EUROCODE BASED STUDIES ON BOLTED T-STUB MOMENT RESISTANT BEAM-TO-COLUMN JOINTS

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INTRODUCTION

The numerous recent failures of rigid beam-to-column joints under earthquake events has called attention to the disadvantages of fully welded connections. For this reason, significant experimental and analytical research has been conducted at several institutions in the area of bolted moment resistant joints with the aim to develop standardized design methods. From the SAC research conducted at the Georgia Institute of Technology [1,2], from amongst a wide range of bolted joint types, this paper focuses on the fully bolted T-stub beam-to-column joint, as shown in *Figs. 1 and 2*. As part of the senior author's work as a visiting scholar, the results of the SAC work were re-examined based on the Eurocode recommendations. This fully bolted joint type is partially covered by the EC3. For this reason, the aim was to study the basic EC3 design method and find supplementary design rules in the resistance model to be able to evaluate tension and moment resistance. The results of the basic EC3 method and the proposed supplementary design recommendations are compared with the test results and verified qualitatively by the failure modes and quantitatively by the tension and moment resistance and shown good coincidence between test and design values.

1 SUMMARY OF THE EXPERIMENTAL TESTS

An extensive experimental program was carried out by Swanson and Leon [1, 2] on bolted connections and component behaviour as part of the SAC Steel Project [3]. The test studied both the monotonic and cyclic behaviour of bolted T-stub beam-to-column joints and their components, with the aim to increase the experimental databank and provide bases for the development of a robust, mechanistic design method. In this section a short summary on the test program and the results are given.

1.1 Test program, specimens

Two types of test were carried out:

- Component test – on 48 T-stub (*Fig. 1*) and 10 clip angle components.
- Full beam-to-column joint – 6 specimens (*Fig 2*).

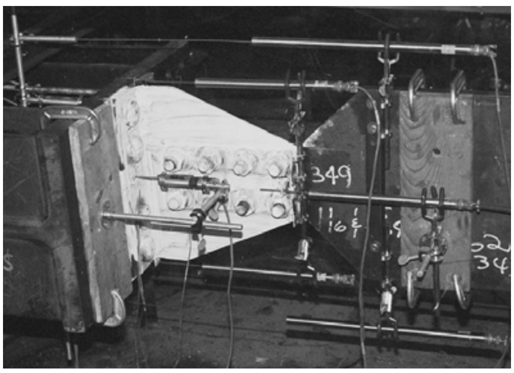


Fig. 1. T-stub component test [1]

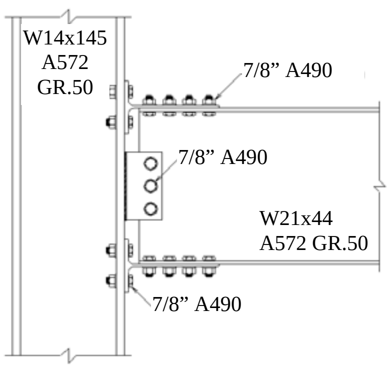


Fig. 2. Full beam-to column joint tests [1]

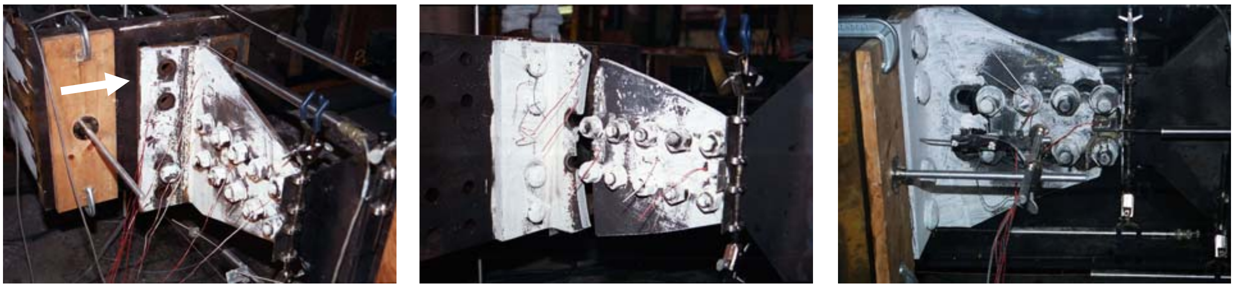
Most of the T-stub specimens were subjected to cyclic load history applied axially. Four duplicate T-stubs were tested monotonically to provide reference points for comparing the cyclic data to the existing monotonic data. The full beam-to-column joint specimens were subjected to cyclic bending. The cyclic load history specified in the SAC [3] testing protocol was used for each specimen.
Four series of T-stub component tests were carried out, labelled as the TA, TB, TC and TD series. Within each of the different series, parameters such as bolt grade, diameter, gage, and spacing, were systematically varied, for T-stubs cut from four different wide flange sections. The components were subjected to axial loads based on expected beam flange forces in actual connections. In case of the full-scale beam-to-column tests (named FS), the T-stubs similar to those tested as components were incorporated.

