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Assessment of the semi-rigid double-angle steel connections and parametric analyses on their initial stiffness using FEM

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Abstract. In this paper, the semi-rigid connections, such as Double-angle Web (DW) connections, which are welded to the beam web and bolted to the column flange, are investigated. This study tries to establish the effect of clearance setback between beam end and column flange and/or web. When the beam rotates, it is desirable to avoid bottom flange of the beam bearing against the column as this can induce large forces on the connection. The usual way of achieving this is to ensure that the connection extends at least a few millimeters beyond the end of beam. For this purpose, several connections are designed and considered based on two different shear capacities for the beam. For each connection, two different bolt gage distances and three values for clearance setback are analyzed. Analyses are performed to establish the moment-rotation relationship for this type of connection and the stress distribution of each specimen is observed. In this study, connections are subject to shear loads. Material and geometric non-linearities, as well as contact and friction, have also been implemented in the model. The model is validated through comparison on experimental data found in literature.

1. Introduction

Each connection type has been classified in a disparate way based on its resistance to applied loads on the structural steel frame. There are two main categories for connection types in the Load and Resistance Factor Design (LRFD) Specification [1]. The FR (Fully Restrained) type connections have the same characteristics as of Type 1 connections of the Allowable Stress Design (ASD) Specification [2], while the PR (Partially Restrained) type connections are similar to Type 2 and Type 3 connections of the ASD Specification [2]. Despite the various connection types, most connections have been idealized as either "fixed" or "pinned" in analytical, as well as practical, design problems for the purpose of simplicity. Double-angle web connections are usually considered as simple shear connections. This means that double-angle connections are modeled as pins and are assumed to transfer only shear to the supporting structural elements without any bending moment. However, it has been found that they may transfer some moments to the supporting members, up to approximately 20 percent of those of fully fixed connections, and can fairly get called PR type connections. Most previous studies have been conducted to clarify the moment-rotation curves in the connections with an

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applied moment resulting from application of transverse forces on the beams. As the flexural rigidity of each connection plays an important role in behavior of the entire structural steel frame, therefore, most of the research on various connection types has been focused on investigation of the moment-rotation relationships. For this purpose, many experimental tests have been conducted to obtain moment-rotation curves. Considering the moment-rotation curves obtained from experimental tests, simplified analytical models have also been suggested to predict the behavior of entire angle connection by the application of curve fitting techniques. In addition to this, the Finite Element Method (FEM) can also be an effective technique to investigate the behavior of different types of connections. Another numerical technique deeply used at the global level for this kind of structures is the Fiber Element Method as clearly highlighted by the research done in past. Nascimbene et al. [3] presented a modeling approach for concentrically braced frames to be used in multi-story buildings, including two inelastic force-based beam-column elements, each of which having five integration points and a discretized fiber section. They set the limits of slenderness and the width-to-thickness ratio in which inelastic beam-column brace model can predict the hysteretic responses of a brace member with adequate accuracy.

To provide realistic connection behavior, the previous works have revealed that basic parameters such as "thickness of the connection angles", "length of the angle, gage distances", "type and size of fasteners", "friction coefficient", "bolt preload force", "depth and length of the connected beam", "supporting member", and "material properties" are the most effective parameters that affect the behavior of connection. Mofid et al. [4-5], using plate theory, presented analytical methods for semi-rigid and semi-hinged steel connections. They concluded that the initial stiffness of connection is mostly affected by the plate thickness, beam depth, plate width and height, and the distance between the centerline of bolts. Citipitioglu et al. [6] also concluded that by increasing the friction coefficient, the bending capacity of connection increases and the moment-rotation curves get shifted upward in the nonlinear part. This shows that friction and slip have more effects on the response of connections with higher moments and stiffer connecting elements. They also concluded that the effect of pre-tensioning is relatively important and can vary the ultimate moment-rotation by 25 percent. Charis et al. [7] suggested that the required correction in bolt length is heavily dependent on both the applied preload level and the developed failure mechanism. It is noteworthy that in addition to the aforementioned parameters, the distance between beam end and column's flange and/or web, namely the clearance setback, has also a significant effect on the behavior of such connections, which has not yet been considered. Therefore, in this study, the presented FE model has firstly been fairly verified through previously conducted tests. Then, the effect of this clearance setback between beam and column on the moment-rotation behavior of such connections has reasonably been investigated.

In this research, to obtain the load-displacement curves, moment-rotation curves, and stress distributions, a nonlinear finite element program SUT_DAM, developed at the Sharif University of Technology, has been utilized.

As experimental study of steel connections is very expensive and time-consuming, Finite Element (FE) and approximate simplified analytical models can be reliable representatives of the experimental tests. These models can simply be constructed to predict the behavior of such connections. The objectives of this investigation are as follows:

- To study the behavior of semi-rigid connections, specifically double-angle connections, which are vastly used in the construction of steel structures;
- To study the load-displacement and moment-rotation curves of such connections and verify existing models, accordingly;
- To model double-angle connections, that are welded to the beam web and bolted to the column flange, to establish effects of the gap distance between beam end and column on the behavior of such connections.

2. Literature review

Because the two main characteristics of simple shear connections are strength and ductility, most of the previous works on such connections have been carried out to show the shear-rotation and/or the moment-rotation relationship. Even-though these connections are idealized as pins during design procedures for simplification, the actual behavior of them has shown to have more complex characteristics [8]. Several experimental tests have verified these existing complexities. Unfortunately, very little or even no information is available on the behavior of these kinds of connections subjected to variable gap distances. Therefore, the effect of this clearance setback parameter on the behavior of such connections is extensively investigated in this study.

Hong et al. [9] conducted tests on double-angle beam-to-column connections, which were welded to the beam web and bolted to the column flange, to establish the effects of bolt gage distances and the angle thicknesses. Later, Yang et al. [10] investigated the moment-rotation relationship of those connections based on experimental tests and a three-dimensional nonlinear Finite Element Analysis (FEA). Eventually, they proposed two simplified analytical models for predicting the initial stiffness and ultimate connection moment [11]. Charis et al. [7] worked on development and implementation of a FE model for simple T-stub steel connections. They concluded that the impact of bolt length is of primary importance in these connections. Maxwell L. Chisala [12] proposed a three-parameter exponential model to describe the non-linear moment-rotation relationship of flexible beam-to-column connections.

