1. INTRODUCTION

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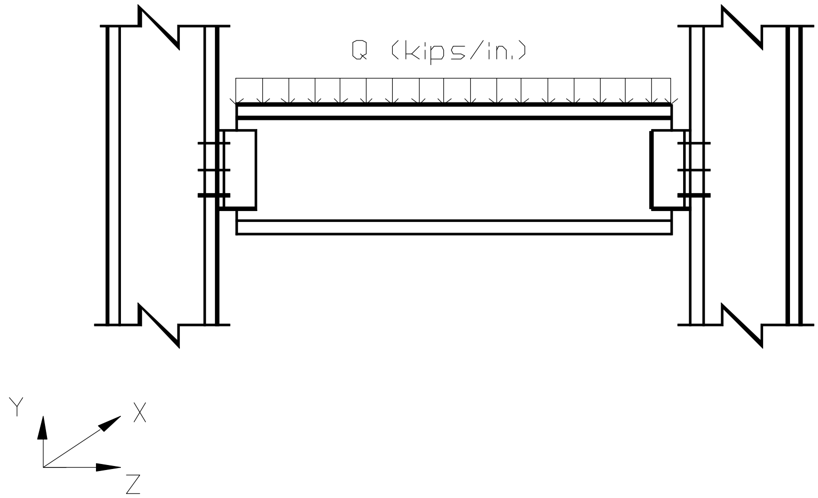
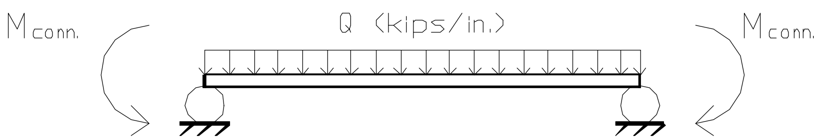
Each connection type has been classified in a different way based on its resistance to applied loads on the structural steel frame. There are two main categories for connection types in the Load and Resistance Factor Design (LRFD) Specification (1994). The FR (Fully Restrained) type connections have the same characteristics as Type 1 connections of the Allowable Stress Design (ASD) Specification (1989), while the PR (Partially Restrained) type connections are similar to the Type 2 and Type 3 connections of the ASD Specification. Despite the various connection types, most connections have been idealized as either fixed or pinned in analytical methods and in practical design for the purpose of simplification.

Double angle web connections are usually considered as PR type connections or more specifically 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, even though PR type connections can transfer moments up to approximately 20 percent of those of fully fixed connections. Figure 1.1 shows the configurations of a double angle connection and an idealized double angle connection.

Because the flexural rigidity of each connection plays an important role in the behavior of the entire structural steel frame, most of the research on various connection types has focused on the investigation of 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, a simplified analytical model has been suggested to predict the behavior of the entire angle connection by the application of curve fitting techniques.



(a) Configuration of a Double Angle Connection



(b) Configuration of an Idealized Double Angle Connection

Figure 1.1 Double Angle Connection Configurations

1.2 LITERATURE REVIEW

Because the two main characteristics of simple shear connections are strength and ductility (Nethercot 1985), most of the previous work on double angle web connections has been carried out to show the shear-rotation relationship or the moment-rotation relationship. Even though double angle web connections are idealized as pins during design procedures for simplification, the actual behavior of double angle web connections has been shown to have more complex characteristics (McMullin and Astaneh 1988). Several experimental tests have verified these existing complexities. They are mainly due to the complex stress distributions of the angles, the location of inflection points in a beam, the location of the center of rotation of the angles, and the nonlinear behavior of angles during loading. Without clarifying these features, the realistic behavior of double angle web connections can not be analyzed and appropriate simplified analytical models can not be developed. Unfortunately, very restricted information is available on the behavior of double angle web connections subjected to combined shear, moment, and axial tensile loads (McMullin and Astaneh 1988).