1.2 Experimental results

On the basis of the measured data the monotonic and cyclic force-displacement relationship was determined, which gives results for the load and deformation capacity, initial stiffness and the dissipated energy in case of each specimen. The observed failure modes of the T-stub component and the full beam-to-column joints were as follows:

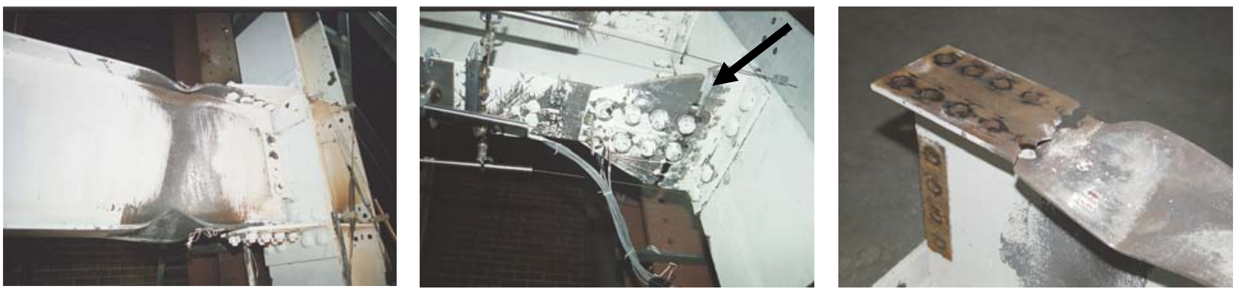
- Tension bolt failure: The most sudden and brittle of the failure modes, shown in *Fig. 3.a),*
- Net-section fractures of the stem preceded by extensive yielding: Fractures first developed between the last two bolts and then spread out towards the edges *Fig. 3.b)* and *Fig 4.b),*
- Block shear failure: Developed in one T-stub, shown in *Fig. 3.c),*
- Shear bolts fracture: T-stubs were designed to avoid shear bolt failures,
- Plastic hinging: Forming in the beam directly adjacent to the end-of the T-stub, see *Fig. 4.a),*
- Beam fracture: At the holes of fasteners, occurred after the plastic mechanism, see *Fig. 4.c).*

In the different test series, the effect of the varied parameters to the behaviour is also determined.



a) bolt fracture (TA-03) b) net-section failure (TA-05) c) block shear failure (TA-26)

Fig. 3. Failure modes –T-stub component test [1]



a) plastic hinge (FS-06) b) net-section failure (FS-03) c) flange fracture (FS-07)

Fig. 4. Failure modes – Full-scale beam-to-column joints [1]

2 EUROCODE BASED STUDY

After close examination of the experimental behaviour of the SAC results, a study for a joint type considered by Eurocode 3 [4] (hereinafter EC3) was performed with the aim to evaluate the tension resistance of the T-stub ($F_{j,Rd}$) component and the moment resistance ($M_{j,Rd}$) of the beam-to-column joint and to compare them with experimental results and verify the design method.

2.1 Eurocode recommendations

The EC3 standard [4] recommendations partially cover the studied joint type. For the EC3 study, first the basic EC3 method is used and compared to experimental results. After finding out that the current EC3 method produces results with a wide scatter and not always conservative, some supplementary design rules to the EC3 ones – found during international literature review – are applied and verified against test results. In assessing the applicability of the EC3 rules to the SAC specimens tested, the following lack of recommendations are found:

- During the experimental program all except six of the T-stubs tests included 8 tensioned bolts (4 bolts in one row) to connect the flange of the T-stub to the column flange (see *Fig. 6*).
- Because the column flanges were wider than the flanges of the beams, the stems of all of the T-stubs were tapered. The tension resistance of the tapered stem needed to be evaluated (see *Fig. 7*).

