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# Numerical estimation of the initial stiffness and ultimate moment capacity of single-web angle connections

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ABSTRACT

Single-web angle connections bolted to the beam web and the column flange are studied to investigate the effect of the thickness, length, and material properties of the angles, number of bolts, and gage distances of the fasteners on their moment–rotation behavior. ABAQUS software is used to analyze the nonlinear behavior of a single-web angle connection. Identical geometric and material properties with Lipson's test are utilized to verify the finite element models. A simpler and more accurate equation for the initial stiffness is suggested, and good agreement between the proposed model and Lipson's test data is demonstrated. The type of collapse mechanisms for single-web connection is established. The ultimate moment capacity modified from Kishi and Chen's equation is also proposed, and it agrees well with Lipson's test data.



## 1. Introduction

A single-web angle connection consists of an angle either bolted or welded to both the column flange and the beam web. As this connection requires less material and labor costs, it is among the popular simple connections in steel structures. In general, this type of connection is ideal as a pin, and it is assumed to transfer only shear loads to the column. However, in practical engineering, a single-web angle connection shows semi-rigid behavior, which can contribute substantially to the overall force distribution in the structures. As the characteristics of connections play a very important role in steel structural analysis and design, the effects of connections should be considered in structural analysis. Therefore, it is necessary to determine the moment–rotation characteristics (i.e., initial stiffness, ultimate moment capacity) of a connection.

In past years, several researchers have published papers discussing moment–rotation behavior of single-web angle connections. In 1968, Lipson carried out an experiment on single-angle and single-plate beam framing connections [1]. In 1970, Thompson investigated rotation characteristic of web shear framed connections using A-36 and A-441 steels [2]. In 1977, Lipson published another paper about single angle welded-bolted connections [3]. From the seventies through the nineties, several researchers proposed different models of the moment–rotation characteristics, initial stiffness, and ultimate moment [4–13]. For example, Kishi and Chen derived the equation of the initial stiffness and ultimate moment based on a series of assumption [10]. Yang and Lee proposed two simplified analytical models for predicting the initial stiffness and ultimate moment [11]. Yanglin Gong carried out experiments and proposed new models of the ultimate moment [12,13]. However, these models are generally composed of parameters of the thickness, length, and material properties of the angles, as well as gage distances of fasteners, and the models proved to be accurate only for the limited range of data used in the analysis [14]. Hence, selection of simple and accurate models to predict the initial stiffness and ultimate moment of single-web angle connections is a difficult but necessary task.

In Eurocode 3, three different methods of global analysis of elastic, rigid-plastic, and elastic–plastic analysis are suggested [15]. When elastic–plastic analysis is chosen, the moment–rotation characteristics of joints should be used to determine the distribution of internal forces and moments. The design moment–rotation characteristics of a joint used in the analysis may be simplified by adopting a bi-linear curve, as shown in Fig. 1. For the design, the equations of the initial stiffness and ultimate moment for connections are given [16]. However, single-web angle connections are not covered in this code.

In AISC, the types of joint are divided into fully restrained (FR), partially restrained (PR), simple connections. When a connection is classified as PR connection, the relevant response characteristics of connection must be included in the analysis of the structure to determine the member and connection forces and displacements. Therefore, PR construction requires, first, that the moment–rotation characteristics

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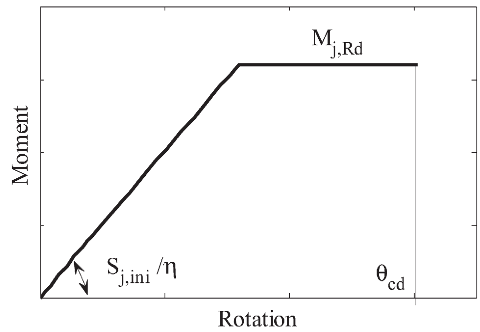


**Fig. 1.** Simplified bi-linear design moment–rotation characteristic.

of the connection be known and, second, that these characteristics be incorporated in the analysis and member design. Typical moment–rotation curves for many PR connections are available from several databases, such as Kishi and Chen [17]. However, these databases do not cover all parameters and all types of connections. While the finite element method has been used to study the behavior of different types of connections, few studies have concentrated on single-web angle connections. The purpose of this study is to develop new formulations for predicting the initial stiffness and ultimate moment of the single-web angle connection.

