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# Moment-rotation curves of ultra-large capacity end-plate joints based on component method

Gang Shi [a,b,*], Xuesen Chen [a]

[a] Key Laboratory of Civil Engineering Safety and Durability of China Education Ministry, Department of Civil Engineering, Tsinghua University, Beijing 100084, China
[b] Beijing Engineering Research Center of Steel and Concrete Composite Structures, Tsinghua University, Beijing 100084, China

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ABSTRACT

The behavior of the beam-to-column joints in steel frames can be represented by the moment-rotation curves in the structural analysis. The moment resistance and the rotational stiffness are two basic parameters in the moment-rotation relationships. For the ultra-large capacity end-plate joint, which is a new bolted beam-to-column joint form in steel frames with large spans or heavy loads, investigations are necessary to predict these two parameters as well as the moment-rotation relationships. Summarizing the existing results of experiments and finite element analysis, the behavior of the ultra-large capacity end-plate joint was analyzed based on the component method specified in the Eurocode 3, and a new component referred to as cruciform stub was proposed for this new joint form. Systematical methods to decide the moment resistance and the rotational stiffness were introduced based on component analysis, while the experimental results and the finite element analysis results were employed to validate the methods. A new representation to predict the moment-rotation curve of this joint form was proposed based on the moment resistance and rotational stiffness obtained by the component analysis, and the moment-rotation curves obtained by the proposed representation showed good agreements with the curves obtained from the experiments, indicating that these curves according to the proposed representation can be adopted in the design and analysis of the ultra-large capacity end-plate joints.


## 1. Introduction

The design of the beam-to-column joints is an important part in the design of steel frames. Because of the satisfactory ductility and the convenience in construction, bolted end-plate joints are widely applied in practice especially in situations where the field welding is required to be avoided [1,2]. The ordinary extended end-plate joint has been investigated extensively [3,4,5], and several practical analysis methods have been proposed [6,7,8,9]. Also, design methods for end-plate joints can be found in the Eurocode, the American code and the Chinese code [10,11,12]. However, as the joint moment resistance demand increases, the application of the ordinary extended end-plate joints, which arrange four bolts in the tension side generally, is limited because an upper boundary of the moment resistance is determined by the number of the bolts in tension. Therefore, the large capacity end-plate joint with 8 bolts in the tension side, as well as the ultra-large capacity end-plate joint with 16 or 12 bolts in the tension side, has been proposed. Several investigations of the large capacity end-plate joints have been conducted to provide design methods for this joint form [13,14,15,16], and a design method has been specified in the American code for the stiffened long end-plate joints with 8 bolts in tension [11]. However, the investigation of the ultra-large capacity end-plate joint is just in the initial stage [17,18].

A view of the configurations of the ultra-large capacity end-plate joint is illustrated in Fig. 1. To analyze the performance of the ultra-large capacity end-plate joints, four full-scale specimens have been tested subjected to monotonic loads [17]. Also, finite element analysis was conducted and a simplified design method was proposed based on the analysis [18]. However, the proposed method only covered the joint moment resistance, while the rotational stiffness, which has an important influence on the distribution of the internal force and the deformation of the structure, was not involved. In fact, all the actual joints applied in practice, with the ultra-large capacity end-plate joint included, behave as semi-rigid ones [19], so it is necessary to have a comprehensive knowledge of the rotational stiffness in order to conduct the structural analysis accurately.

In the structural analysis, the behavior of the beam-to-column joint can be represented by its moment-rotation curve ($M$-$\varphi$ curve) because the moment resistance, as well as the change of the rotational stiffness in the elasto-plastic analysis, can be considered with this curve [19]. $M$-$\varphi$ curves can be obtained from experiments or finite element

* Corresponding author at: Key Laboratory of Civil Engineering Safety and Durability of China Education Ministry, Department of Civil Engineering, Tsinghua University, Beijing 100084, China.
*E-mail address:* shigang@tsinghua.edu.cn (G. Shi).

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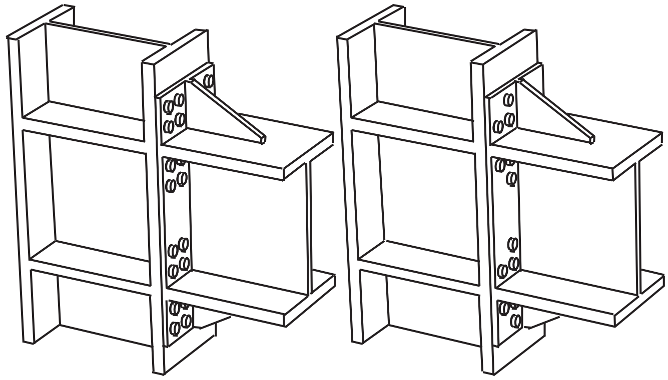


**Fig. 1.** The typical configurations of ultra-large capacity end-plate joints: (a) bolt layout A with 16 bolts in tension; (b) bolt layout B with 12 bolts in tension.

analysis. A relatively accurate curve can be obtained in these two ways, but a large economic or time cost is required and more experiments or finite element analysis should be conducted if the parameters of the joints change. Therefore, other methods were proposed to decide $M$-$\varphi$ curves by empirical models or mechanical models [6,7,19,20,21], where expressions for $M$-$\varphi$ curves were provided with several variables. Although $M$-$\varphi$ curves obtained from the empirical models or mechanical models are not so accurate as the ones from experiments or finite element analysis, they are still widely used because the change of joint parameters can be considered for a certain joint form directly. Therefore, it is essential that an $M$-$\varphi$ relationship model for the ultra-large capacity end-plate joint should be established to analyze the performance of structures with this joint type conveniently.

