BEHAVIOR OF WELDED T-STUBS SUBJECTED TO TENSILE LOADS

R.A. Herrera[1], G. Desjouis[2], G. Gomez[2], M. Sarrazin[3]

[1] *Assistant Professor, Dept. of Civil Engineering, University of Chile, Santiago, Chile*
[2] *Civil Engineer, Former Student, Dept. of Civil Engineering, University of Chile, Santiago, Chile*
[3] *Professor, Dept. of Civil Engineering, University of Chile, Santiago, Chile*
Email: riherrer@ing.uchile.cl

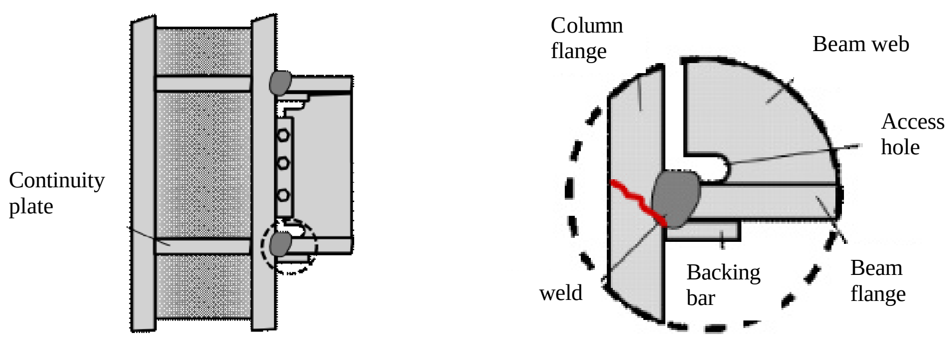
ABSTRACT :

T-stub moment connections are an alternative to welded steel beam-to-column moment connections. Significant research has been conducted on the behavior of the connection and the T-stub, resulting in models and design procedures. However, most research has been conducted on hot-rolled T stubs. Welded T stubs are a promising alternative to hot-rolled T-stubs, considering the freedom of sizing, and the absence of hot-rolled sections in several countries.
Analytical and experimental studies on the behavior of welded T-stubs subjected to tensile loading were conducted. The objectives of these studies included determining the controlling limit states for welded T-stubs, increasing the database of tests for these components, and evaluating applicability of current design recommendations to welded T-stub moment connections.
A finite element model of a welded T-stub was created and subjected to monotonic tensile loads to study the effects of stem-to-flange thickness ratio and bolt arrangement. Fillet welds between stem and flange were modeled. The analysis results indicate that yielding of the T stem may not be the controlling limit state because of the presence of the weld, and that allowing for a controlled prying of the T flange may be more appropriate.
A series of T-stubs with configurations similar to those studied analytically, scaled to one-half the original sizes, were tested under monotonically increasing tensile loads. The test results show that the strength of the T stub is above that predicted by current strength models and the dominating failure mode is bolt fracture due to prying action.

KEYWORDS: Connections, Steel structures, Testing, Modeling, T-stub

1. INTRODUCTION

One of the main goals of seismic resistant design is to achieve ductile structural behavior, which enables the structure to sustain considerable damage during a severe earthquake without collapsing, and provides it with a large source of energy dissipation through hysteretic behavior.
Strong column-weak beam design is one of the established means to achieve ductile structural behavior. In this type of design, the plastic collapse mechanism plastic hinges develop in the beams at every floor and at the base of the first story columns. To ensure that plastic hinges can form in the beams, the connections must be designed with enough capacity to transfer the largest forces and moments that will develop in the beams. In the 1970s, several research programs were conducted (Popov and Stephen, 1970; Krawinkler and Bertero, 1971) to verify the most used connections for moment resisting frames at the time. One of the most extended was the welded unreinforced flange (WUF) connection, shown in Figure 1(a). In this connection, the flanges were welded using complete joint penetration welds to the column flange and the beam web was connected through a plate to the column flange. The studies determined that if the welds were properly executed, these connections were adequate.



(a) Overview (b) Fracture detail

Figure 1 Pre-Northridge WUF connection

Following the damage observed on this type of connections after the Northridge, 1994 earthquake, a large research effort was carried out to study the behavior of moment connections between steel beams and columns. The main objectives of such efforts were to investigate the causes of the damage observed and to elaborate improved design procedures and recommendations for new steel moment resisting frames. The conclusions of the research conducted were summarized in the FEMA 350 report (FEMA, 2000) and they formed the basis for the new AISC Seismic Provisions (AISC, 2005). One innovation introduced by FEMA 350 was a list of prequalified connections, complete with design procedures and modeling recommendations. These connections had been extensively studied experimentally and analytically, such that their use for seismic resistant construction was approved, without further testing required. Among these connections was the Double Split Tee (DST) connection, shown in Figure 2. In this connection, the beam and column flanges are connected through a pair of bolted T stubs, while the beam web is connected through a shear tab to the column.