From the observations and experimental test data, it has been shown that the tested double-angle web connections can develop up to 20 percent of the beam moment and transfer approximately 10 percent of the currently neglected moment to the supporting elements such as columns and girders [13]. Therefore, well-defined analytical models are necessary for prediction of the actual behavior of double-angle connections under various loading conditions. Simple models have usually been developed by introducing curve-fitting techniques of experimental test data, whereas simple analytical procedures have been developed since no test data were available for certain connection types. There are several available experimental test results for double-angle web connections [14,15]. Using this data, various analytical models have been developed. Kishi and Chen [16] proposed a power model which was composed of three parameters representing initial elastic stiffness, ultimate moment capacity of the connections, and shape parameter, respectively. Beland et al. [17] developed a test program to characterize the inelastic behavior of individual angles subjected to monotonic and cyclic demands. They also examined the cyclic inelastic response of beam-to-column joints. A simple analytical procedure was used for the initial elastic stiffness and ultimate moment capacity of the connections. Furthermore, Mohamadi and Mofid [18-21] developed an analytical approach for end-plate steel connections.

Brunesi et al. [22] developed refined non-linear solid FEM models, accounting for the influence of friction, pretension of bolts, and prying and relative slippage of components through highly non-linear contact elements to reproduce the cyclic-reversal test protocol. They later proposed an alternative and conservative method for quick rotational stiffness estimates of PR bolted beam-to-column connections by performing a series of detailed parametric solid FEs [23]. Moreover, Lin et al. [24] presented design equations to estimate the stiffness of beam-to-column connections using finite element simulation. The FEM is an alternative method to analyze the behavior of angle connections under various loading conditions. Bursi and Leonelli [25], and also Mofid and Mohammadi [26] used finite element approach towards this problem. Danesh et al. [27] investigated the effect of shear force on the initial stiffness of top and seat angle connections with double web angles, using FEA.

3. Semi-rigid connections

Double-angle web connection is one of the most common semi-rigid connections. By definition, a semi-rigid connection, which is categorized as a simple connection, is too flexible to qualify as rigid, but is not a pin. These connections are defined as those connections that transmit end shear only and have negligible resistance to rotation and therefore do not transfer significant moments at the ultimate limit state. To comply with the design assumptions, simple connections must allow adequate end rotation of the beam as it takes up its simply-supported deflected profile and practical lack of fit. At the same time, this rotation must not impair the shear and tying capacities of connection. When the beam rotates, it is desirable to avoid the bottom flange of the beam bearing against the column as this can induce large forces on the connection. The usual way of achieving this is to ensure that the connection extends at least a few millimeters beyond the end of beam. Though angles can be connected to the beam web and column flange both with bolt and weld, the angles bolted to the column and welded to the beam are more preferable. The reason is that they have the facility to provide for minor site adjustments, including tightening of the field bolts, when using bolts to connect angle to column, and ensure the welding precision when making welds in an equipped shop. By the way, moment-rotation curves and the impact of gap distance between beam end and column flange on the behavior of semi-rigid connections and their rotational capacity is studied here to refine the lack of information about it.

3.1. Finite element model and element types

FEM is a numerical technique for finding approximate solutions to boundary value problems for partially differential equations. It uses subdivision of a whole problem domain into simpler parts, called finite elements, and variational methods from the calculus of variations to solve the problem by minimizing an associated error function. Riahi and Curran [28] compared the formulation of finite element Cosserat smeared approach with the combined finite element-explicit interface element approach, when both applied to the analysis of layered continua.

The actual connection behavior is difficult to formulate in a simple mathematical expression, due to the geometrical and material nonlinearities of angle specimens, as well as the complex phenomena occurring between each connection elements such as contact, friction, stick, and slip conditions [25]. It is also difficult to model stress concentrations, prying forces,

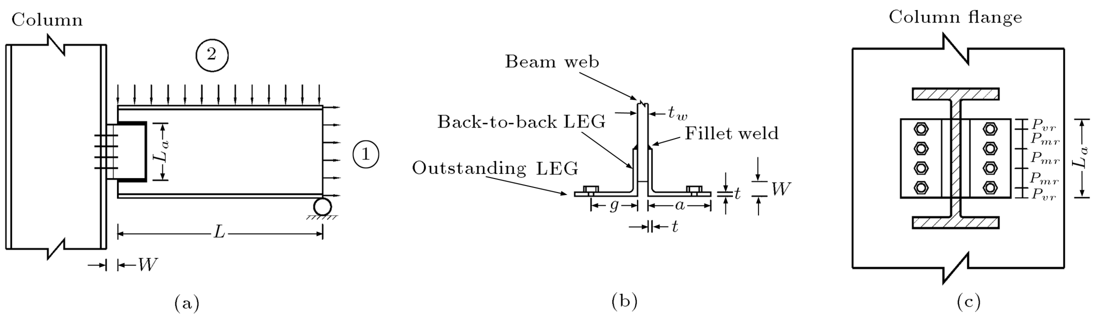

Figure 1. Semi-rigid connection: (a) Loading condition, (b) and (c) geometric configurations.

and bolt forces with simple expressions. Even-though it is not easy to model these complex phenomena, the actual behavior of angle connections including them can be analyzed through using existing finite element programs. However, much attention should be given to the selection of appropriate element types, boundary conditions, and contact coefficients when using the FEM [25]. In general, higher order elements offer better accuracy per degree of freedom; however, they require laborious mesh implementations. As there is a sophisticated interaction between bolted connection components, a 3D nonlinear FE connection model for the semi-rigid connections of the type, shown in Figure 1, is generated. The technique of FEA lies in the development of a suitable mesh arrangement. The mesh of connection model does characterize all the major components such as: angle, beam, bolt, and weld. However, instead of the column, a rigid target surface is modeled to play the role of column in the connection. Since the mesh configuration must balance the need for a fine mesh to give an accurate stress distribution and reasonable analysis time, the optimal solution uses a fine mesh in areas of high stress and a coarser mesh in the remaining areas. Also appropriate contact interactions are considered between the column web angles, beam web angles, and especially bolt and column flange surface. Besides, bolt pretension load equal to 50% of the minimum tensile strength of bolt, based on test data is considered for the all bolts of the model. The model includes 12436 elements, 162285 nodes, and 152201 degrees of freedom. Iteration's algorithm is modified Newton-Raphson.

