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# Secondary prying of column flange in Tee-connections: Experimental investigation and mechanical modeling

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ABSTRACT

Column flange failure due to *secondary* prying effect needs to be addressed when designing Tee-connections associated with deep beams in seismic areas. This study investigates experimentally the effect of column flange thickness and the associated *secondary* prying on the response of double Tee moment connections. The objectives of this study are: (1) to provide insight as to whether continuity plates are necessary in columns when designing and detailing Tee-connections, (2) and to quantify the *secondary* prying forces and the contribution of the column flange ductility to the overall ductility of the connection. The results of a series of seven component tests on column flange/thick Tee connected back-to-back are presented and discussed providing all possible failure modes and yielding mechanisms encountered in the column flange. The component tests are subjected to both monotonic and cyclic loadings and cover the range of thin, medium, and thick column flanges connected to thick Tees. A proposed mechanical model is developed and is able to predict the strength, stiffness, ductility, and all possible failure modes of the column flange. The results show that increasing the column flange thickness decreases the *secondary* prying forces and increases the strength and stiffness capacities of the connection. Detailing columns without continuity plates reduces the fabrication cost and eliminates the need to weld in regions of low notch toughness. Adding the secondary prying failure mode check to the current ANSI/AISC 358-16 and Eurocode 3 part 1–8 guidelines is recommended to ensure a safe design.



## 1. Introduction

Bolted rolled double Tee moment connections have undergone extensive experimental and analytical investigations for the past two decades resulting in their prequalification in the ANSI/AISC 358-16 [1] for use in moment resisting frames (MRF) in seismic areas. The design approach is based on plastic hinging in the beam when used in special moment resisting frames (SMF) or in combination with shear yielding of the column panel zone when used in ordinary moment resisting frames (OMF) [2]. When addressing the column in double Tee moment connections, the following limit states are accounted for in the design procedure: flange flexural yielding, web yielding, web crippling, and panel zone shear failure.

One of the major behavioral characteristics associated with double Tee moment connections is the prying effect. Prying forces are defined as the additional tensile forces added to the tension bolts due to the flexural bending of the plates they are connected to. Prying can be divided into two types: (1) *primary* prying when the Tee flange undergoes flexural deformation and (2) *secondary* prying when the column flange undergoes bending [3]. The induced flexural deformation can cause unexpected failure of tension bolts leading to failure of the connection. All existing design codes consider the column flange as rigid where almost no deformation exists either by supplying thick column flange or by providing continuity plates. For instance, ANSI/AISC 358-16 [1] explicitly states that providing continuity plates eliminates the need to check for prying forces resulting from column flange deformations (i.e., *secondary* prying).

Ductility based design is being introduced into design codes to reduce the fabrication cost of steel moment connections while achieving the required seismic performance of structural members. The practice is to allow some inelastic deformations to occur in various elements of a connection to enhance its ductility and energy dissipation capacities without sacrificing its strength. In moment connections, continuity plates are often used to stiffen the column flange and web in order to resist large forces transmitted by the beam flange and to provide more ductile connection performance. However, detailing columns without continuity plates reduces the fabrication cost. Also in areas of high seismic risk, it is recommended to avoid welding in regions of potentially low notch toughness in wide flange sections and the corners of the continuity plates are required to be clipped as per ANSI/AISC 341-10 [4] and NIST [5]. As a result of omitting continuity plates in columns, column

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flange bending may cause *secondary* prying forces [1]. Thus, it is important to quantify the *secondary* prying forces in designing double Tee moment connections as an alternative of providing continuity plates, specifically for column flange thickness less than that of the Tee flange. And larger bolt diameter can be used to account for the additional forces caused by the flexural deformation of the column flange. Furthermore, ANSI/AISC 358-16 [1] explicitly states in the commentary section 13.5 that further research is needed before the requirement of including continuity plates can be relaxed.

Extensive experimental, finite element (FE), and analytical research dealt with the characterization of the monotonic and cyclic behavior of double Tee moment connections. Strength and mechanical models were proposed and validated against experimental and FE results [6–10]. All developed models dealt only with *two-bolted* thin and medium thickness Tees associated with thicker column flanges. For such connections, three failure modes are defined: (1) full Tee flange yielding, (2) Tee flange yielding at the K-zone followed by bolt fracture, and (3) pure bolt fracture. However in MRF thick flange double Tee connections are needed with deep girders to resist the large moment expected. This may lead to a connection where the Tee flange is thicker than the column flange. All existing models focused on thin to medium thickness double Tee connections connected to rigid columns. A modification of existing models was needed to accurately predict the response of thick double Tee connections. Hantouche et al. [3,11] proposed strength and stiffness models for thick Tees whereby partial yielding of the Tee flange occurs followed by bolt fracture. The authors also investigated numerically the effect of column flange deformation associated with thick double Tee connections in which the column flange is thinner than the Tee flange. It was concluded that, if continuity plates are supplied in columns, *secondary* prying becomes negligible [1,3]. Moreover, the authors proposed a mechanical based model to predict the behavior of thick double Tees including *primary* and *secondary* prying forces. However, no experimental work was performed and their proposed model was limited to a mixed mode failure in the column flange where full plastification at the K-zone is followed by interior bolt fracture. For this reason, an experimental work is performed and a mechanical model is developed in this research to cover all failure modes encountered in column flange/bolt system associated with thick double Tee moment connections.