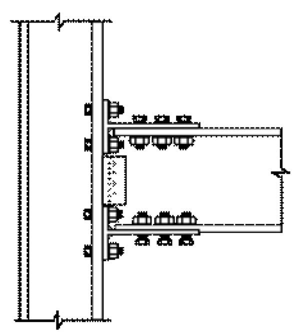


Figure 2 DST connection

The advantages of this connection are that it moves the plastic hinge in the beam away from the column flange and it can be easily installed on the field. However, all the research conducted to prequalify this connection was done using hot-rolled T stubs obtained from wide flange sections, which provide limited flexibility in the choice of flanges and stem dimensions, and are not readily available in all countries. Therefore, further studies on welded T stubs are needed to overcome these limitations.

This paper presents the results of analytical and experimental studies on the behavior of welded T stubs subjected to monotonic tensile loading. The objectives of these studies were to determine the parameters that control the behavior of these elements when used in DST connections.

2. PREVIOUS RELATED RESEARCH

A number of studies have been carried out using hot-rolled T stubs. Only the most relevant to the research reported are presented here.

Swanson and Leon (2000) conducted tests on 48 T stubs under monotonic and cyclic loading. They found that most of the specimens failed by shear fracture of the T stem and fracture of the tension bolts due to the increased tension and bending caused on them by the prying of the T flanges, and that the energy was dissipated through bending of the T flanges due to prying effect and slippage of the T stem with respect to the T flange. Following the T stub tests, Swanson and Leon (2000) tested six full scale beam-column connections, where similar failure modes were observed, but only after significant plastic hinging had developed in the beams. Tests on back-to-back T stubs loaded through the stems, performed by Piluso et al. (2001a), confirmed these conclusions.

Regarding welded T stubs, Coelho et al. (2004) tested 32 specimens, where the parameters studied included the thickness and type of weld, the type of steel, and the bolt properties. Again, the most common failure mode was fracture of the tension bolts due to prying of the T flange; however, some specimens developed fractures in the heat affected zone in the stem of the T. These fractures were attributed by the authors to defects in the fabrication process of the T stubs.

Several models have been developed to reproduce the stiffness and strength of a DST connection. The multiple failure modes involved and possible interaction between them make the analytical formulation complex, but they can be readily implemented numerically.

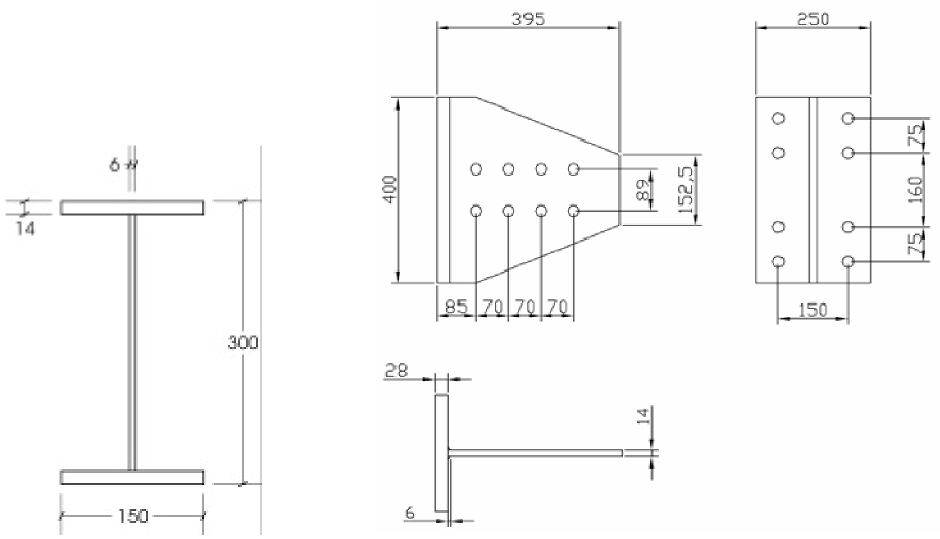
Piluso et al. (2001b) developed a model based on the failure modes observed in their tests: T flange bending due to prying effect, T flange bending combined with fracture of the tension bolts, and fracture of the tension bolts alone. The model adequately reproduced the test results of the same authors. However, it neglects the influence of the stem of the T, which can control the strength of the T stub (Swanson and Leon, 2000). Swanson and Leon (2001) extended this model to include the effects of the deformations developed in the T stub in a DST connection, namely tension bolt elongation, T flange flexure, T stem deformation, slip between T stem and beam flange, and bearing of the bolts on the T stem and beam flange. The model, known as the component model, was a combination of springs acting in series and in parallel, which represented the different deformation components previously indicated. They validated the component model with their own experimental data.