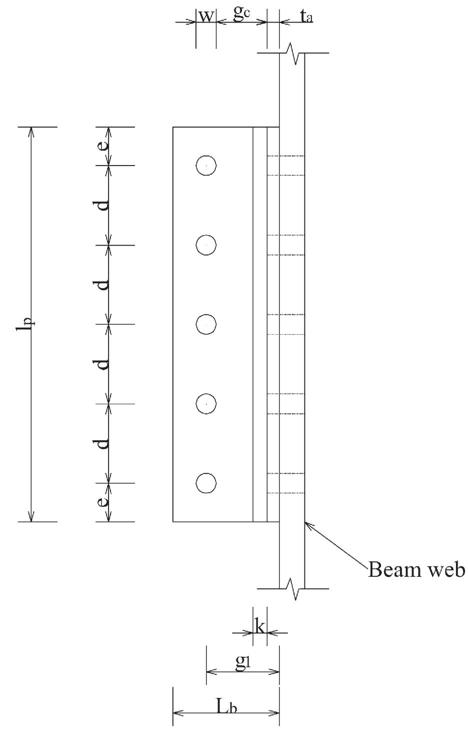


**Fig. 2.** Parameters of angle.

## 2. Initial stiffness

The initial stiffness of a single-web angle connection is one of the most influential parameters of the overall behavior of a connection. In this study, four major parameters – angle thickness, angle length, gage distance, and number of bolts – are studied to discover their effects on the initial stiffness.

### 2.1. Finite element analysis and verification

In order to verify the finite element analysis, three finite element models, corresponding to Lipson's experiment [1], are made as listed in Table 1. Each connection specimen consists of an unequal leg angle and several 19 mm diameter A325 high-strength bolts. All the specimens have only one vertical row of bolts at each leg. The A36 steel beam used is W530 × 62 for all test specimens, and the A36 steel angle investigated is L102 × 90 × 6.4. The distance from the angle heel to the center of the bolt holes near the beam web on the outstanding leg (connected to column flange), $g_1$, is 65 mm, and the bolt spacing, d, is 76 mm [1]. The parameters of angle are shown in Fig. 2.

ABAQUS, a nonlinear finite element analysis program, is used to analyze the connection. The angle, beam, column, and bolts are modeled using C3D8 eight-node constant-strain brick element. Fig. 3 shows the finite element meshes for the angle and bolt. A bi-linear model for material behavior is assumed for the angle, beam, and column members [1]. All the contact conditions of bolt nut to angle, bolt head to column flange/beam web, bolt shank to bolt hole, and angle to column/beam are simulated. Pre-stressing force is applied to each bolt as initial stresses to simulate fully-tightened bolts.

As the bending moment is applied, the beam rotates slowly as a result of the deformation of the angle, as shown in Fig. 4. The value of rotation is easily obtained by surveying the horizontal displacement of the upper and lower ends of the beam. Consequently, the moment-rotation behavior and initial stiffness can be obtained from Lipson's test and the finite element analysis. According to the results, the initial stiffness of the finite element models agrees well with Lipson's test data, as shown in Fig. 5 and Table 1. Hence, the finite element models are accurate and can be utilized for determining the initial stiffness.

### 2.2. Development of a new model for initial stiffness

To date, several models of the initial stiffness have been developed. In 1990, Kishi and Chen derived an equation from the test data conducted by Lipson [10].

$$R_{ki} = G\frac{t_a^2}{3}\frac{\alpha\cosh(\alpha\beta)}{(\alpha\beta)\cosh(\alpha\beta) - \sinh(\alpha\beta)} \quad (1)$$

**Table 1**
Comparison of FEM results with Lipson's test.

| Specimen ID | Angle thickness $t_a$ (mm) | Angle length $l_p$ (mm) | $g_1$ (mm) | Bolt spacing $d$ (mm) | Number of bolts, $n$ | Initial stiffness $R_{ki}$ (kN-m/rad) | | Discrepancy |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Lipson's test [1] | FEM results | |
| AA-4/1 | 6.4 | 292 | 65 | 76 | 4 | 649 | 1116 | 71.96% |
| AA-4/2 | | | | | | 1099 | 1116 | 1.55% |
| AA-5/1 | 6.4 | 368 | 65 | 76 | 5 | 1787 | 2716 | 51.99% |
| AA-5/2 | | | | | | 2633 | 2716 | 3.15% |
| AA-6/1 | 6.4 | 444 | 65 | 76 | 6 | 4284 | 4289 | 0.12% |