3.2. Material properties

For a good correlation with experimental results, the full actual stress-strain relationship of materials must be adopted in the large displacement and large strain numerical simulation. In the current study, the mechanical properties of beam, endplate, and bolt materials are taken from the numerical studies of Mohamadi and Mofid [21,26] as follow.

The four typical regions of the stress-strain curve of a low carbon structural steel, such as S235, are very clear: linear elastic region, yield plateau, strain hardening region, and strain softening. Therefore, the stress-strain relationship for all elements of the connection, except bolts, is taken as elastic-strain hardening for A36 or S235 which is modeled by means of a quadrilinear relationship. Yield stress and ultimate stress of these components models are assumed as the respective values of 235 MPa and 350 MPa. The strains at plastic point and ultimate point are defined as $11e_y$ and $120e_y$, respectively. The tangential stiffness beyond yield point and plastic point is defined as 0.2% and 0.5% of the initial modulus of elasticity, respectively. For the grade 8.8 high strength bolts material, a trilinear relationship with $e_u = 8e_y$, $f_y = 640$ MPa, and $f_u = 800$ MPa is considered [26]. For both models a rate- and temperature-independent plasticity law with hardening was used for the connection components. The value of Young's modulus and the Poisson's ratio of steel are determined equal to 206 GPa and 0.3, respectively. The Von-Misses yield criterion is adopted. Effective material properties of connection assemblage are shown in Table 1.

3.3. Boundary conditions and loading

Based on experiences carried out through other researchers and also to save time numerical precision, due to symmetry, only half of the connection is replicated. This model does include half of the equivalent beam web, web angle, fillet weld, and bolts which are shown in Figure 2. This figure demonstrates the appropriate boundary conditions applied to FE models. All nodes of the column angle, facing web, and bolt shank end have been constrained to the rigid target base. To enforce the concept of connection symmetry, in the middle section of beam parallel to 1-2 plane, all nodes are also restrained in the direction of 3, as shown in Figure 2. The analysis is performed with two incremental loading steps for all models. During the first step, a prescribed preload force is applied to the pretension nodes of a pre-defined section of bolt shank. In the second step, a monotonically distributed load is introduced on connection by employing downward vertical load on the upper surface of the equivalent beam web, which induces bending moments on the connection. Load increments in both steps are in-

Table 1. Material properties of connection elements used in analysis [26].

Connection components	ASTM designation	Yield stress (MPa)	Ultimate strength (MPa)	Ultimate elongation (%)	Modulus of elasticity (MPa)	Poission's ratio
Angle, beam	Steel grade	235	350	20	200000	0.3
Bolt	Bolt grade	640	800	8	200000	0.3

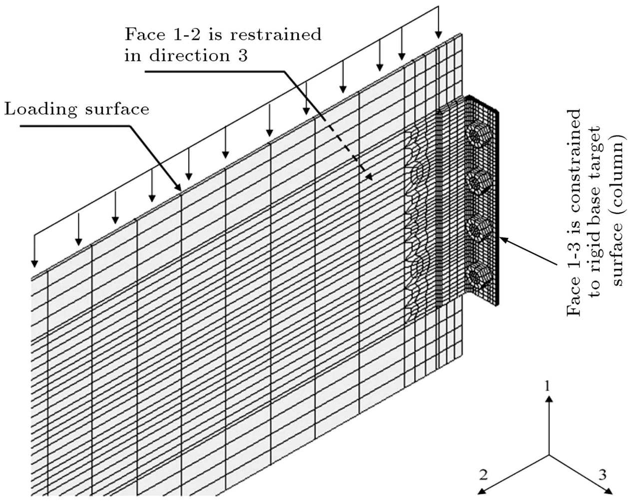

Figure 2. Boundary conditions of FE model.

creased manually to reach a reasonable computational efficiency.

3.4. Contact modeling

For accurate simulation of the connection behavior, small sliding contact pair definition is applied between two interacting surfaces, one of which is defined as target surface and the other as contact surface.

Friction is a resistive force that prevents two surfaces from sliding freely against each other. The coefficient of friction (μ) is a number that is the ratio of resistive force of friction divided by the normal or perpendicular force pushing the objects together. The two main frictions used are static friction and kinetic friction. The coefficient of static friction for steel is around 0.15-0.6 and the coefficient of kinetic friction is around 0.09-0.6. In this study, friction coefficient between steel contact surfaces is considered equal to 0.6 for all specimens as used in Charis et al. [7]. Therefore, A Coulomb coefficient of 0.6 is defined for sliding resistance in all contact surfaces.

3.5. Shear locking

In FEA, locking is one of the major numerical problems, because it may cause spurious solutions in certain situations. This phenomenon may be in three types, including (1) Volumetric locking, (2) Membrane locking, and (3) Shear locking. Locking means the effect of a reduced rate of convergence in dependence of a critical parameter, such as slenderness of the plate in case of transverse shear locking. Because of locking, wrong displacements, and false stresses, spurious natural frequencies are encountered [29,30]. In SUT_DAM FE program utilized in this research, element technologies, like Reduced Integration and Extra Shape Function, have been adopted to overcome Shear locking. For Membrane Locking, the remedy is judicious selection of appropriate elements, i.e. linear elements instead of curved elements in deep arches and shells.

4. Verification

4.1. The physical problem

In order to validate the performance of the model, the experimental data found in literature has been used. Firstly, T-stub connections are investigated here. This type of connection is composed of two T-shape sections connected by means of one or more pairs of bolts, as illustrated in Figure 3.

