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Experimental investigation and design of extruded aluminium alloy T-stubs connected by swage-locking pins

Zhongxing Wang^{a,b}, Yuanqing Wang^a, Ying Zhang^a, Leroy Gardner^{b} and Yuanwen Ouyang^c*

^a *Department of Civil Engineering, Tsinghua University, Beijing 10084, PR China*

^b *Department of Civil and Environmental Engineering, South Kensington Campus, Imperial College London, London SW7 2AZ, UK*

^c *Shanghai Tongzheng Aluminium Engineering Co., Ltd., Shanghai 200030, PR China*

*Corresponding author, Email: Leroy.gardner@imperial.ac.uk

Abstract: The structural behaviour and design of extruded aluminium alloy T-stubs connected by swage-locking pins under monotonic loading are investigated in this study. Thirty experiments were performed and the test set-up, testing procedure and experimental results, including failure modes, ultimate load-carrying capacity, deformation capacity and load-displacement response, are reported. Component tests were also carried out on the swage-locking pins to assess their load-carrying capacities under pure tension, pure shear and combined tension and shear; these tests were complemented by tensile coupon tests on the pin and T-stub plate material. Resistance functions to predict the capacity of the swage-locking pins were developed and assessed against the test results. The EN 1999-1-1 (EC9) design rules for predicting the resistance of extruded aluminium alloy T-stubs were also evaluated and found to be safe-sided, but rather conservative relative to the experimental results. Improved resistance predictions were achieved through application of the continuous strength method (CSM).

Keywords: Aluminium alloy; T-stub joints; Experiments; Continuous strength method (CSM); Swage-locking pin; Testing.

1 Introduction

Aluminium alloys have been widely used in many thousands of space structures as well as different types of bridges [1] due to their sound structural characteristics combined with good corrosion resistance, high strength-to-weight ratio and aesthetic appearance. Although research into the behaviour of aluminium alloy beams and columns dates back to early last century, research into aluminium alloy beam-to-column joints is far more limited. De Matteis and Brando [2] highlighted the virtues of testing T-stubs as an efficient and cost-effective means of evaluating the key components affecting the performance characteristics of beam-to-column joints. Following this, designers or researchers can apply the well-known ‘component method’ [3] set out in EN 1993-1-8 [4] to analyse the flexural response of a given joint. An equivalent T-stub can represent the behaviour of angle cleats in bending, end plates in bending and column flanges in bending, as shown in Fig. 19, through the component method [5]. Research on T-stubs is therefore an essential first step to studying the behaviour of aluminium alloy beam-to-column joints and to applying them in practical engineering applications.

Owing to the nonlinearity, strain hardening behaviour and limited ductility of the material, the structural behaviour of aluminium alloy T-stubs may differ significantly from that of steel T-stubs, which have been widely studied [6-11]. De Matteis and his co-workers conducted 26 tests on welded aluminium alloy T-stub joints connected by bolts under both monotonic loading [12] and cyclic loading [13] and carried out corresponding numerical [14] and parametric analyses [15]. Xu et al. [16] performed a finite element

study into the behaviour of bolted aluminium alloy T-stubs to investigate the failure modes, ultimate load-bearing capacity and effective length of flanges. Building on this previous research, the purpose of the present paper is to provide test data on extruded aluminium alloy T-stubs connected by swage-locking pins, which have not been studied to date, under tensile force and to utilise the results to evaluate the accuracy of current design methods.

In total, thirty extruded aluminium alloy T-stub joints were tested under monotonic loading, with the key varied parameters being the distance between the fasteners and the T-stub web, the flange thickness, the swage-locking pin collar type and the diameter and layout of the fasteners. All the T-stub joints were connected by swage-locking pins which can be very rapidly fastened using a specialized tool and are resistant to loosening and vibration. The load-carrying capacity, deformation capacity and failure modes obtained from the T-stub joint tests are presented and analysed. Finally, the test results are used to evaluate existing design methods and to assess the reliability of a proposed new design approach. Inclusion of provisions for T-stubs and swage-locking pins are anticipated in the next revision of the Chinese code for design of aluminium structures GB 50429 [17].

2 Experimental programme

An experimental programme comprising tests on T-stubs and their constituent components, i.e. plate material and swage-locking pins, is described in this section. The experimental results are reported in Section 3.

2.1 Test specimens

Thirty extruded aluminium alloy T-stubs connected by swage-locking pins were tested to study their structural behaviour under tensile loading. The configuration of the test specimens is shown in Fig. 20, where TSS refers to T-stub specimens with a single row

and a single column of pins, TSD refers to T-stub specimens with a single row and double columns of pins, TDS refers to T-stub specimens with double rows and a single column of pins and TDD refers to T-stub specimens with double rows and double columns of pins. The specimens were tested in pairs, back-to-back, rather than as single T-stubs assembled against a rigid support, to avoid premature shear failure of the fasteners [5]. The T-stubs were connected together by swage-locking pins, which are a new type of fastener, resistant to loosening and vibration. The pins were made of stainless steel, while the collars were made of either aluminium alloy or stainless steel, neither of which lead to electrochemical corrosion with the aluminium alloy T-stubs. The stainless steel-collar pins have a larger load-carrying capacity than the aluminium alloy-collar pins, but at a higher cost. In the tests performed herein, two swage-locking pin diameters were considered – 9.66 mm and 12.70 mm. Since the 9.66 mm pins are the most widely available, these were used in the majority of the experiments; a limited number of tests using 12.70 mm pins with aluminium alloy collars were performed. The connecting process is shown in Fig. 21. The installation tool is a hydraulic rivet gun, which preloads the swage-locking pin and plastically deforms the collar in order to tightly grip the thread. The preload provides an increase in axial stiffness to the T-stubs [6].