Limited research work has been performed on the behavior of columns in thick double Tee connections. In such connections, the column flange is *four-bolted* as opposed to the Tee flange which is *two-bolted* (Fig. 1). In spite of the extensive studies performed on the double Tee connections, the research of past decades has almost neglected looking at column flange with four bolts per row. Pisarek and Kozłowski [12] conducted two experimental tests on double Tees having four bolts per row subjected to monotonic loading. The authors proposed a strength model to predict the behavior of *four-bolted* Tees based on the virtual work method and a mechanical based model that was limited to predicting the initial stiffness. Demonceau et al. [13] conducted experimental tests on extended endplates with four bolts per row. The authors suggested modifications to the strength model proposed by Eurocode 3 [14] which is applicable to Tees with two bolts per row. More recently, Massimo et al. [15] studied the behavior and failure

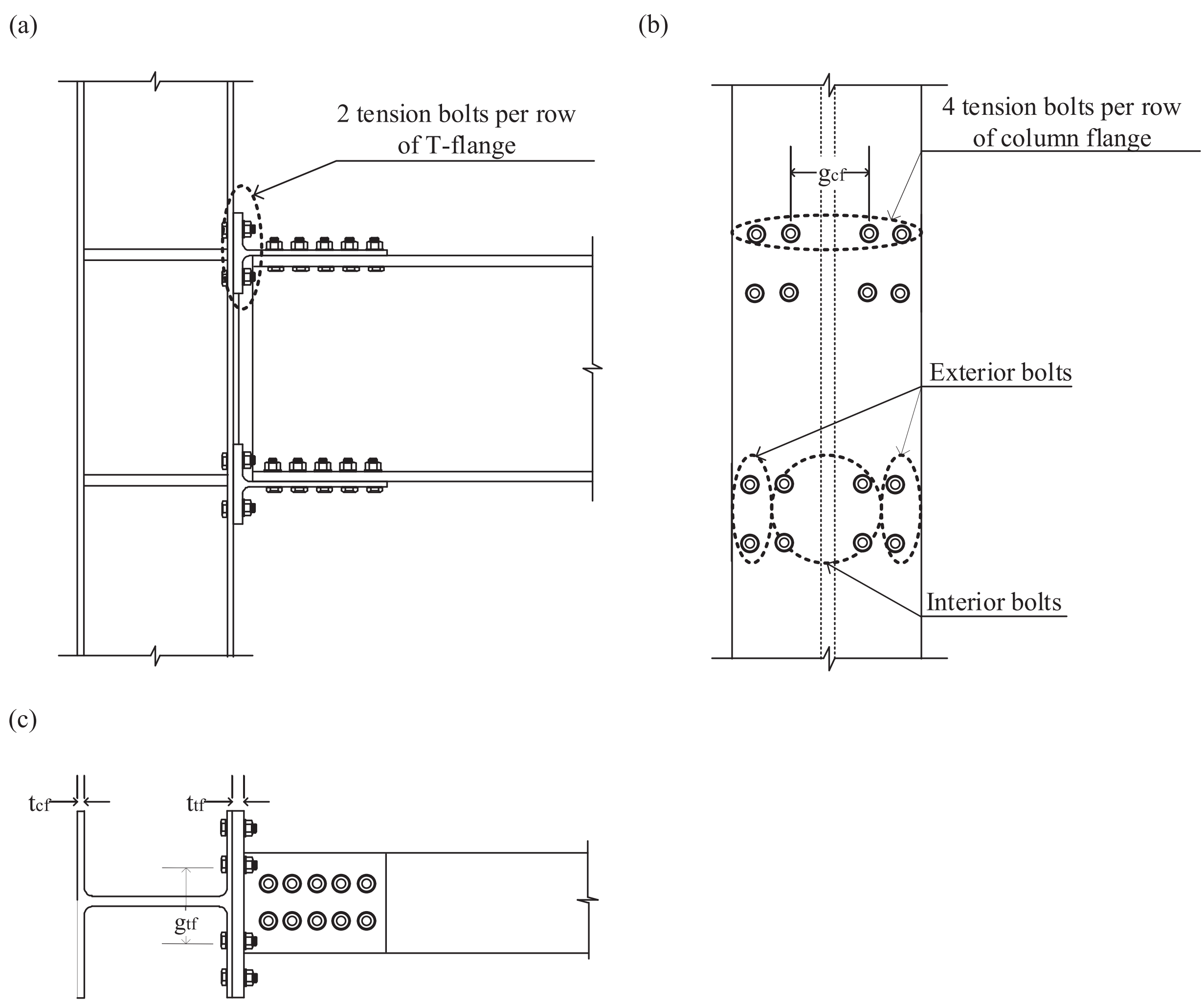


**Fig. 1.** Typical double Tee connection: (a) profile view of connection, (b) front view of column, (c) top view of connection.