The EC3 applies the component method to establish the resistance and the stiffness of the joints. The EC3 only partially covers the studied connection type, and for this reason modification to two components (6* and 9*) are proposed. The basic components are as follows (see *Fig. 5*.).

- column web panel in shear (1),
- column web in transverse compression (2),
- column web in transverse tension (3),
- column flange in bending (4),
- T-stub (6*) – modified component,
- beam flange and web in compression (7),
- beam web in tension (8),
- plate in tension or compression (9*) – modified component,
- bolts in tension (10),
- bolts in shear (11),
- bolts in bearing (12).

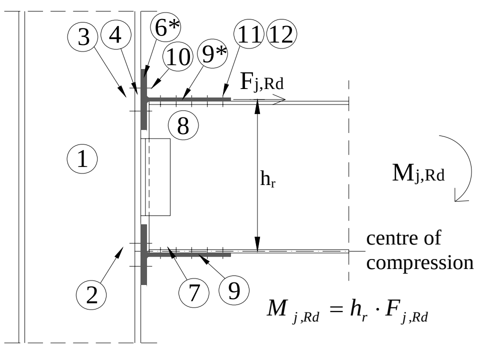
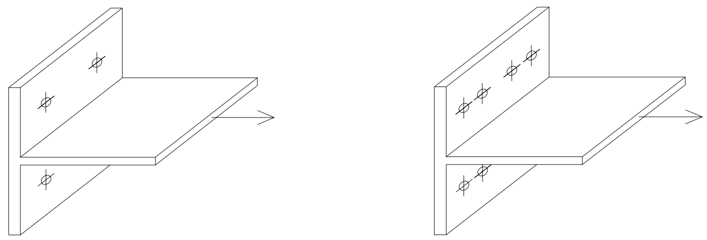


Fig. 5. Basic components

In the component model the moment resistance of the joint is coming from the smallest resistance of the above basic components (1)–(12). The presented study is based on experimental observations of the failure modes. As it was found that the failure occurred in the beam side in all cases, the column side is not investigated and thus components (1)–(4) are neglected from the resistance calculation. The moment resistance of the joint is therefore determined by the smallest contribution of components (6*), (7), (8), (9*), (10), (11) and (12).

2.2 The proposed supplementary design rules

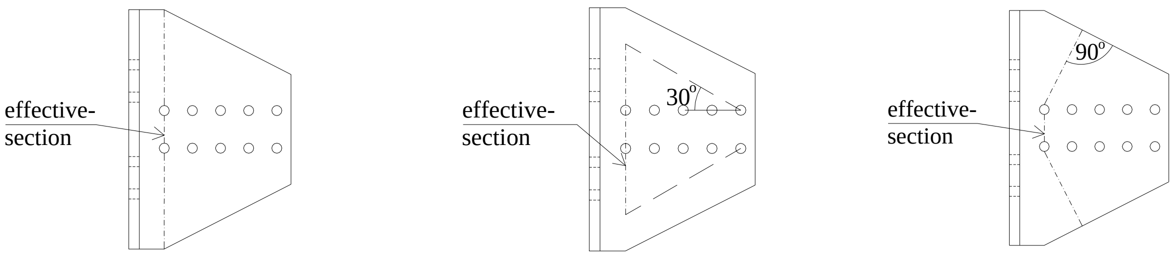
The current limitations of the rules in EC3 to address the SAC results, the following modifications are proposed:
The resistance of the component (6*) is investigated by the equivalent T-stub. The EC3 gives recommendations to evaluate the resistance of T-stubs with 2 bolts in one row configuration, as shown in *Fig 6. a*). In most of the experimental tests 4 bolts in one row type configuration were tested, which is not covered by the EC3. To handle this difficulty a method, presented in [5], is applied for the current study. In [5] the design method for 4 bolts configuration is developed and all the effective lengths (ℓ_{eff}) are calculated, considering all possible yield line patterns.