The measured dimensions of all the specimens are presented in Table 7, in which d_{pin} is the diameter of the swage-locking pins, $F_{\text{p,C}}$ is the preload in the fasteners (i.e. the swage-locking pins) measured by a specially devised load cell and other symbols are as defined in Fig. 20. The nominal value of d_p and d_e for the TSD and TDD specimens was 30 mm and 25 mm respectively, while the nominal value of t_w was 8 mm for all specimens.

The specimens are labelled such that the key parameters including the T-stub type (TSS, TSD, TDS, or TDD), the pin collar material (aluminium alloy (A) or stainless steel (S)), the flange thickness (8 mm, 10 mm or 12 mm) and the distance between the pin and web

(from 20 mm to 50 mm) can be identified from the label. For example, the label TSDA-8-20 indicates a TSD-type T-stub, with aluminium alloy pin collars (if the fourth letter is “S”, it indicates that the material of the pin collar is stainless steel), a nominal flange thickness of 8 mm and a nominal distance between the pins and the web of 20 mm. However, for the specimens with double rows of pins (i.e. the TDS- and TDD- type specimens), the last group of number indicates the fastener pitch e_2 , which is defined in Fig. 2; for example, the label TDDA-10-30-25 indicates a TDD-type specimen with aluminium alloy pin collars, a flange thickness of 10 mm, a distance between the pins and the web of 30 mm and a fastener pitch of 25 mm.

2.2 Tests on swage-locking pins

Prior to the testing of the T-stubs, 42 experiments on swage-locking pins under pure tension, pure shear and combined tension and shear were conducted. As well as the familiar failure modes associated with ordinary bolts in tension and shear, swage-locking pins also exhibit an additional failure mode termed collar pull-out.

A special fixture [18] was devised to load the swage-locking pins with different combinations of tension and shear force, as shown in Fig. 22 (a). By changing the position of the loading bar, the pins could be loaded at a variety of angles, at 15 degree intervals. The tests were performed using a 300 kN hydraulic testing machine under load control and the test setup is illustrated in Fig. 22 (b). The deformation was measured using a video gauge which is detailed in Section 2.4. The measurement points were marked onto the front surface of the fixture.

Swage-locking pins with both aluminium alloy and stainless steel collars were tested at seven different angles, as shown in Table 8, in which θ_s is the angle between the direction of the load and the longitudinal axis of the pin and $F_{s,\text{test}}$ is the test failure load. Each test was repeated three times to evaluate the consistency of performance. The load-carrying

capacity of all specimens is shown in Table 8, where r_1 , r_2 and r_3 indicate the serial number of the repeated tests. From the table, it is evident that the tensile strength of the pins with the stainless steel collars is much larger (around 40% on average) than that of the pins with the aluminium alloy collars. However, since all pins are of the same material and diameter, the resistances of the specimens loaded predominantly in shear ($\theta_s = 60^\circ$, 75° and 90°) are almost the same, regardless of the collar material. Fig. 23 shows the load-axial deformation responses of the swage-locking pins under pure tension, which reveals that the pins with the stainless steel collars have slightly higher stiffnesses than those with the aluminium alloy collars. The deformation of one of the pins with a stainless steel collar was not measured successfully, and hence only two curves are presented for this case.

The failure modes of all the specimens are shown in Fig. 24; three modes of failure were observed: (i) Mode 1: collar pull-out, (ii) Mode 2: shear deformation of the bar combined with collar pull-out and (iii) Mode 3: fracture of the bar. It was found that with increasing values of θ_s , the shear deformation of the pins became increasingly prominent.

Formulae to predict the load-carrying capacity and failure mode of swage-locking pins loaded at different angles are given in Eq. (1) and Eq. (2),

For swage-locking pins loaded predominantly in tension, failing in Mode 1 or Mode 2:

$$F_{Rd} = F_{t1} / \cos \theta_s \quad (1)$$

For swage-locking pins loaded predominantly in shear, failing in Mode 3:

$$\left(\frac{F_{Rd} \cos \theta_s}{F_{t2}} \right)^2 + \left(\frac{F_{Rd} \sin \theta_s}{F_v} \right)^2 = 1 \quad (2)$$

in which F_{Rd} is the design resistance of the swage-locking pin, taken as the lower value (hence defining the critical mode) from Eq.(1) and Eq.(2), F_{t1} is the resistance of the collar to pull-out ($F_{t1} = 34.9$ kN for the aluminium alloy collar and $F_{t1} = 49.6$ kN for the stainless steel collar are the mean values from the tests performed herein), F_v is the shear resistance

of the bar, which had a mean value of 53.6 kN from the six experimental results and F_{t2} is the tensile resistance of the bar, calculated as $F_{t2} = Af_u$, which was equal to 65.4 kN based on the measured material properties of the pin shown in Table 10.

A comparison between the test $F_{s,\text{test}}$ and predicted F_{Rd} resistances of the swage-locking pins loaded at different angles is presented in Table 9. A mean value of $F_{Rd}/F_{s,\text{test}}$ of 1.01 with a coefficient of variation (COV) of 0.058 and maximum relative error of 0.08 for the pins with the aluminium alloy collars and a mean value of $F_{Rd}/F_{s,\text{test}}$ of 1.03 with a COV of 0.027 and maximum relative error of 0.06 for the pins with the stainless steel collars were obtained, representing very good agreement. Owing to the limited number of tests, the value of $F_{Rd}/F_{s,\text{test}}$ was also compared with the characteristic values from the Student's t distribution [19] which is applicable for small sample sizes. Through application of the distribution model, the confidence intervals associated with a 90% confidence level in the ratio of $F_{Rd}/F_{u,\text{test}}$ for the swage-locking pins with aluminium alloy collars and stainless steel collars were obtained as (0.96, 1.06) and (1.01, 1.06), respectively.