1.2.1 Experimental Tests

Numerous tests have been conducted to predict the behavior of double angle web connections during the past sixty years. To provide realistic connection behavior, the previous tests have been conducted based on parameters such as the thickness of the connection angles, length of the angle, gage distances, type and size of fasteners, depth and length of the connected beam, supporting member, and material properties of the angles.

Nethercot *et al.* (1980, 1983) noted that Batho and Rowan (1931, 1934, 1936) conducted a series of tests. Three tests of double angle web connections were performed with rivets as fasteners. Rathbun (1936) and Wilson and Moore (1917) also tested double angle web connections with rivets which were used as fasteners. Even though the riveted connections showed very similar behavioral characteristics to those of bolted connections, the obtained test data are no longer useful for current design purposes, because high strength bolts or fully tensioned high strength bolts are usually used as fasteners in recent steel structural designs.

Munse *et al.* (1959) conducted four experimental tests at the University of Illinois. The tested specimens consisted of a W18x50 beam connected to a W12x65 column with two L6x4x3/8x11-1/2 angles. High strength bolts were used as fasteners to study their effects on connection behavior when used in conjunction with rivets. The moment-rotation relationships were also established. During the experimental tests, Munse *et al.* noted the following:

i) The behavior of the double angle web connection was independent of the moment-to-shear ratio.

ii) The failure of the double angle web connection was mainly due to the flexure of the angles, as none of the fasteners failed.

iii) The location of the center of rotation moved from its initial position at mid-depth of the beam toward the compression flange to about 80% of the length of the angle from the tension end.

Lewitt *et al.* (1969) conducted eight experimental tests at the University of Illinois to supplement the data obtained from the previous research. They analyzed the moment-rotation characteristics of double angle beam-to-column connections and suggested a formula for the moment-rotation relationship using load-deformation results obtained from the experimental tests. For this purpose, they conducted additional tensile tests and compression tests on double angle specimens. They divided an angle into several sub-elements in order to apply the load-deformation characteristics, as Beaufoy *et al.* (1948) did in their research.

Sommer (1960) conducted a series of comprehensive experimental tests on shear connections at the University of Toronto. Four experimental tests were conducted to predict the moment-rotation relationship of the double angle web connections. The 3/8 in. thick angle specimens were welded to a beam web and bolted to a column flange with 3/4 in. diameter A325 bolts. From the experimental tests, Sommer found the following results:

i) The behavior of the double angle web connections tested was similar to that of header plate connections except for the case when the compression flange of the beam came in contact with the column flange.

ii) The double angle web connections developed larger moments in the case when bearing occurred due to the stiffening effect of the angles on the beam web in the compression region.

Thompson *et al.* (1970) conducted experimental tests on double angle web connections with various geometrical and material properties of the angles and fasteners in order to predict their effect on the connection behavior. They concluded that the recommended AISC design method was reasonable and the connections were strong enough to maintain the anticipated rotations. However, they did not suggest any analytical model to predict the connection behavior.

McMullin and Astaneh (1988) conducted seven full scale tests on double angle beam-to-column connections at the University of California, Berkeley. The tested angle connections were subjected to a combination of shear and moment to obtain realistic moment-rotation and shear-rotation curves. Experimental tests were performed with different geometrical properties of the angles, number of bolts, and bolt diameters. The tested angle specimens were bolted to a beam web and welded to a column flange with weld sizes of 1/4 in. and 5/16 in. and weld lengths of 8.5 in. to 26 in. They summarized some of the findings based on the observations of the behavior of the double angle web connection during the experimental tests:

i) Double angle web connections can be divided into three distinct regions of behavior during loading: a tee-hanger region, a shear beam region, and a compression region.
ii) The inflection point of a beam connected by double angles can be obtained by static analysis and moves toward the back of the bolt hole during the loading history.
iii) The most common failure mode for the tested double angle connections was fracture of the weld at the top of the connection.
iv) The overall performance of double angle web connections was very good.