The simple connection is not directly used in frame design. Charis et al. [7] and Bursi and Jaspart [31] described a series of physical T-stub tests which they executed. Two specimen configurations are available reflecting different geometric and strength parameters. Specimen, named T1, features a relatively weak flange plate and specimen named T2, features a relatively strong flange plate. They are parts of IPE and IPB beam sections, respectively. Geometrical properties for both configurations are shown in Figure 4. Material properties and results with preloaded

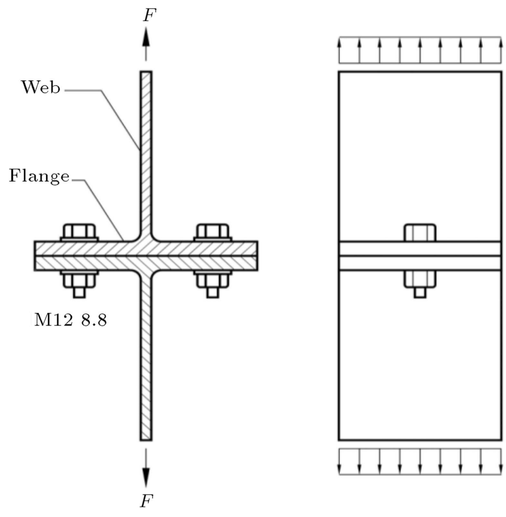

Figure 3. T-stub geometry.

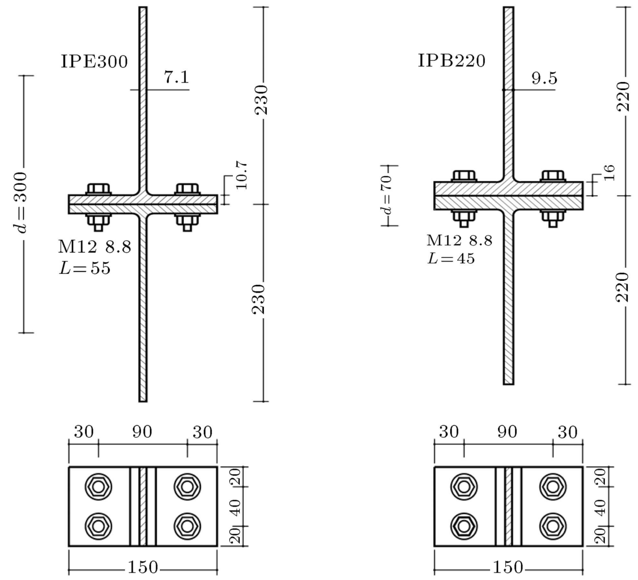

Figure 4. Geometrical properties of T1 (left) and T2 (right) specimens (all dimensions are in millimeter) [7].

and non-preloaded bolts are also available. In these cases, pre-tensioned high-strength bolts were used and a preload force equal to 60.7 kN was applied to each bolt. Additionally, a 0.25 friction coefficient was used in contact surfaces.

Secondly, a double-angle connection, which is welded to the beam web and bolted to the column flange, is validated under tension loads. This connection is assumed to be one of the most popular semi-rigid connections. This connection was tested by Hong et al. [9] under tension loads (case 1 in Figure 1(a)) and lateral loads (case 2 in Figure 1(a)), and the comparison between tests and numerical results was presented. To establish the effects of angle thickness and bolt gage distance, a 3/8″ thick plate was connected to an equivalent W14×90 column with a double-angle connection. L5×3×1/4, L5×3×1/2, and L5×3×3/8 angle sections were used for the double-angle connection. Each outstanding leg of the angle was connected to the column with four 3/4″ diameter A325-N bolts. Each back-to-back leg of this angle was connected to the 3/8″ thick plate with 3/16″ E70XX fillet welds. A 0.6 friction coefficient was used in contact surfaces. The results of these tests are used for verification of the 3D finite element model analysis. For this purpose, several factors are compared with each other, such as the load-displacement relationship and the initial stiffness.

4.2. Model geometry

Figures 1 and 4 depict the geometrical configurations of double-angle web and T-stub connections, respectively. A substantial reduction of the model size can be achieved by exploiting the symmetries of problem. For instance, in T-stub connections and double-angle web connections under tension loads, two planes of symmetry can be defined. Thus, only one quarter of the whole connection needs to be modeled. On the other hand, double-angle web connections under shear loads have only one plane of symmetry and one half of the connection should be modeled. The reduced model needs to be complemented by suitable boundary conditions in the symmetry planes, constraining normal to plane displacements and in-plane rotations.

4.3. T-stub specimens of T1 and T2

In Figure 5, the comparison between experimental and numerical load-displacement curves of specimens T1 and T2 is depicted where F is the total applied force,

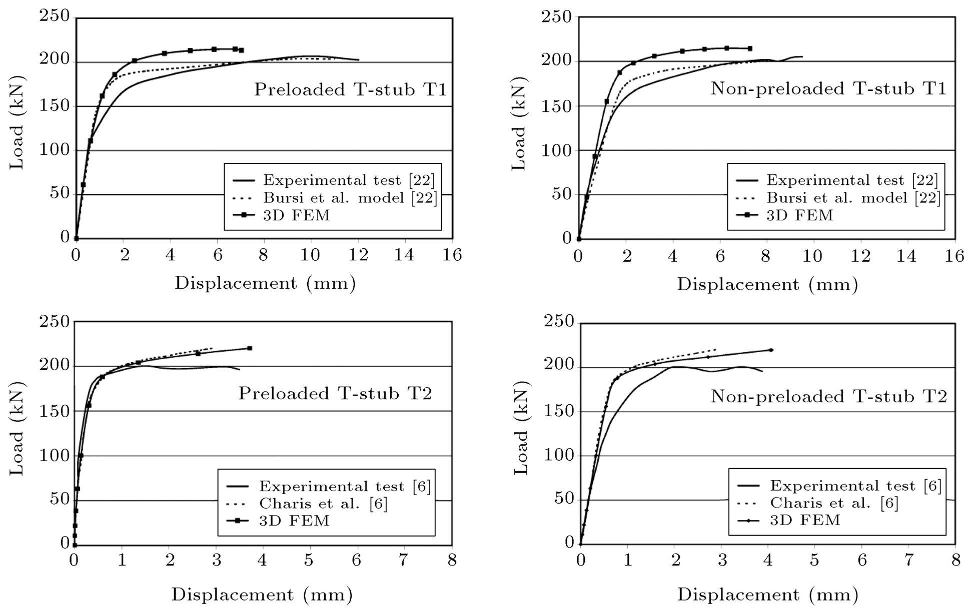

Figure 5. Load-displacement curves of preloaded T1 and T2 models (left) and non-preloaded T1 and T2 models (right).

and d is the corresponding displacement, as shown in Figure 3. The curve match is satisfactory for the elastic region and initial part of the plastic region. The initial stiffness is predicted accurately.