Owing to the limited number of 12.70 mm diameter swage-locking pins, only one pure tension test and one pure shear test were conducted, with capacities of $F_{t1} = 56.7$ kN and $F_v = 83.5$ kN, respectively.

2.3 Material testing

Tensile coupon tests were conducted according to the standard GB/T 228.1 [20] and AS 1391-2007 [21] to determine the material properties of the aluminium alloy T-stubs and the swage-locking pins. Flat coupons with nominal thicknesses of 8 mm, 10 mm and 12 mm were extracted from the T-stubs. The thickness of the coupons from the web was 8 mm, while the thicknesses of the coupons from the flange were 10 mm and 12 mm. Note though that T-stubs with 8 mm flanges, that were machined down from 10 mm, were also tested; the 8 mm flange material therefore shared the same material properties as the 10

mm flange material. Each coupon test was repeated three times. The test setup and dimensions of the flat tensile coupons are shown in Fig. 25.

For the swage-locking pins, round tensile coupons were used to carry out the material tests. The ends of the coupons were threaded to facilitate connection within the Zwick/Roell Z050 testing machine. The test setup and nominal dimensions of the tensile coupons are shown in Fig. 26. An extensometer was used to measure the longitudinal strain.

The material properties derived from the tests are summarized in Table 10, in which E is the Young's modulus, f_o is the yield (0.2% proof) stress, f_u is the ultimate stress, ϵ_u is the strain at the ultimate stress, n_p is the exponent of the Ramberg-Osgood (R-O) expression [22] and m_u is the hardening exponent for the second segment of the two-stage R-O model [23-25]. The stress-strain curves of the aluminium alloy plates are accurately represented by the R-O expression, as shown in Fig. 27 (a)-(c). The two-stage R-O model [23-25] was employed to represent the stress-strain curves of the stainless steel material from the swage-locking pins, as illustrated in Fig. 27 (d), where good agreement can be seen.

2.4 T-stub test configuration and instrumentation

All the T-stub tests were conducted in the 300 kN hydraulic testing machine shown in Fig. 28. The T-stubs were aligned with the aid of a laser, before vertical load was applied through the tightly clamped webs.

To overcome measuring difficulties encountered previously [7], an iMETRUM video gauge was adopted to measure the displacement at key positions on the test specimens. The video gauge comprises two main elements: a pair of high-resolution lenses and a host computer. The video gauge could measure displacements at the gauge points (U1-U3 and D1-D3 located as shown in Fig. 28) in three dimensions to an accuracy of 0.001 mm.

Strain gauges were also applied to the test specimens to monitor strains at the key locations shown in Fig. 29; strain gauge G1 was attached to the web in the direction of loading, while the other strain gauges were attached in a symmetrical configuration to the flange.

The load was applied at a rate of 1.0 mm/min under displacement control throughout the whole loading process, and all T-stubs were tested to failure. Load and strain were recorded in real time using an IMP (Isolated Measurement Pod) Data Acquisition System, while the video gauge displacements were recorded simultaneously at the same data recording frequency on its host computer.

3 Experimental results

3.1 Failure modes of T-stubs

According to EN 1999-1-1:2007 (EC9) [26], four distinct modes of failure can be identified for aluminium alloy T-stub joints, as illustrated schematically in Fig. 30: Mode 1 corresponds to flange failure through the development of four hardening plastic hinges, two of which are at the bolt locations with the other two at the web-to-flange junction. Mode 2a corresponds to flange failure with the formation of two hardening plastic hinges at the web-to-flange junction with the bolts at the elastic limit, while Mode 2b is defined by the flanges at or above the elastic limit with bolt failure. Mode 3 is characterised by bolt failure only. The failure modes of the tested specimens were determined by examining the deformed shapes and by analysing the data from the strain gauges and video gauge. The strain gauges were utilised to determine the stress levels at the pin locations and at the web-to-flange junction while the video gauge was used to measure the pin elongation and hence to estimate when the elastic limit was reached. From Fig. 31, it can be seen that for Specimen TSDS-8-50, the strain at both the pin location and at the web-to-flange junction exceeded the yield strain, indicating Mode 1 failure, while for Specimen TSDS-10-20, the

yield strain was only reached at the web-to-flange junction, indicating Mode 2a failure. The failure modes determined using the procedures described above are summarized in Table 11.

The failure modes of the test specimens are compared in Fig. 32 to assess the influence of (a) the distance between the pins and the web, (b) the flange thickness, (c) the collar type and (d) the number of rows of pins. The following observations are made:

- (a) Influence of the distance between the pins and the web ($m+0.8r$), as defined in Fig. 2:
For series TSDA-8-, although the failure modes did not change with increasing distance between the pins and the web, the ultimate deformation increased significantly. For series TSDA-10-, on the other hand, the failure modes changed from Mode 3 to Mode 1 (as shown in Fig. 32 (a)) as the distance $m+0.8r$ increased from 20 to 50 mm, indicating that the distance between the pins and the web plays an important role in determining the failure mode.
- (b) Influence of flange thickness t_f : Comparing the failure modes of Specimens TSDA-8-30, TSDA-10-30 and TSDA-12-30, the influence of the flange thickness can be clearly seen. With increasing flange thickness, failure of the swage-locking pins occurs earlier relative to failure of the flanges, and the ultimate behaviour of the specimens tend to become governed by the pins; the deformation capacity of the specimens also reduced with increasing flange thickness.
- (c) Influence of collar type: Fig. 32 (c) shows the effects of collar type on the failure modes of the T-stubs. Clearly, the pins with the stainless steel collars exhibited higher load-carrying capacity than those with the aluminium alloy collars. In fact, the pins with the stainless steel collars did not fail in any of the T-stub tests.
- (d) Influence of the number of rows of pins: The deformation at peak load of the T-stubs with two rows of pins was greater than that for T-stubs with a single row of pins. For

the Specimens TSDA-10-30 and TDDA-10-30-30 – see Fig. 32 (d), adding a row of pins changed the failure mode from pin failure to flange cracking, though for Specimens TSSA-12-30 and TDSA-12-30-38, pin failure occurred in the case of both a single and double row of pins.