a) 2 bolts in one row   b) 4 bolts in one row

Fig. 6. T-stub configuration

To evaluate the tension resistance of the tapered T-stub stem the effective section needs to be determined. The conventional way of net-section calculation is shown in *Fig. 7. a*). In the American literature [6] a well-established design method was found to evaluate the theoretically effective width of the tapered T-stub stem taking into consideration the stress distribution, as shown in *Fig. 7. b*). This is the so called Whitmore section with a spread-out angle of 30° along both sides of the connection, beginning at the start of the connection. In [1] the modification of the above angle is introduced for plates with smaller thicknesses the spread-out angle of 22,5° is recommended. In [7] the effective sections of *Fig. 7. c)* found, where the net-section perpendicular to the edge of the tapered stem.
In the present calculation all three definitions of the effective sections are evaluated and the smaller of them, which depends on the geometry of the stem, is taken into consideration to evaluate the resistance of component (9*).



a) conventional effective section   b) effective section of [6]   c) effective section of [7]

Fig. 7. Tapered T-stub stem

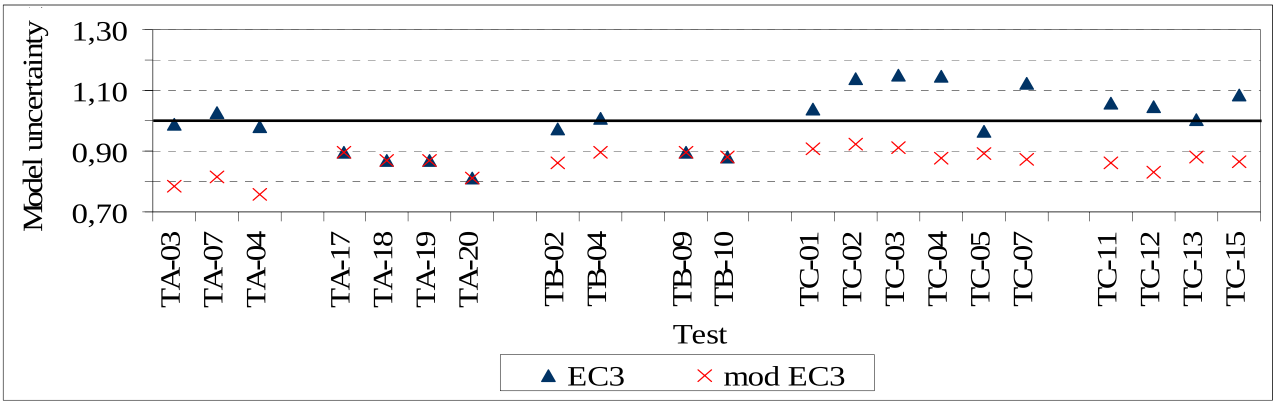
The EC3 gives procedures to calculate representative joint parameters considering monotonic behaviour. In our case most of the specimens were subjected to cyclic loading; however, in certain cases monotonic tests were performed as well to compare the cyclic and monotonic performance. In this study in case of cyclic tests the envelope curve of the hysteretic moment-rotation diagram is assumed to follow the monotonic response. Due to strain hardening during the cycles, the average of the yield and ultimate stress is used for resistance calculation instead of the yield stress.

2.2 Comparison of design values and experimental results

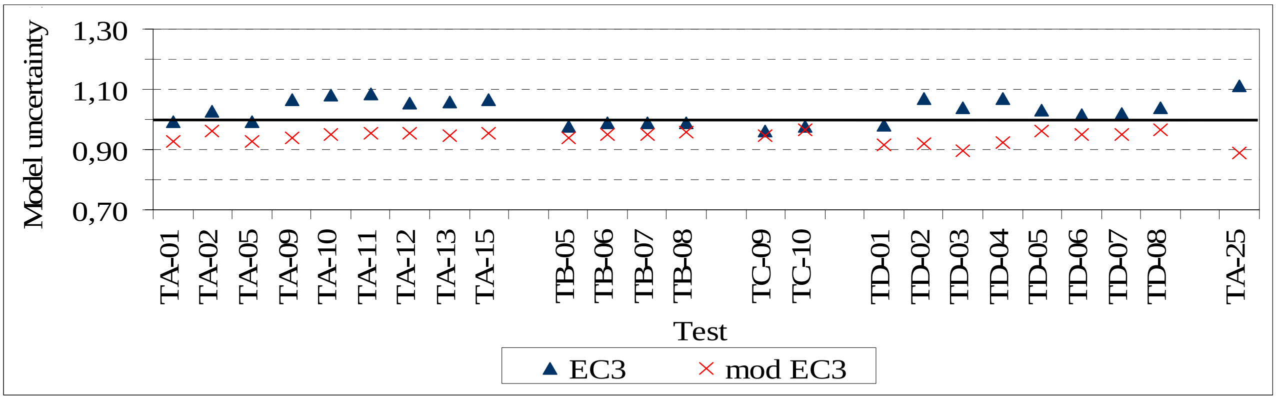
In this section the moment resistance evaluated by different definitions are compared with experimental results. The uncertainty in the material property (γ_m) is eliminated by using the experimentally tested material properties. The design resistance contains the model uncertainty (γ_{Rd} =predicted resistance/test resistance), which can be determined from the comparison of the experimental and design values.

