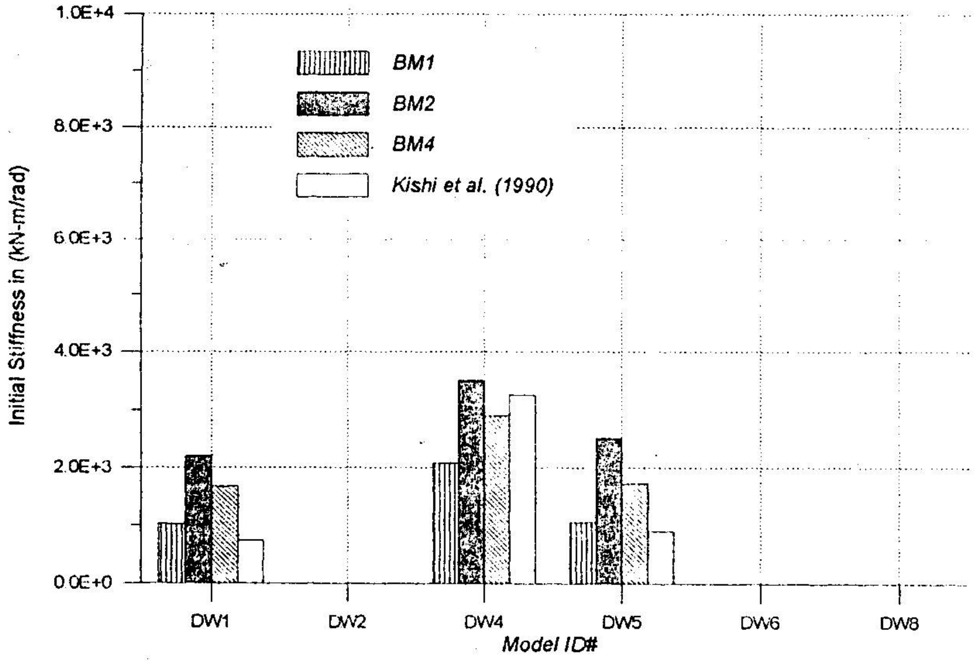

Figure 7. Initial Stiffness Results for Double Web Angle Connections.

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