From Fig. 32, it can be seen that flange fracture does not occur at the web-to-flange junction, where the maximum bending moment arises, but in the flat portion of the flange – this is due to the presence of the fillets and is the reason for the use of m instead of $m+0.8r$ for defining the distance between the bolt location and the plastic hinges near the web-to-flange junction in the EC9 [26] design formulae. It can also be observed that cracking of the flanges always initiated on the side of the pin collar; this is due to the different size of the head and collar of the pins, as explained in Section 4.3.

3.2 Mechanical behaviour of tested T-stubs

The ultimate resistances ($F_{u,test}$) and corresponding deformation capacity (Δe) of all the tested aluminium alloy extruded T-stubs connected by swage-locking pins are summarised in Table 11, while the load versus axial displacement curves are illustrated in Fig. 33. Note that the curves that showed no peak, or exhibited an abrupt drop in load, are associated with specimens that failed by fracture of the T-stub flange; in these cases, the load at the end point of the curve was taken as the load-carrying capacity. The deformation at peak load of Specimen TSDS-12-20 was not recorded due to the limitations of the video gauge.

It can be observed from Table 11 and Fig. 33 (a) that as the distance between the pins and the web ($m+0.8r$) increases, the ultimate resistance and initial stiffness of the T-stubs within each control group decreases, while the deformation capacity increases significantly. As shown in the table and Fig. 33 (b), the influence of the flange thickness t_f on the ultimate resistance and initial stiffness is clear, particularly for specimens failing

in Mode 1 and Mode 2a, for which increasing flange thickness represents the most effective means of improving $F_{u,test}$ (e.g. comparing Specimens TSDA-8-40 and TSDA-10-40, the ultimate resistance of the latter is enhanced by almost 60% over the former, and comparing Specimens TSDS-8-50 and TSDS-10-50, the ultimate resistance of the latter is enhanced by almost 35% over the former). In addition, it can be observed that the specimens with pins with the stainless steel collars have larger ultimate resistances but inferior deformation capacity compared to those with aluminium alloy collars; however, if both of the T-stubs fail in Mode 1, without taking full advantage of the pin strength, the collar type has no apparent influence on the structural behaviour, as the curves of Specimens TSDA-10-20 and TSDS-10-20 show in Fig. 33 (c). As for the number of rows of pins, the results shown in Table 11 and Fig. 33 (d) reveal that there is no clear influence on the behaviour of the T-stubs because the second row of pins (further from the T-stub web) barely participate in resisting the applied force and experience little deformation; EC3 [3] therefore recommends that only one row of pins is used to connect the angle cleat to the column flange in beam-to-column joints, as shown in Fig. 19 (b). For the two specimens (TSSA-12-30 and TSSA-12-50) with 12.70 mm diameter swage-locking pins, although the number of pins was halved compared to Specimens TSDA-12-30 and TSDA-12-50, which were connected by 9.66 mm diameter fasteners, their ultimate resistances were almost the same, confirming the improved load-carrying capacity of the larger-diameter swage-locking pins.

4 Evaluation of current design methods and other approaches

4.1 EN 1999-1-1:2007 (EC9) [26]

Design methods for the evaluation of the resistance of aluminium alloy T-stubs are provided in EC9 [26]. According to the four failure modes shown in Fig. 30, the resistances are defined as follows (Eq. (3)- Eq. (6)):

$$\text{Mode 1:} \quad F_{u,Rd} = \frac{2(M_{u,1})_w + 2(M_{u,1})_b}{m} \quad (3)$$

$$\text{Mode 2a:} \quad F_{u,Rd} = \frac{2M_{u,2} + n \sum B_o}{m+n} \quad (4)$$

$$\text{Mode 2b:} \quad F_{u,Rd} = \frac{2M_{o,2} + n \sum B_u}{m+n} \quad (5)$$

$$\text{Mode 3:} \quad F_{u,Rd} = \sum B_u \quad (6)$$

in which $F_{u,Rd}$ is the design resistance of the T-stub with the partial safety factor γ_M set equal to unity, $n = e$ but $\leq 1.25m$ (see Fig. 20), B_o and B_u are the elastic and ultimate tensile resistances of the swage-locking pins respectively, the values of which are shown in Table 12, $(M_{u,1})_w$ and $M_{u,2}$ are the ultimate bending moment resistances of the flange at the flange-to-web junction for Mode 1 and Mode 2a respectively, as given by Eq. (7) and (8), considering different flange effective lengths ($l_{eff,1}$ and $l_{eff,2}$), $(M_{u,1})_b$ is the ultimate bending moment resistance of the flange at the pin location considering the net area, which can also be calculated from Eq. (7) and $M_{o,2}$ is elastic bending moment resistance of the flange, as given in Eq. (9),

$$M_{u,1} = 0.25t_f^2 \sum (l_{eff,1} f_u) \frac{1}{k} \quad (7)$$

$$M_{u,2} = 0.25t_f^2 \sum (l_{eff,2} f_u) \frac{1}{k} \quad (8)$$

$$M_{o,2}=0.25t_f^2\sum(l_{\text{eff},2}f_o)\frac{1}{k} \quad (9)$$

where $l_{\text{eff},1}$ and $l_{\text{eff},2}$ are effective lengths of flange for Mode 1 and Mode 2 respectively, considering different failure modes of T-stubs and the development of different (circular and non-circular) yield line patterns, the formulae for which are presented in EC9 and $1/k$ is a reduction factor which is given by Eq. (10),

$$\frac{1}{k}=\frac{f_o}{f_u}\left[1+\left(\frac{\varepsilon_u-1.5\varepsilon_o}{1.5\varepsilon_u-1.5\varepsilon_o}\right)\left(\frac{f_u-f_o}{f_o}\right)\right] \quad (10)$$

where ε_u is the ultimate strain of the T-stub flange material and $\varepsilon_o=f_o/E$ is the yield strain.