Due to the difficulties involved in testing, finite element (FE) models have been developed to conduct parametric studies on the behavior of DST connections. Most of them are 2-dimensional models, with all the limitations associated with trying to represent a 3-dimensional problem with a planar model. Sherbourne and Bahaari (1996) developed a detailed FE model which included the interaction between T stub and columns and beams, and the nonlinear friction between the stem of the T and the beam flange. The main conclusion of this study was the need to use 3D models to include the biaxial flexure developed in the T flanges. More recently, Coelho et al. (2006) developed a 3D FE model to reproduce their experimental results. The model included only one quarter of the connection and the model of the T did not consider the discontinuity in material properties and geometry induced by the fillet welds.

3. ANALYTICAL STUDIES

Considering all the limitations in previous analytical studies, a FE model of a T stub in a DST connection was constructed using the finite element package ANSYS multiphysics (ANSYS, 2005). This model was used to conduct parametric studies on the behavior of welded T stubs. The parameters considered were: distance

between tension bolts, layout of tension bolts, and flange-to-stem thickness ratio.
The basic T stub dimensions were obtained from the design of a DST connection for a IN30x45.8 beam. The beam was made of A42-27 steel, according to NCh 203 (INN, 1977), which has a yield strength F_y of 270 MPa and a tensile strength F_u of 420 MPa. The T stub was made of ASTM A572 Gr. 50 steel, which has nominal F_y and F_u values of 350 MPa and 450 MPa, respectively. A490 bolts, 7/8" diameter were assumed, in order to be able to compare with the results of Swanson and Leon (2000). The dimensions of the beam and the resulting T stub dimensions are shown in Figure 3, where all dimensions are in millimeters. The bending strength of the connection associated to each failure mode is shown in Table 3.1.



(a) Beam (b) T stub
Figure 3 DST connection design

Table 3.1 Connection moment capacity according to FEMA 350 (FEMA 2000)

Failure Mode	Moment capacity [kN-m]
Shear bolts fracture	726
T stem tension fracture	687
T flange plastification	309
Tension bolts fracture	553
T stem block shear	399

This basic T stub was modified in order to conduct the parametric studies. Table 3.2 shows the parameters for the configurations analyzed under monotonic loading.

(a) TSDD1 (b) TSDD2
Figure 4 Configurations to study the effect of the tension bolts layout

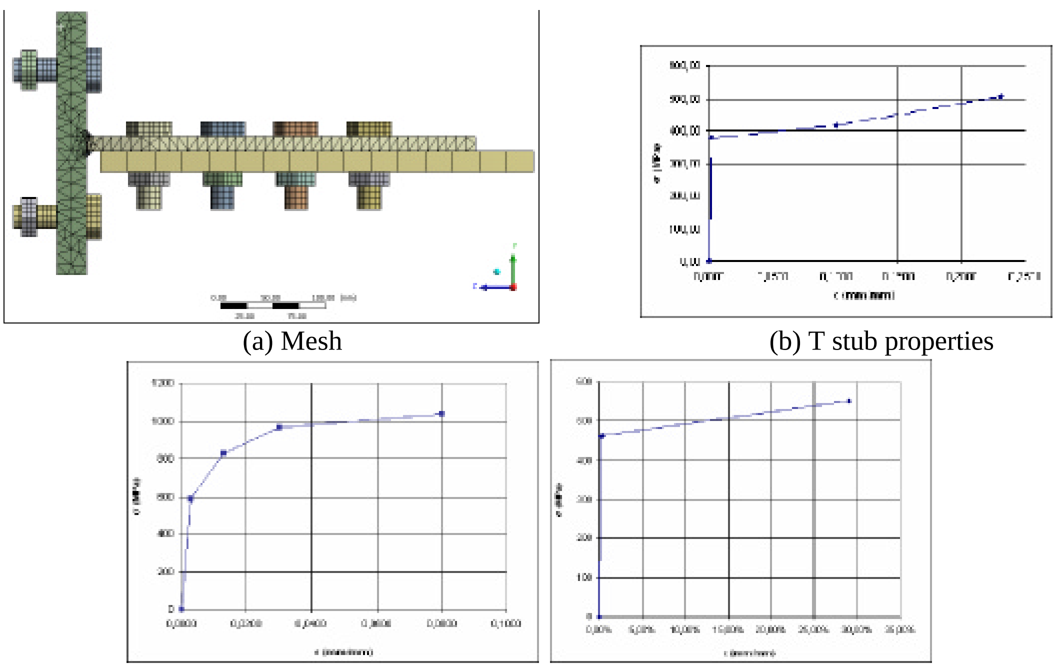
To generate the analysis matrix, the flange thickness was maintained, while the stem thickness and distance between tension bolts were varied. The last two configurations correspond to the outer tension bolts spaced closer and farther than the interior bolts, respectively, as shown in Figure 4.