The 3D finite element models and deformed shapes at the failure stages in preloaded cases are shown in Figure 6, both for the T1 and T2 specimens.

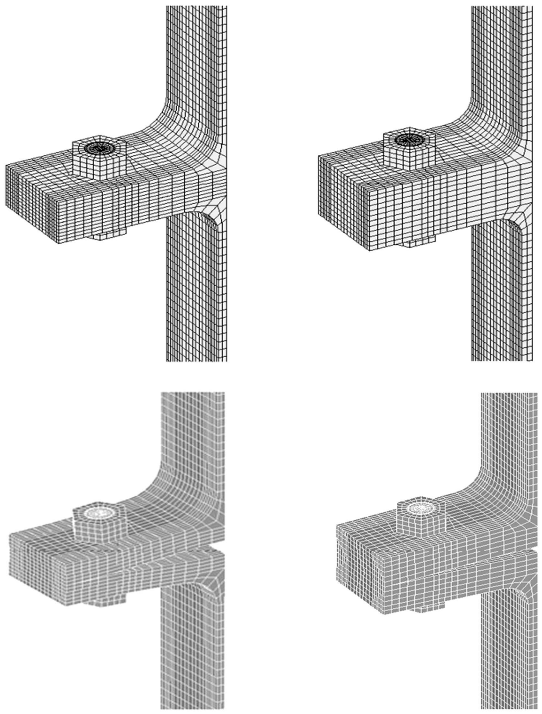

Figure 6. 3D FE models, and deformed shapes at the end of loading for specimens T1 (left) and T2 (right).

4.4. Double-angle web connections

In this section, axial tensile loading is considered, the value of F (the total load acting on one angle) is increased, and the stresses and displacements are determined. Figure 7 illustrates the load-displacement curves for each angle. The initial portion of each curve is almost linear, as is the final portion. In Figure 8, the moment-rotation curves for two specimens are presented. In both curves, there is an acceptable correspondence in linear parts and they are also compatible in non-linear parts. There exist merely slight mutations in the second part which seems insignificant. In addition, Figure 9 presents a 3D finite element model of the connection.

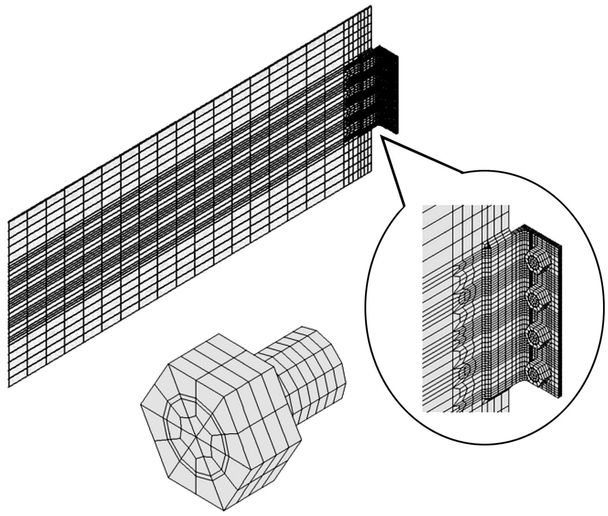

Figure 9. 3D FE model of the double-angle connection.

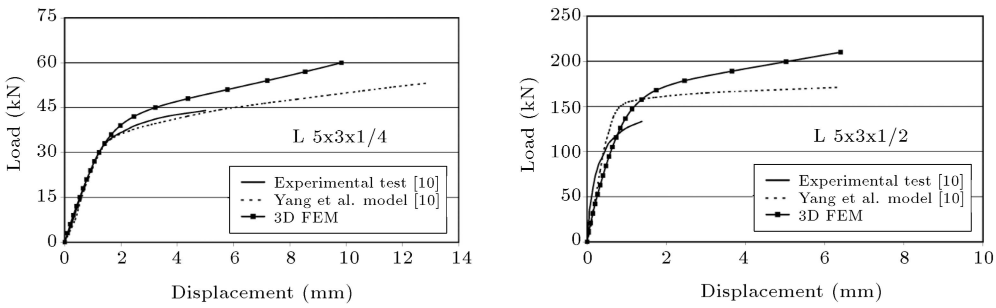

Figure 7. Axial load F versus displacement for axial loading.

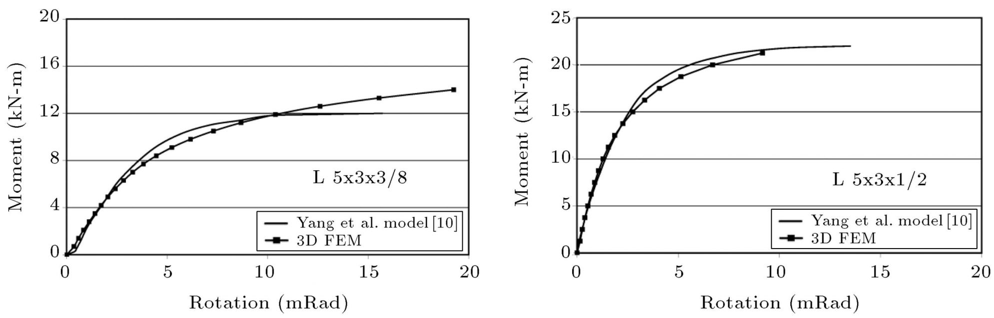

Figure 8. Moment versus rotation for shear loading.