A comparison between the test resistances and the predicted resistances calculated according to EC9 F_{EC9} is presented in Table 11; the EC9 resistance was taken as the smallest value for the above four possible failure modes, although the predicted failure mode sometimes differed from that observed in the corresponding experiment. For the T-stubs with more than one row of pins, EC9 does not provide explicit guidance, so the design resistance for Specimens TDDA-10-30-25 and TDDA-10-30-30 was taken as that for Specimen TSDA-10-30; similarly, the design resistance of Specimens TDSA-12-30-32 and TDSA-12-30-38 was taken as that for Specimen TSSA-12-30.

From Table 11, it is evident that EC9 yields safe-sided, but unduly conservative predictions of the ultimate resistance of aluminium alloy extruded T-stubs connected by swage-locking pins, with the mean value of $F_{\text{EC9}}/F_{u,\text{test}}$ for all the specimens being 0.735 and the coefficient of variation (COV) being 0.090. The coefficient of determination (R^2) was also calculated to evaluate the goodness-of-fit of the predictions relative to the experimental results; an R^2 value of 0.953 was obtained considering the full experimental data set. Improved design provisions are explored in the following sections.

4.2 Continuous strength method (CSM)

The continuous strength method (CSM) is a recently developed deformation-based design framework that allows for the beneficial influence of strain hardening; the method has been developed for the design of aluminium alloy cross-sections over the full range of section slenderness [27-29]. The two key features of the CSM are: (i) a base curve that defines the level of strain (ε_{csm}) that a cross-section can tolerate as a function of section slenderness and (ii) a material model that can capture strain hardening.

For the Mode 1 and Mode 2a failure mechanisms, hardening plastic hinges form in the T-stub flange, as illustrated in Fig. 34, which also shows the corresponding analytical model behind the EC9 design method for T-stubs in tension. In the model, the T-stub flange is represented as a continuous beam, the swage-locking pins are modelled using springs and, taking advantage of symmetry, a roller support is located at the flange-to-web junction. For the hardening plastic hinges, $(M_{u,1})_w$, $(M_{u,1})_b$ and $M_{u,2}$ can be calculated using the CSM. The maximum strain that the cross-section at the web-to-flange junction and at the pin location can tolerate is the ultimate strain of material i.e. ε_u . Thus, assuming a linearly varying strain distribution through the flange thickness and adopting the CSM material model, the corresponding moment resistance can be obtained. The CSM elastic, linear hardening material model established for aluminium alloys in [27] is used, featuring the Young's modulus E and the CSM strain hardening modulus E_{sh} , which is defined in Eq. (11),

$$E_{\text{sh}} = \frac{f_u - f_o}{0.5\varepsilon_u - \varepsilon_o} \quad (11)$$

The predicted ultimate resistances F_{csm} of the T-stubs, derived by using the CSM to calculate the moment resistance at the plastic hinges, are listed in Table 11, and can be seen to be more accurate and less scattered compared to the resistance predictions from

EC9. Yuan et al. [5] also reported better predicted results for stainless steel T-stubs using the CSM, rather than the design rules in Eurocode 3. Further improvements are sought in the following sub-section.

4.3 Proposed design method based on the CSM

Although in the above comparisons the strain hardening behaviour of the plastic hinges was captured using the CSM, the predicted ultimate resistances of extruded aluminium alloy T-stubs connected by swage-locking pins remained substantially below the test results, highlighting the need for a new design method considering the particular mechanical response of the studied T-stub system, as well as the strain hardening behaviour of the material.

For the Mode 1 failure mechanism, failure is caused by the formation of hardening plastic hinges in the T-stub flange. However, because of the existence of the pin head and collar, the plastic hinges cannot develop at the pin location, as noted and accounted for in the case of steel T-stubs in EN 1993-1-8 (EC3) [3], but the design method presented therein is not suitable for aluminium alloy T-stubs. Hence, a modified expression for predicting the ultimate resistance of aluminium alloy T-stubs failing in Mode 1 is proposed, as given by:

$$F_{\text{prop}} = \frac{4(M_{u,1})_w}{m'} \quad (12)$$

in which the definition of m' is illustrated in Fig. 35 and given by Eq. (13), where w_h is the diameter of the head of the pin and w_c is the diameter of the collar. Note that the thin collar flange, shaded in grey in Fig. 35, is not included in the definition of w_c since it is not stiff enough to provide restraint to the T-stub. With the revised definition of m' , the hinge location shifts from the centre of the pin, with a moment resistance $(M_{u,1})_b$ allowing for

the presence of the pin holes, to the edge of the head of the pin, where the moment resistance is $(M_{u,1})_w$.

$$m' = d - 0.8r - \min\left(\frac{w_h}{2}, \frac{w_c}{2}\right) \quad (13)$$

The diameter of the pin head often differs from that of the collar; in such instances, the resistance of the T-stub should be controlled by the side with the smaller diameter. For all the swage-locking pins considered herein, w_h is larger than w_c suggesting that failure of the T-stubs flange should occur first on the collar side of the pin; this indeed proved to be the case in all tests, as confirmed by the experimental failure modes shown in Fig. 32.