Owens and Moore (1992) summarized a series of tests on double angle web connections and end plate connections which were conducted by the Building Research Establishment. They also presented several large displacement analytical methods which were developed at the Steel Construction Institute. Eleven experimental tests were conducted to investigate the behavior of double angle web connections subjected to tensile axial forces. Ten of the tested angle specimens were bolted both to a beam web and a column flange, while one tested angle specimen was bolted to a column web. An inverted tee arrangement test set-up was selected to simulate the behavior of a double angle web connection under accidental axial loads. The authors summarized the four major failure modes of double angle web connections as bolt pulling through the web cleat, bearing failure of the web cleat, bearing failure of the beam web, and fracture of the web cleat close to the heel. Considering the results of experimental tests, they summarized their conclusions as follows:

i) Double angle web connections provided greater resistance to the axial tensile loads than comparable end plate connections.

ii) Owing to the high deformations, prying forces in the bolts under these axial tensile loads were significantly greater than those normally encountered in bolted connections.

iii) Axial tensile load requirements were unlikely to govern the design of double angle web connections; they may influence the design of end plate connections for tall buildings.

Astaneh *et al.* (1989) summarized the procedures and results of six experimental tests of double angle web connections conducted by Astaneh and Nader. These experimental tests were conducted to establish the moment-rotation hysteresis response of double angle connections and to show the effects of bolts on the double angle behavior when subjected to cyclic loading. The tested angle specimens were bolted to a column flange and welded to a beam web with a weld size of 1/4 in. Two types of bolts, ribbed bolts and A325 bolts, were used as fasteners. A W10x77 short column was used to ensure that it would remain elastic during the experimental tests and would not affect the overall rotation of the tested connections. Considering the results of the experimental tests, the following conclusions were drawn:

i) Connections with structural rib bolts having shallow threads did not perform satisfactorily under cyclic rotation larger than 0.025 rad.

ii) Two main failure modes were the failure of bolts in cyclic tension and the cyclic fracture of angles adjacent to their bolts.

iii) Both structural rib bolts and A325 high strength bolts showed ductile behavior as the maximum rotations did not exceed 0.025 rad.

Astaneh and Ho (1993) summarized test data and observations to establish the actual cyclic behavior of double angle web connections. Two types of double angle connections were tested with various properties of the test specimens. In the bolted-bolted connections, the tested angle specimens were bolted to a column flange and a beam web with A325 bolts. In other tests, the angle specimens were bolted to a beam web and welded to a column flange with weld sizes of 1/4 in. and 3/8 in. From the analysis and observations of test results, the following conclusions were drawn:

i) Double angle connections showed sufficiently high ductility during the experimental tests. The hysteresis response was unsymmetric, showing very small strength and stiffness under pulling action, but much higher strength and stiffness under pushing against the column by the beam.

ii) Bolted-bolted connections failed due to shear yielding and eventual fracture of the angles. On the other hand, bolted-welded connections failed due to the fracture of welds with a small amount of yielding of the angle material.

iii) The shear strength of the connections was weakened by the cyclic axial loading, and this phenomenon was more severe in bolted-bolted connections than bolted-welded connections.

iv) The effect of prying action due to the flexibility of the connection angle should be considered.

1.2.2 Analytical Models

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 (Lewitt *et al.* 1969). Even though the beam size can be reduced due to the end restraints developed by these connections, the moment transferred to the supporting elements could be dangerous in those elements. Therefore, well-defined analytical models are necessary for the 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.

As mentioned earlier in Section 1.3.1, there are several available experimental test results for double angle web connections. Goverdhan (1983), Nethercot (1985), and

Kishi and Chen (1986) have collected and summarized these experimental test data. Using these data, various analytical models have been developed.

Lothers (1960) suggested a linear model for the initial rotational stiffness based on an elastic analysis of the connection angles. Even though the suggested model was easy to use, there were some inaccuracies since the actual connection showed inelastic characteristics from very low loading stages. He also presented an equation for the prediction of the allowable resisting moment capacity of the connection.