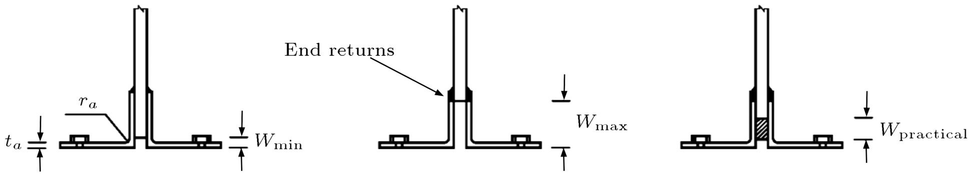

Figure 10. Schematic upper and lower limits for the clearance setback of the semi-rigid connection.

5. Model selection

5.1. Selection of variable parameters for modeling

To implement the parametric study, determination of the range of input variables is very important. In this study, it was decided to vary the geometric variables within the comprehensive practical ranges of double-angle connections. Based on designing and common practical details, the following ranges for geometrical parameters of connection components are given:

1. Five values of beam section were selected as IPE200, IPE300, IPE400, IPE500, and IPE600;
2. Two values of angle section were selected for each beam section, based on the shear capacity of the beam web (50 and 100 percent shear capacities of the beam web);
3. Two values of bolt gage distances were selected for each connection;
4. Three values of gap distances were selected as, $t_a + r_a$, $2t_a + r_a$, and $3t_a + r_a$, in which r_a represents the radius of the fillet of angle and t_a represents the thickness of angle.

Having been familiar with the acceptable range of clearance setback value for a connection, one would be able to determine the necessary gap in different situations. From the results of this study, the minimum reasonable value for clearance setback seems to be at least equal to k, which is the distance between the angle heel and the toe of the fillet of angle of the connection ($k = r_a + t_a$). For smaller values, there would be a sharp increase in initial stiffness of the connection, which is not realistic as well as practical. As AISC Manual recommends the use of end returns to be at least twice the weld size, the maximum theoretical limit (upper bound) for gap should be less than the length of angle leg in order to provide enough space for the end return welds. The returns have the greatest effect when the angle length is short. From the practical point of view, the upper bound is suggested not to be greater than half of the angle leg, which might cause lateral instability in the connection zone. In the parametric study conducted here, the range of non-dimensional ratio W/a varies from 0.2 to 0.5 for all FE models. Although other values were utilized during this study, finally, it was concluded that the aforementioned range seems to give more reasonable results by the trial and error process. These upper and lower bounds for the clearance setback are illustrated in Figure 10.

Consequently, there are 60 specimens according to the aforementioned variables. In addition, the following assumptions for semi-rigid configuration are considered here:

I. For simplicity of modeling, an equivalent beam web is utilized for each beam, which represents half of the moment of inertia of the original beam cross-section [9];

II. In order to avoid modeling the columns for each connection, columns are considered to be much stiffer in comparison with the beam sections;

III. Fillet welds are designed for each connection, separately, based on the thickness of pieces being joined and the available length over which the fillet weld can be made;

IV. Material properties are considered as ST37 steel for all connection parts, except the high-strength bolts which have A325 properties (Table 1);

V. Beam length is considered five times larger than its depth, in order to provide flexural action of the connection;

VI Equal-sided angles are used in this study, as they are more available than other types.

The typical form of these connections and their geometrical properties were demonstrated previously in Figure 1, and geometrical properties of 3D finite element models are listed in Table 2 below.

5.2. Finite element analysis results

After running the program for all 60 specimens mentioned above, the results in the form of moment-rotation curves are shown in Figure 11 for the first 30 specimens [32], as follows.

As seen in moment-rotation curves of Figure 11, the overall impact of varying the gap distance is nearly the same for all specimens. In fact, by increasing the clearance setback, the initial behavior of connection does not change so much, but the connection behavior in the non-linear part changes considerably. It means that the initial rotational stiffness of connection remains unchanged under different gap distances, and the