Table 3.2 Analysis matrix

Name	Stem thickness [mm]	Tension bolt gage spacing [mm]
TSD140	14	140
TSD150	14	150
TSD160	14	160
TSD170	14	170
TSD180	14	180
TSE8	8	150
TSE10	10	150
TSE14	14	150
TSE16	16	150
TSDD1	14	140-180
TSDD2	14	180-140

3.1. Model description

The finite element model developed is shown in Figure 5. To simplify the model, only one half of the T stub was modeled considering symmetry conditions, the beam flange was modeled as a rigid element, and the column was replaced by a rigid surface with compression-only supports. The steel properties for the T stub and the A490 bolts proposed by Swanson and Leon (2001), shown in Figure 5, were used.



(a) Mesh (b) T stub properties

(c) Bolt properties (d) Weld properties

Figure 5 Finite element model of the T stub

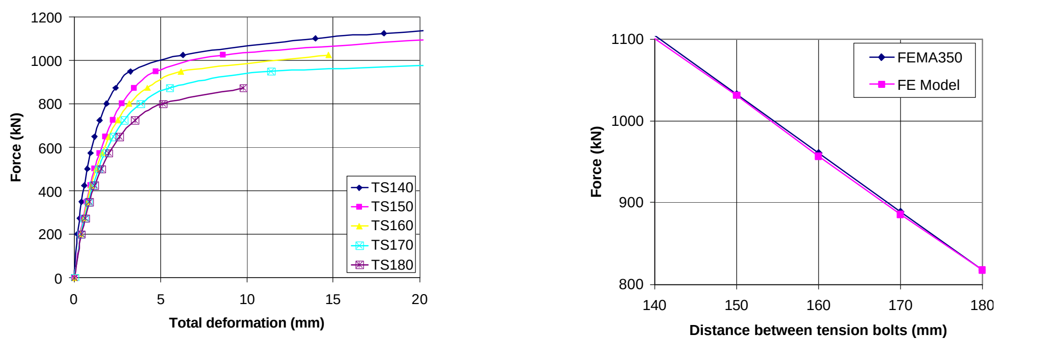
The weld region was modeled with material properties recommended by an electrode provider, considering an

E7010A1 electrode and data from tests performed according to AWS 5.5 specifications (AWS, 1996). A space was provided between the flange and the stem, to simulate the situation of incomplete penetration through the thickness of the stem of the fillet welds.

Solid rectangular 20-node and tetrahedral 10-node elements were used to mesh the T stub and bolts. The load was applied in two stages; first, the bolts were subjected to a pretension, followed by the application of monotonic loading through the beam flange. The analysis was stopped when the fracture strain ε_u was reached on any of the elements of the model (8% for the A490 bolts, 23% for the A572 Gr.50 and 29% for the weld material).

3.2. Analytical results

The total force-deformation behavior of the tees for different tension bolt distances is shown in Figure 6(a). All the configurations failed due to fracture of the tension bolts. It can be seen that the strength and ductility of the T stub decrease with an increase in the distance between tension bolts. The decrease in strength is consistent with that predicted by FEMA 350 (FEMA, 2000), as illustrated in Figure 6(b). The reduced ductility is explained by the increase in the bolt force due to prying action.



(a) T stub force-deformation results (b) Comparison with FEMA 350 (FEMA, 2000)

Figure 6 Effect of tension bolt spacing

It was also observed that, for the configurations with more closely spaced tension bolts (TD140 and TD150), the strains in the welds approached the fracture strains. This may explain in part the fractures observed by Coelho et al. (2004) in their experiments.