Based on the experimental test data, Lewitt *et al.* (1969) suggested a semi-empirical model for the prediction of the moment-rotation relationship of double angle web connections. The moment-rotation curve presented by them was composed of two curves based on the tensile deformation. However, they pointed out that the suggested equations were limited for use with 4x3-1/2 and 6x4 angles with angle thicknesses of 5/16 in. to 7/16 in. and gage distances from 2-1/4 in. to 2-5/8 in.

Frye and Morris (1975) suggested a polynomial model which was based on the procedure by Sommer (1960). In the development of a polynomial model, they made several assumptions and limitations such as: the effects of shear and axial load on connection deformation were ignored; the effects of strain hardening were neglected; the structure behaved linearly except for the nonlinear force-deformation characteristics of the connections; and the material behavior in the member was linearly elastic. The standardization constant and curve-fitting constant were used for this model. The suggested polynomial model is currently used for simple design checks since it represents the moment-rotation behavior reasonably well. However, the connection stiffness may show negative values for some values of moments, which is physically unacceptable.

Ang and Morris (1984) proposed a power model to predict the moment-rotation relationship for five different types of connections by using a standardized Ramberg-Osgood function (1943). An iterative analytical procedure was used to account for nonlinear behavior of the connections as in Frye and Morris (1975). In the development of a power model, several assumptions and limitations were made by them, such as: axial and direct shearing deformations in connections were ignored and connections were assumed to have infinite torsional stiffness; small deflection theory was employed; all members were prismatic and linearly elastic; and possible buckling was ignored. The suggested four-parameter power model shows good agreement with experimental test curves presented by Lewitt *et al.* (1969) and Sommer (1960).

Kishi and Chen (1990) proposed a power model which was composed of three parameters representing initial elastic stiffness, ultimate moment capacity of the connections, and shape parameter, respectively. A simple analytical procedure was used for the initial elastic stiffness and ultimate moment capacity of the connections. The shape parameter was then determined by a least-square curve fitting with experimental tests. In the simple analytical procedure, they made several assumptions such as: the effect of shear force on connection deformation was ignored; the outstanding leg of an angle behaved linear elastically, while the back-to-back leg of an angle behaved as a rigid body; the connection deformation was small; and the part of the angle fastened to the column flange acted as a moderately thick plate. The suggested model is easy to use and shows good agreement with experimental test curves. However, this model may be difficult to apply for test curves that do not flatten out near the final loadings.

Richard *et al.* (1988) suggested a four parameter model by using the concept of load-deformation results obtained from experimental tests of angle segments. Beaufoy and Moharram (1948) used this concept first to derive the moment-rotation curves for double angle web connections. A simple connection model proposed by Richard *et al.* (1988) consisted of a rigid bar and nonlinear spring elements representing beam members and angle segments under either tension or compression, respectively. In the development of the connection model, they made several assumptions such as: all inelastic material behavior of the beam at the connection is lumped into the inelastic angle response; the plane of the beam web remains plane; each segment acts independently; and the shear on the connection does not affect the tension and compression properties of the angle segments.

Lui and Chen (1986) investigated the behavior of flexibly-jointed frames. In their research, they emphasized that the connection flexibility played an important role in the behavior of the entire structure. They also insisted that additional research into connection behavior was necessary. They proposed a multi-parameter exponential model to predict the moment-rotation relationship of connections. The suggested model shows good agreement with experimental test results. However, this model can not represent moment-rotation curves adequately if the rotational stiffness exhibits sharp changes.

Kishi and Chen (1986) collected experimental test data obtained by some other researchers on the moment-rotation characteristics of commonly used connections. They also developed a modified exponential model to refine the exponential model suggested by Lui and Chen (1986). This modified model has several merits such as: the formulation is relatively simple and straightforward; it can deal with connection loading and unloading for the full range of rotation in a second-order structural analysis; and abrupt changing of the connection stiffness among the sampling data is only generated from inherent experimental characteristics.