Mode 2a is a distinct failure mode associated with aluminium alloy T-stubs due to the inferior ductility of aluminium alloys relative to steel. In Mode 2a, although failure of the specimens is, as in Mode 1, caused by the formation of plastic hinges in the T-stub flange, the restraint provided by the head of the pin and the collar at the pin location is not as stiff as in the Mode 1, due to the tensile and bending deformations of the swage-locking pins. The analytical model for Mode 2a is illustrated in Fig. 36, neglecting the difference between the head of the pin and the collar. To satisfy the requirement for compatibility of deformations, bending of the flange also results in bending of the pins. The design method in EC9 [26] neglects the additional moment resistance (M_a) resulting from the restraining effect of the head of the pin and the collar, which is beneficial to the load-carrying capacities of the T-stubs, leading to overly-conservative resistance predictions. If this effect is included, moment equilibrium at the web-to-flange junction in the ultimate state gives:

$$Q(m+n) + \frac{\sum M_a}{2} - \frac{\sum B_o}{2} m + M_{u,2} = 0 \quad (14)$$

The relationship between the prying force Q and the applied load F_{prop} is given by Eq.

(15),

$$2Q + F_{\text{prop}} = \sum B_o \quad (15)$$

Hence, the proposed resistance F_{prop} for failure in Mode 2a is given by as Eq. (16),

$$F_{\text{prop}} = \frac{2M_{u,2} + n \sum B_o + \sum M_a}{m + n} \quad (16)$$

The next step is to calculate M_a by applying Euler-Bernoulli beam theory for half of a swage-locking pin modelled as a cantilever beam under pure bending moment – see Eq. (17). Since the pin is under uniform bending i.e. there is no transverse shear force, Euler-Bernoulli beam theory remains applicable despite the low length-to-height ratio of the element. In the equation, x is the distance from the plane of symmetry in loading direction, θ is the rotation angle of the cross-section of the pin, E_p is the Young's modulus of the material of the pin and d_{pin} is the pin diameter. Applying the boundary condition of $\theta = 0$ at Point O (i.e. at $x = 0$), the constant C is found to be zero. At Point P , $x = t_f$ (neglecting the small elongation of the pin), and the rotation angle θ of the end section is equal to $\alpha \approx \tan \alpha = \Delta_0/2n$, in which Δ_0 (the value is shown in Table 12) is the pin elongation at the elastic limit.

$$\theta(x) \approx \tan \theta(x) = \frac{M_a x + C}{E_p \left(\frac{\pi d_{\text{pin}}^4}{64} \right)} \quad (17)$$

By substituting α into Eq. (17), we obtain the definition of M_a given by Eq. (18). Note that, the additional moment resistance M_a does not arise in Mode 1 and has little or no influence on Mode 2b and Mode 3; hence, the additional moment resistance M_a is only considered for Mode 2a.

$$M_a = \frac{\Delta_0}{2n} \frac{E_p}{t_f} \left(\frac{\pi d_{\text{pin}}^4}{64} \right) \quad (18)$$

The resistance predictions obtained through application of proposed design method are presented in Table 11. From the table, it can be seen that the proposed method provides good predictions of the experimental results, with a mean value of $F_{\text{prop}}/F_{\text{u,test}}$ of 0.918, improving the design accuracy by almost 25% over EC9.

5 Conclusions

Thirty tests were conducted in this paper to investigate the structural behaviour of extruded aluminium alloy T-stubs connected by swage-locking pins under monotonic loading. The specimens were designed with different geometric parameters, including the distance between the pins and the web ($m+0.8r$), the thickness of the flange t_f , the pin diameter d_{pin} , the collar type (aluminium or stainless steel) and the number of rows of pins, to study their influence on the load-carrying behaviour of the T-stubs. The main conclusions are drawn as follows:

1. Prior to the tests on the T-stubs, material tests on aluminium alloy coupons cut from the T-stubs and stainless steel coupons machined from the pins were performed. Forty-two component tests on the swage-locking pins under pure tension, pure shear and a combination of tension and shear were also conducted. Three different failure modes were observed and a design method to predict the load-carrying capacities of the pins was proposed.
2. In the experimental programme on the extruded aluminium alloy T-stubs, the four failure modes identified in EC9 were observed. The test failure mechanisms, ultimate resistances, load versus vertical displacement responses and deformation capacities were determined, reported and utilized to analyse the influence of a number of key parameters. The results showed that with decreasing distance between the pins and the web or increasing thickness of the T-stub flange, the ultimate resistance and the initial

stiffness of the T-stubs increased significantly, though decreasing the distance between the pins and the web led to reduced deformation capacity. Through their influence on the load-carrying capacity of the swage-locking pins, the collar type and pin diameter also affected the structural behaviour of the T-stubs. Increasing the number of rows of pins resulted in no significant change to the resistance of the T-stubs.

3. The experimental results were used to evaluate the accuracy of the design methods in EC9 – the comparisons presented showed that the code generally underestimates the load-carrying capacity of extruded aluminium alloy T-stubs connected by swage-locking pins. Through application of the CSM, the accuracy of the predictions was improved. Finally, a new design method, based on the CSM, was proposed and shown to provide substantially improved agreement with the experimental results.
4. Future work will feature finite element modelling and parametric analyses to develop a more comprehensive understanding of the behaviour of aluminium alloy T-stubs connected by swage-locking pins; the reliability of the design rules proposed herein will then be evaluated against the resulting dataset.