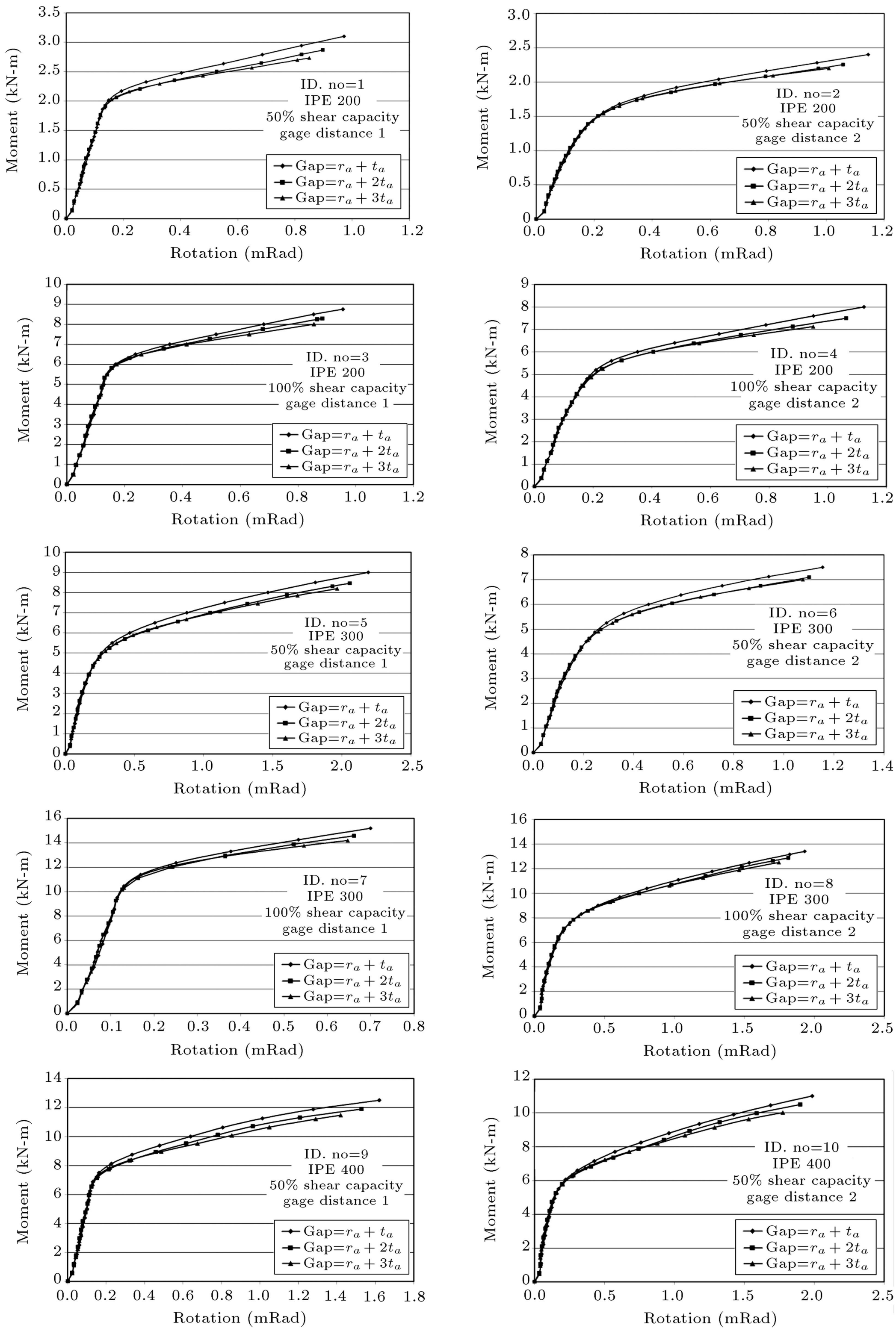

Figure 11. Moment-rotation curves of 3D FE models [32].

ultimate moment capacity of connection reduces. On the other hand, as the area of moment-rotation curve represents the concept of energy, the dynamic behavior of connection along with its ductility is affected by varying the gap distance. The changes that happen by differing the clearance distance are shown schematically in Figure 12.

In addition, by increasing the gap distance, the ultimate moment decreases from M_1 to M_2 and the ultimate rotation reduces from θ_1 to θ_2 (as shown in

Table 2. Summary of the geometrical properties of specimens.

ID. no.	t_{wb}	d_{bolt}	g	r_a	t_a	L_a	a_w	P_{mr}	P_{vr}	a
1	5.6	10	24	6	4	140	3	36	16	40
2	5.6	10	28	6	4	140	3	36	16	40
3	5.6	16	35	8	6	190	6	48	23	60
4	5.6	16	38	8	6	190	6	48	23	60
5	7.1	16	30	8	6	200	4	48	28	60
6	7.1	16	40	8	6	200	6	48	23	60
7	7.1	20	40	9	7	240	7	60	30	70
8	7.1	20	50	9	7	240	7	60	30	70
9	8.6	18	37	8	6	215	6	54	26.5	60
10	8.6	18	42	8	6	215	6	54	26.5	60
11	8.6	27	54	11	9	320	7	81	238.5	90
12	8.6	27	60	11	9	320	7	81	38.5	90
13	10.2	22	36	8	6	320	6	80	40	60
14	10.2	22	39	8	6	320	6	80	40	60
15	10.2	30	55	12	10	375	8	90	52.5	100
16	10.2	30	65	12	10	375	8	90	52.5	100
17	12	27	46	10	8	340	6	82	47	80
18	12	27	51	10	8	340	6	82	47	80
19	12	36	68	13	12	450	10	110	60	120
20	12	36	75	13	12	450	10	110	60	120

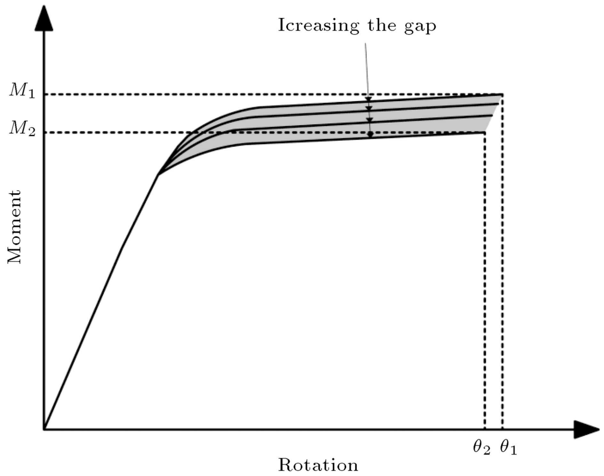

Figure 12. Effects of gap distance on semi-rigid double-angle connections.

Figure 12). In addition to the gap parameter, it can be seen from the FE analyses that the bolt gage distance has also a significant effect on the initial stiffness of connection. The more the gage distance becomes, the more reduction in initial stiffness occurs and the ductility of the connection increases accordingly. It is also observed that small gage distances would result in sharp slopes in the initial portion of moment-rotation curves, and this is an indication to brittle failure of the connection. Moreover, preloading of the bolts would increase the initial stiffness of connection. For instance, in T1 and T2 specimens, compared to the non-preloaded model, the strength remained almost identical while the initial stiffness increased by almost 40%. Consequently, in an effective design procedure, one should consider all these parameters together to achieve an optimum design.

5.3. Equivalent initial stiffness of connection

Most of the commonly used approaches to express the moment-rotation relationship involve curve-fitting of the result data to make the expressions simple or involve development of a simple analytical procedure to predict the behavior of connections. One of the most prevailing methods in predicting the moment-rotation parameters is power function [26]. To simulate the behavior of a system, it is necessary to prescribe a set of parameters and then analyze the relations between this particular set and the outcome result. For a given connection, prominent size parameters could be identified. The objective parameters, initial stiffness for instance, are expressed as a power function of these size parameters. For the prediction of initial stiffness of a DW connection, Kishi and Chen [16] suggested an analytical model, shown in Eq. (1), using plate theory:

$$K_{e,\text{Kishi}-\text{Chen}} = 2.\left[G\frac{t_a^3\alpha\cosh(\alpha\beta)}{3(\alpha\beta)\cosh(\alpha\beta)-\sinh(\alpha\beta)}\right], \quad (1)$$

where:

Table 3. Description of the considered basic variables (P_i terms).