However, the existing methods to predict the moment resistance and the rotational stiffness of the end-plate joints, which are two of the most critical parameters, cannot be applied to the ultra-large capacity end-plate joint directly because of the inhomogeneous distribution of bolt tensile forces and the complicated stress state of the end plate [17,18]. To obtain the moment resistance and the rotational stiffness of this novel joint, the component method specified in the Eurocode 3 can be adopted provided that the joint can be divided into components reasonably [10,19]. Unfortunately, the existing basic components seem not sufficient for this disassembly, indicating that new components need to be introduced to support the component analysis for the ultra-large capacity end-plate joint.

In this paper, a new component referred to as cruciform stub was proposed, and with this new component in consideration, systematical calculation methods for the moment resistance and the rotational stiffness of the ultra-large capacity end-plate joints were provided based on component analysis. The method was validated by the results of the experiments and the finite element analysis. Taking the moment resistance and the rotational stiffness obtained by this method as parameters, a new representation for the $M$-$\varphi$ curve of this new joint form, which combined several advantages of the existing representations, was proposed in this paper and validated by the experimental results.

## 2. Joint components

The component method specified in the Eurocode 3 is a mechanical method to predict the moment resistance and the rotational stiffness of the beam-to-column joints [10]. In this method, a joint is divided into basic components and the method to calculate the stiffness as well as the resistance of each basic component is provided. Then the moment resistance and the rotational stiffness of the whole joint can be obtained by assembling these components together. Every beam-to-column joint can be designed with this method if it can be divided into basic components reasonably [19]. The T-stub is one of the basic components, and it is the most important and widely-used component in the bolted end-plate joints. However, the ultra-large capacity end-plate joint, which shows an inhomogeneous distribution of bolt tension forces and a complex biaxial bending in the end plate, cannot be divided into basic T-stubs reasonably. In order to analyze the performance of this joint form with the component method, a new component referred to as cruciform stub is proposed.

A cruciform stub is constituted of two orthogonal vertical plates and a horizontal plate with the bolts in its region as shown in Fig. 2. Taking the cruciform stub and the existing basic components in the Eurocode 3 into consideration, the ultra-large capacity end-plate joint can be divided into five components as illustrated in Fig. 3. The beam flange in compression (bfc), the column web in shear (cws) and the column web in compression (cwc) are three basic components which have been investigated and specified in the Eurocode [10,19], so the design methods can be adopted with only slight modifications. The end plate in tension (ept) and the column flange in tension (cft) are two complicated components proposed in this investigation. Extended stiffeners and continuity plates are recommended for the ultra-large capacity end-plate joints to get a larger moment resistance and a larger rotational stiffness [22,23], and when the recommended configurations are adopted, the end plate in tension and the column flange in tension can be analyzed as the cruciform stubs, which will be discussed in detail in this paper. In addition, the cruciform-stub analysis was proposed for stiffened ultra-large capacity end-plate joints, so the configurations without extended end-plate stiffeners or continuity plates, which were not recommended to be applied, are not involved in this investigation.

To assemble all the components stated above, a mechanical model constituted of four elasto-plastic components and a rigid-plastic component is proposed as illustrated in Fig. 4. It is assumed that the moment is transferred from the beam to the column in the form of axial forces in the centerlines of the beam flanges [10]. The beam flange in compression is simulated by a rigid-plastic component because it is involved only to check the moment resistance of the beam section [19], while the other components are simulated by elasto-plastic components to calculate the moment resistance as well as the rotational stiffness of the joint. In this paper, the axial resistance as well as the stiffness of each existing component is determined based on available investigations, while the newly-proposed component is analyzed to provide the method to calculate its axial resistance and stiffness.

## 3. Moment resistance

### 3.1. Resistance of the existing components

The column web in shear, the column web in compression and the beam flange in compression are three basic components in Eurocode 3, where the methods to determine the tension resistance of these components can be found [10]. Even so, some modifications are still proposed to make the procedure more easily applicable.

The resistance of the column web in shear ($F_{y\cdot cws}$) is corresponding to the shear resistance of the panel zone. Eq. (1), Eq. (2) and Eq. (3) are formulas to determine this resistance specified in the Eurocode, the American code and the Chinese code respectively [10,24,25]. In Eq. (1)

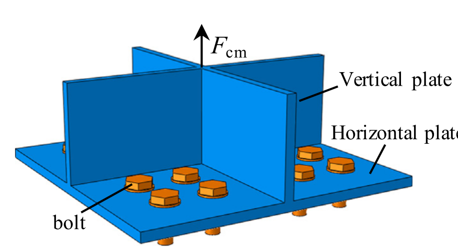


**Fig. 2.** A view of the cruciform stub.