The results of the variation in T stem thickness are shown in Figure 7. For the thinner stem configurations (TSE8 and TSE10) the failure occurred due to tension fracture in the net section of the stem, while for the others, minor inelastic deformations were observed in the stem and the failure occurred by fracture of the tension bolts.

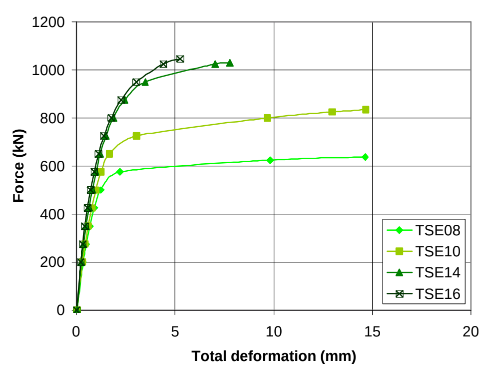
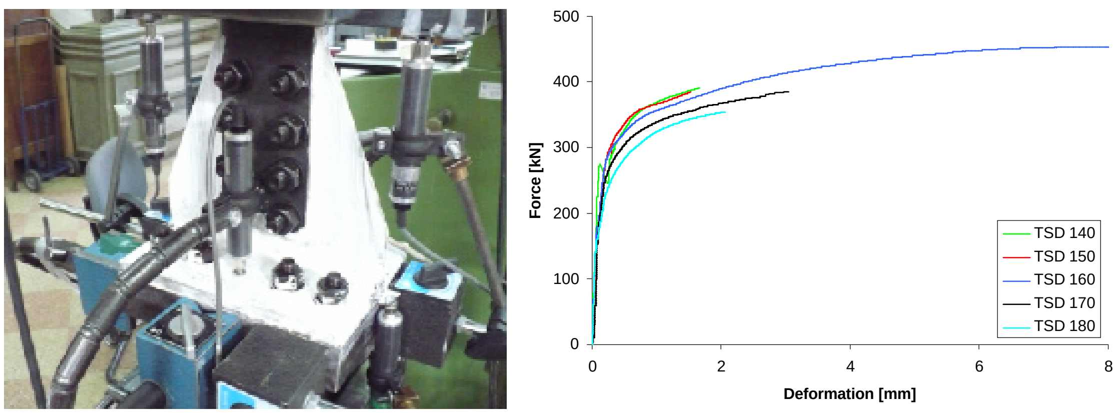


Figure 7 Effect of stem-to-flange thickness ratio

It can be seen that the configurations with thinner stems developed less capacity, but more ductility than the others. However, the large inelastic deformations in the stem affect the weld and the resulting design is inefficient with respect the use of the available bolt strength.
No significant effects on the behavior and strength of the T stub were observed when the layout of the tension bolts was modified (TSDD1 and TSDD2 configurations).

4. EXPERIMENTAL STUDIES

In order to validate the analytical conclusions, 2 series of 11 T stub configurations were tested under monotonically increasing tension. The specimens were one-half scale models of the configurations studied analytically. The specimens were tested under load control using a 600 kN universal testing machine. The instrumentation used included strain gages to measure strains in the T stem; LVDTs to measure total deformation, T flange prying, and uplift in the line of tension bolts; and a pressure gage to determine the applied load. The test setup is shown in Figure 8(a), and the results for different tension bolt spacing in Figure 8(b). These results confirm the conclusions of the analytical studies about the relationship between bolt spacing and strength.



(a) Experimental setup (b) Effect of tension bolt spacing
Figure 8 Experimental studies

The results for different stem thicknesses also confirm the analytical results: specimens TSE8 and TSE10 failed by tensile fracture of the T stem and had significantly lower strength than specimens TSE14 and TSE16. No significant damage was observed on the welds.

5. CONCLUSIONS

Analytical and experimental studies on the behavior of welded T stubs under tension were conducted. The objective of these studies was to evaluate the behavior of welded T stubs for use in DST connections.
The analytical studies involved the development of a finite element model of the T stub in the connection, which included material nonlinearities and geometric discontinuities. The analytical results showed the potential for weld fracture when thin stems are used, or when the tension bolts to one side of the stem are spaced close to the tension bolts on the opposite side of the stem.
The experimental studies verified some of the conclusions of the analyses. Tension bolt fracture was the main failure mode for all specimens, with the exception of the specimens with thinner stems. The strength was larger than the strength predicted by current design recommendations and the analytical model.
The analytical and experimental results will be used to revise and improve model for strength and stiffness of DST connections, when using welded T stubs.

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