P_i terms	Definition	Minimum	Average	Maximum	Standard deviation
		$P_{i,\min}$	$P_{i,\mathrm{avg}}$	$P_{i,\max}$	$P_{i,\sigma}$
P_1	d_a/g_1	4.8	6.84	8.89	1.079
P_2	t_a/g_1	0.14	0.17	0.20	0.0146
P_3	W/g_1	0.32	0.59	0.87	0.142
P_4	tw_b/g_1	0.14	0.21	0.28	0.043
P_5	P_{mr}/g_1	1.20	1.71	2.22	0.261

Table 4. Curve-fitting exponent parameters.

Curve fitting equation	Exponents parameters						
	α_0	α_1	α_2	α_3	α_4	α_5	α_6
K_{ini-eq}	0.065	-0.363	-3.395	0.217	4.207	-0.732	-10.085

$$\alpha = \sqrt{\frac{24}{(1+v)}}$$

($\alpha = 4.2967$ when Poisson's ratio is $v = 0.3$),

$$\beta = \frac{g_1}{d_a}, \quad g_1 = g - k.$$

For convenience, the various size parameters are lumped to form the standardization constant K as in the following mathematical form:

$$K = \Pi_i p_i^{\alpha_i}. \tag{2}$$

The P_i terms in Eq. (2), their definitions, their extreme value, and their statistical properties were calculated and are listed in Table 3.

To determine the α_i, coefficients corresponding to each P_i term, Eq. (2) can be written in a linear form as:

$$Ln(K) = \sum_i \alpha_i Ln(p_i). \tag{3}$$

Accuracy of this method in prediction relies on the range of input size parameters. They only apply to the geometrical range of analyzed data [26].

Consequently, regression equations were developed for the aforementioned parameters of each equation in terms of geometric variables of the connection region.

Based upon the aforementioned linear regression analyses procedure, the DW connection equivalent initial stiffness can be estimated by the following equation:

$$K_{ini-eq} = \frac{3(\alpha\beta)\cosh(\alpha\beta) - \sinh(\alpha\beta)}{2Gt_a^3\alpha\cosh(\alpha\beta)} g_1^{\alpha_0} \times d_a^{\alpha_1} \times t_a^{\alpha_2} \times W^{\alpha_3} \times tw_b^{\alpha_4} \times P_{mr}^{\alpha_5} \times \mathrm{EXP}(\alpha_6). \tag{4}$$

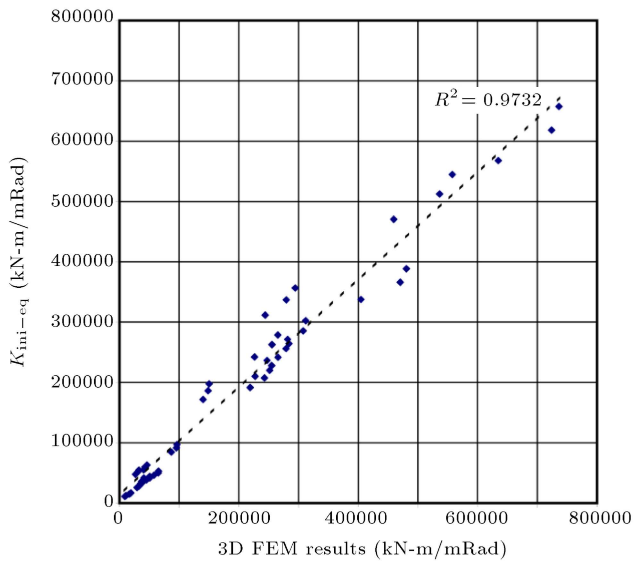

Figure 13. Comparison of 3D FEM and fitted power model.

The dimensionless exponent parameters, α_i, for each equivalent stiffness are listed in Table 4. Figure 13 illustrates the results obtained by 3D FEM. The R-squared value for the equivalent initial stiffness regression analysis was 0.9732. This indicates that the proposed function prediction is acceptable. Evidently, by augmentation of specimens, the accuracy would be improved.

6. Summary and conclusion

A double-angle and a T-stub finite element model were developed. Their performance in reproducing the actual load-displacement and moment-rotation curves was fairly validated throughout the experimental data and did perform satisfactory in various configurations. After the aforementioned modeling verification, a parametric analysis for the significant effect of "gap distance" on the semi-rigid model's response has been carried out. Several models under varying shear force and geometrical conditions are designed and utilized to show the importance and significance of "gap distance" variations. According to this study, the significance of this gap is fairly shown; and necessary suggestions for engineers, in real design conditions, are reasonably made. Inattention to a safe and secure set-back (gap distance), which is recommended in this investigation, will definitely result in severe and extremely large forces between the bottom flange of beam and the column when bearing against it. Eventually, a regression analysis was conducted to estimate a formula for predicting the initial stiffness of DW semi-rigid connections. Though the gap distance parameter was not seen in previously made formulae, it is inserted in this newly made formula. After all, it is concluded that in DW semi-rigid connections, the clearance setback value has considerable effects on the behavior of such connections, especially on the initial stiffness.

Nomenclature

t_{wb}	The beam-web thickness
d_{bolt}	Diameter of the bolt shank
g	Bolt gage distance
r_a	Radius of the fillet of angle
t_a	Thickness of the angle
L_a	Length of the angle
a_w	Weld size
P_{mr}	Vertical bolt to angle-edge distance
P_{vr}	Vertical bolt to bolt distance
a	Length of the angle leg
k	Distance from the angle heel to the toe of the fillet of the angle
W	Clearance setback between the beam end and column web (or flange)
G	Shear modulus of elasticity of steel

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