As the first step the EC3 basic rules are applied, and the moment resistance is evaluated by the original EC3 model. This means that the T-stub model developed for 2 bolts in one row is used (*Fig. 6. a*), so the possible failure of the group of four bolts are not taken into consideration. The net-section is also evaluated by the conventional way, the effective width of the stem is equal to the total width with the reduction of the bolt holes (*Fig. 7. a*). These results are marked by "EC3" and the model uncertainty (predicted-to-measured capacity) is plotted in the *Figs. 8-9*.

After this, the basic EC3 method is modified by the supplementary rules found in international literature, detailed above. The T-stub model applicable for 4 bolts in one row is applied, taking into consideration the possible group failure of fasteners (*Fig. 6. b*). The net-section is evaluated by the smaller of the effective sections of *Fig. 7. b*) and *c*). These results are marked by "mod EC3" and the model uncertainty is plotted in the *Figs. 8-9*.



a) T-stub failure



b) net-section failure

Fig. 8. Tension resistance of the T-stub ($F_{j,Rd}$) component

T-stub type failure – component test (*Fig. 8. a*):
Specimen TA-17 – TA-20, TB-09 and TB-10 are the control test having 4 tension bolts in the T-stub (similar to *Fig. 6 a*). In case of these specimens there is no mean of modification of the basic EC3 T-stub model.
The rest of the specimens in *Fig. 8 a*) have 8 tension bolts. By comparing the experimental and design tension resistances, it is found that the basic EC3 method overestimates the resistance in

most of these cases, so neglecting the bolt group failure leads to an unsafe resistance estimation in the current connection type. Calculating the tension resistance by the modified EC3 method results in safe predictions for all specimens.

Net-section fracture type behaviour – component test (*Fig. 8. b*):
By calculating the effective section by the conventional EC 3 method, in most of the cases the tension resistance is overestimated, as shown in *Fig. 10 b*). Applying the effective sections the model uncertainty is less than 1 for all the specimens.

Moment resistance – full beam-to-column joints (*Fig. 9.*):
For specimens FS-03, FS-04 and FS-07 the failure modes from the EC3 calculation are the "beam flange and web in compression"; however, the tests showed fracture of the T-stub stem, and the moment resistance is overestimated by the EC3. Applying the effective section of *Fig. 7 b*) or *c*) the test failure mode can be predicted, except for the FS-07. The failure of the FS-05, FS-06 and FS-08 is governed by the plastic hinge of the beam and EC3 calculations gives model uncertainty between 0,9 and 1,0.

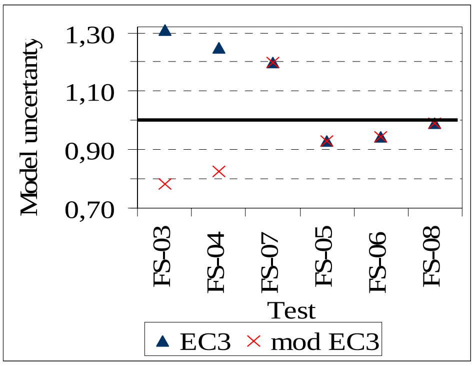


Fig. 9. Moment resistance ($M_{j,Rd}$)

3 SUMMARY AND ACKNOWLEDGMENT

The paper presents the comparison of the design and the tested resistance of bolted T-stub components and full bolted beam-to-column joint. In this paper a short summary of the specimens and the behaviour modes are given, more details can be found in [1].
The design recommendations of EC3 partially covers the studied joint type, and for this reason a literature review was performed to find supplementary design recommendation for evaluation of the design resistance.
From the comparison of design and experimental values, it is found that in case of the studied joint the basic EC3 resistance model results in an overestimation of capacity, which can be occurred by the intent to address in this standard smaller connections than those tested by SAC. Building up a more detailed model by application of supplementary rules, the estimated resistance is under the experimental one with a reasonable model uncertainty.

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