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Table 1. Dimensions of tested T-stubs

Type	Label	t_f (mm)	$m+0.8r$ (mm)	d_{pin} (mm)	b_f (mm)	e (mm)	e_1 (mm)	e_2 (mm)	b (mm)	$F_{p,C}$ (kN)
TSD	TSDA-8-20	8.03	20.41	9.66	148.05	49.62	—	—	79.72	23.71
TSD	TSDA-8-30	8.07	30.36	9.66	148.06	39.67	—	—	79.48	23.71
TSD	TSDA-8-40	8.04	40.51	9.66	148.00	29.49	—	—	78.98	23.71
TSD	TSDA-8-50	8.03	50.31	9.66	148.04	19.71	—	—	79.39	23.71
TSD	TSDA-10-20	10.10	19.93	9.66	147.59	49.87	—	—	80.39	23.71
TSD	TSDA-10-30	10.11	31.89	9.66	148.04	38.13	—	—	80.60	23.71
TSD	TSDA-10-40	10.13	40.79	9.66	148.04	29.23	—	—	80.78	23.71
TSD	TSDA-10-50	10.10	51.95	9.66	147.87	17.99	—	—	80.89	23.71
TSD	TSDA-12-20	12.02	20.65	9.66	147.48	49.09	—	—	80.57	23.71
TSD	TSDA-12-30	12.05	30.47	9.66	147.36	39.21	—	—	80.32	23.71
TSD	TSDA-12-40	12.05	41.79	9.66	147.35	27.89	—	—	80.56	23.71
TSD	TSDA-12-50	12.19	51.00	9.66	148.41	19.21	—	—	80.48	23.71
TDD	TDDA-10-30-25	10.01	29.84	9.66	167.95	—	25.33	24.81	80.09	23.71
TDD	TDDA-10-30-30	10.05	29.90	9.66	168.12	—	20.36	29.80	78.74	23.71
TSS	TSSA-12-30	12.21	28.07	12.70	148.20	42.03	—	—	81.37	24.63
TSS	TSSA-12-50	12.17	48.16	12.70	148.20	21.94	—	—	79.02	24.63
TDS	TDSA-12-30-32	12.26	27.47	12.70	179.88	—	26.73	31.74	80.34	24.63
TDS	TDSA-12-30-38	12.00	27.84	12.70	179.25	—	20.10	37.69	77.13	24.63
TSD	TSDS-8-20	8.06	20.28	9.66	148.14	49.79	—	—	79.76	29.42
TSD	TSDS-8-30	8.01	30.49	9.66	148.12	39.57	—	—	79.60	29.42
TSD	TSDS-8-40	8.01	40.41	9.66	148.06	29.62	—	—	78.27	29.42
TSD	TSDS-8-50	8.00	50.58	9.66	148.09	19.47	—	—	80.62	29.42
TSD	TSDS-10-20	10.06	20.59	9.66	148.19	49.51	—	—	79.75	29.42
TSD	TSDS-10-30	10.10	30.41	9.66	148.11	39.65	—	—	81.26	29.42
TSD	TSDS-10-40	10.02	40.49	9.66	148.10	29.56	—	—	80.26	29.42
TSD	TSDS-10-50	10.14	50.62	9.66	148.09	19.43	—	—	79.98	29.42
TSD	TSDS-12-20	12.15	20.46	9.66	147.78	49.43	—	—	78.75	29.42
TSD	TSDS-12-30	12.06	30.63	9.66	148.02	39.38	—	—	80.51	29.42
TSD	TSDS-12-40	12.06	40.53	9.66	148.04	29.49	—	—	79.52	29.42
TSD	TSDS-12-50	11.99	50.67	9.66	147.90	19.28	—	—	79.88	29.42

Table 2. Summary of loading angle and test results on swage-locking pins

Angle θ_s (°)	$F_{s,test}$ of pins with aluminium alloy collars (kN)				$F_{s,test}$ of pins with stainless steel collars (kN)			
	r ₁	r ₂	r ₃	Average	r ₁	r ₂	r ₃	Average
0 (pure tension)	35.62	35.11	33.93	34.89	49.00	49.18	50.52	49.57
15	35.82	36.15	35.10	35.69	50.19	51.67	50.55	50.80
30	39.11	46.98	45.74	43.94	62.44	56.58	53.10	57.37
45	49.68	48.5	48.63	48.94	56.30	57.38	54.56	56.08
60	53.18	50.18	52.96	52.11	53.23	53.16	51.99	52.79
75	53.22	50.61	52.89	52.24	49.66	53.11	51.56	51.44
90 (pure shear)	52.13	55.66	52.79	53.53	53.34	54.86	52.94	53.71

Table 3. Comparison of experimental resistances $F_{s,test}$ with design values F_{Rd}

Angle θ_s (°)	Pins with aluminium alloy collars		Pins with stainless steel collars	
	F_{Rd} (kN)	$F_{Rd}/F_{s,test}$	F_{Rd} (kN)	$F_{Rd}/F_{s,test}$
0	—	—	—	—
15	36.12	1.01	51.32	1.01
30	40.29	0.92	57.24	1.00
45	49.34	1.01	58.62	1.05
60	55.95	1.07	55.95	1.06
75	54.21	1.04	54.21	1.05
90	—	—	—	—
Mean value		1.01		1.03
COV		0.058		0.027
Maximum relative error		0.08		0.06

Table 4. Summary of measured material properties of T-stubs and swage-locking pins

T-stub and swage-locking pin material	E (MPa)	f_o (MPa)	f_u (MPa)	ϵ_u (%)	n_p	m_u
Web of T-stub (8 mm)	69,400	263.7	298.4	8.44	31.8	—
Flange of T-stub (8/10 mm)	69,600	253.4	290.2	9.27	30.0	—
Flange of T-stub (12 mm)	67,200	250.6	274.2	5.26	35.5	—
9.66 mm swage-locking pin	204,200	581.7	891.6	17.73	7.9	18.7
12.70 mm swage-locking pin	185,100	635.2	994.9	4.30	6.9	8.5

Table 5. Summary of experimental results of T-stubs and comparison with design methods