Stefano and Astaneh (1991) proposed analytical models based on the experimental tests conducted by McMullin and Astaneh at the University of Oklahoma in 1985. In the analytical model, the outstanding leg of the double angle connections was considered as a beam element with clamped-shear released ends. It was also assumed that the back-to-back leg of an angle behaves elastically during the loading history. The results given by their analytical model subjected to axial tensile loads show good agreement with those of the experimental tests. However, it was suggested that further studies are necessary to determine the failure modes.

1.2.3 Finite Element Method Models

The finite element method is an alternative method to analyze the behavior of angle connections under various loading conditions. 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 element such as contact, friction, stick and slip conditions (Bursi and Leonelli 1994). It is also hard to model stress concentrations, prying forces, 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 by using a commercial finite element package such as ABAQUS (1994). However, much attention should be given to the selection of appropriate element types, boundary conditions, and contact coefficients when using the finite element method (Bursi and Leonelli 1994).

Krishnamurthy and Graddy (1976) analyzed unstiffened four-bolt-extended end plate connections by 2D and 3D modeling with finite element techniques in order to provide the correlation between these two models. The angle specimens studied were welded to the beam and bolted to the supporting elements. In the 3D modeling of connections, constant strain triangle and eight-noded subparametric brick elements were used to predict the linearly elastic behavior of end plate connections. Both contact and bolt pretensioning were simulated in this analysis.

Kukreti *et al.* (1987) analyzed flush end plate connections by 2D and 3D finite element modeling to predict the moment-rotation relationship. Since the 3D finite element analysis was much more complicated and rigorous, the 2D finite element analysis with rectangular plane stress elements was also conducted to develop simple prediction equations. 3D subparametric elements developed by Levy (1971) were used for the end plate, bolt shank, bolt head, and the weld connecting the beam flanges with the end plate, while eight-noded rectangular hybrid plane stress elements were used for the beam web and the web connecting it to the end plate. Then, similar to Krishnamurthy and Graddy (1976), a correlation between the 2D and 3D finite element analyses was established to determine the effects of various geometric and loading conditions on the flush end plate connection behavior.

Patel and Chen (1984) analyzed the stiffness, the stress distribution in the panel zones, and the spread of plastic zones for three different types of moment connections, using the nonlinear finite element program developed at the University of California, Berkeley. 2D plane stress isoparametric finite elements were used for flange moment connections. In the bolted connection, bolts were modeled with two bar elements carrying the pretension and shear load of the bolt. Comparing with the experimental test data, the finite element analysis gives good results for flange welded only connections.

Bursi and Leonelli (1994) analyzed the elasto-plastic behavior of end plate steel connections by using the commercial ABAQUS finite element package. A 3D nonlinear finite element model was used for the entire connection, with twenty-node second-order hybrid solid elements and simple contact elements. Standard two-node beam elements were used to represent bolt shanks and heads. The behavior of the beam flange, beam web, and weld beads was modeled with rigid solid elements.

Similarly, Sherbourne and Bahaari (1994) used the ANSYS finite element package to evaluate the moment-rotation relationships for steel bolted end plate connections.

1.3 OBJECTIVES AND METHODS

A few studies have been conducted regarding the behavior of double angle web connections subjected to axial tensile loads.

The objectives of this research are to analyze the behavior of column flange bolted-beam web welded double angle connections subjected to either axial loads or shear loads, and to provide some basic data for the design of double angle web connections. A 3D nonlinear finite element model, a simplified angle model, and an equivalent spring model will be suggested for these purposes.

From the regression analysis of the results of a 3D finite element model, the main parameters, such as the initial stiffness, the plastic stiffness, and the curve sharpness parameter, can be obtained for use in Richard's formula (Richard *et al*. 1988). Using these main parameters, the behavior of a double angle connection can be easily analyzed within the given loadings. The simplified angle model and the equivalent spring model are suggested to replace the complex 3D nonlinear finite element model, and to save computer costs required for the analysis of a double angle connection. Experimental tests will be conducted for a double angle connection to confirm the acceptance of the 3D nonlinear finite element model.