Label	Failure modes	$F_{u,test}$ (kN)	Δe (mm)	F_{EC9} (kN)	$F_{EC9}/F_{u,test}$	F_{csm} (kN)	$F_{csm}/F_{u,test}$	F_{prop} (kN)	$F_{prop}/F_{u,test}$
TSDA-8-20	2a	94.81	2.70	71.96	0.759	74.37	0.784	90.64	0.956
TSDA-8-30	1	66.15	5.50	45.89	0.694	47.43	0.717	76.17	1.151
TSDA-8-40	1	48.40	6.95	32.92	0.680	34.02	0.703	49.40	1.021
TSDA-8-50	1	37.82	10.64	26.16	0.692	27.04	0.715	37.23	0.984
TSDA-10-20	3	116.67	1.15	91.90	0.788	92.92	0.796	101.25	0.868
TSDA-10-30	2b	96.67	5.91	69.28	0.717	71.61	0.741	82.82	0.857
TSDA-10-40	2a	77.35	10.40	53.22	0.688	55.01	0.711	69.71	0.901
TSDA-10-50	1	59.75	12.62	42.56	0.712	43.99	0.736	55.83	0.934
TSDA-12-20	3	123.09	2.34	101.07	0.821	101.92	0.828	108.37	0.880
TSDA-12-30	3	106.23	3.13	86.95	0.818	87.49	0.824	90.13	0.848
TSDA-12-40	2b	90.74	4.30	69.96	0.771	70.46	0.777	73.43	0.809
TSDA-12-50	2b	68.93	6.62	55.54	0.806	56.05	0.813	60.28	0.875
TDDA-10-30-25	2a	101.32	6.62	69.28	0.684	71.61	0.707	82.82	0.817
TDDA-10-30-30	2a	100.49	6.03	69.28	0.689	71.61	0.713	82.82	0.824
TSSA-12-30	2b	93.64	1.63	74.19	0.792	74.81	0.799	80.38	0.858
TSSA-12-50	2b	59.58	3.36	49.19	0.826	49.71	0.834	57.08	0.958
TDSA-12-30-32	2b	106.88	2.69	74.19	0.694	74.81	0.700	80.38	0.752
TDSA-12-30-38	2b	99.24	2.46	74.19	0.748	74.81	0.754	80.38	0.810
TSDS-8-20	1	106.95	2.83	73.08	0.683	75.54	0.706	108.18	1.012
TSDS-8-30	1	73.88	5.60	45.07	0.610	46.58	0.631	74.28	1.005
TSDS-8-40	1	51.66	6.40	32.42	0.628	33.51	0.649	48.59	0.941
TSDS-8-50	1	42.79	13.40	26.28	0.614	27.16	0.635	37.17	0.869
TSDS-10-20	2a	147.98	3.61	107.70	0.728	108.66	0.734	116.21	0.785
TSDS-10-30	1	100.21	4.91	73.60	0.734	76.07	0.759	101.57	1.014
TSDS-10-40	1	76.07	9.32	52.11	0.685	53.86	0.708	77.76	1.022
TSDS-10-50	1	58.04	8.21	41.80	0.720	43.20	0.744	59.18	1.020
TSDS-12-20	2a	150.13	—	118.86	0.792	119.72	0.797	126.07	0.840
TSDS-12-30	1	115.98	2.61	98.63	0.850	100.78	0.869	107.37	0.926
TSDS-12-40	1	86.49	3.28	71.45	0.826	73.00	0.844	89.04	1.029
TSDS-12-50	1	70.18	4.83	55.83	0.796	57.04	0.813	68.66	0.978
Mean Value					0.735		0.751		0.918
COV					0.090		0.083		0.101
Maximum relative error					0.390		0.369		0.248
R^2				0.953		0.957		0.901	

Table 6. Geometric properties and resistances of swage-locking pins with different diameters and collar types

Swage-locking pin diameter (mm) and collar type	Δ_o (mm)	w_c (mm)	w_h (mm)	B_o (kN)	B_u (kN)
9.66-aluminium alloy collar	0.38	15.35	19.05	27.76	34.89
9.66-stainless steel collar	0.37	15.11	19.05	34.48	49.57
12.70-aluminium alloy collar	0.50	20.32	22.99	40.84	56.65

Fig. 1. Equivalent T-stubs in beam-to-column joints

Fig. 2. Details of aluminium alloy TSS, TSD, TDS and TDD T-stub test specimens

Fig. 3. Connecting process for swage-locking pins

Fig. 4. Experimental setup for tests on swage-locking pins

Fig. 5. Load-axial deformation responses of swage-locking pins under pure tension

Fig. 6. Failure modes of all tested swage-locking pins

Fig. 7. Test set-up and dimensions of flat tensile coupons extracted from T-stubs

Fig. 8. Test set-up and dimensions of round tensile coupons extracted from swage-locking pins

Fig. 9. Stress-strain curves of aluminium alloy web and flange plates and swage-locking pins

Fig. 10. Experimental set-up for T-stub tests

Fig. 11. Layout of strain gauges on T-stub test specimens

Fig. 12. Failure modes of aluminium alloy T-stubs according to EN 1999-1-1:2007

Fig. 13. Strain development at key locations in Specimens TSDS-8-50 and TSDS-10-20

(a) Comparison of T-stub failure modes with varying distances between the pins and the web

(b) Comparison of T-stub failure modes with varying flange thickness

(c) Comparison of T-stub failure modes with different collar types

(d) Comparison of T-stub failure modes with varying numbers of rows of pins

Fig. 14. Comparison of experimental T-stub failure modes

(a) Influence of distance between pins and web (b) Influence of flange thickness

(c) Influence of collar type (d) Influence of number of rows of pins

Fig. 15. Load-axial displacement curves of tested T-stubs

Fig. 16. Simplified models for Mode 1 and Mode 2a failure mechanisms of T-stubs featuring hardening plastic hinges

Fig. 17. Schematic diagram showing geometric dimensions of diameter of head of pin w_h and diameter of collar w_c

Fig. 18. Proposed analytical model for Mode 2a failure of T-stubs