Testing and design of stainless steel staggered bolted connections

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Abstract:

The present paper reports a thorough experimental investigation into the net section failure behaviour and capacity of stainless steel staggered bolted connections in tension. The testing programme was carried out on 31 stainless steel staggered bolted connection specimens, with 18 made of austenitic stainless steel (grade EN 1.4301), 7 made of duplex stainless steel (grade EN 1.4462) and 6 made of ferritic stainless steel (grade EN 1.4016). The geometric parameters, including the transverse and staggered pitches, and the staggered bolt hole patterns of the connection specimens, were varied. The test setup and procedures, as well as the key experimentally observed results, including the net section failure modes and loads, are reported in detail. The experimentally obtained net section failure loads and modes are analysed and discussed, and then utilised to assess the accuracy of the established design rules for stainless

steel staggered bolted connections, given in the European, American and Australian/New Zealand standards. All three examined standards consider (i) net section fracture and (ii) gross section yielding in the design of stainless steel staggered bolted connections, and specify that the design failure load shall be taken as the minimum value calculated from all potential failure modes. It was found that the current design standards lead to overly conservative and scattered failure load predictions as well as inaccurate failure mode predictions. A new design approach based on the continuous strength method (CSM) is proposed, and shown to result in substantially improved predictions of both failure loads and failure modes.

Keywords: Continuous strength method; Gross section yielding; International design standards; Net section fracture; Stainless steel staggered bolted connections; Tension tests

1 Introduction

Stainless steel, with its excellent durability, attractive appearance, range of desirable material properties and strong sustainability credentials, has been gaining popularity as a construction material in bridge and structural engineering [1–5]. However, given that the initial material cost of stainless steel is around 3–4 times that of carbon steel, it may not be economical or suitable for the construction of complete structures, even when whole-life costing is considered; it may though be desirable to adopt stainless steel for key components of structures in strategic locations, for example, in the connection regions. In these regions, the high ductility and energy absorption capacity of stainless steel can lead to enhanced robustness and resilience under extreme and fatigue loadings [6–8]. This has prompted experimental, numerical and analytical studies into different types of stainless steel connection. Specifically, Elflah et al. [9,10] carried out a testing and finite element (FE) modelling programme to examine the initial rotational

stiffnesses, moment–rotation responses and failure modes of four types of austenitic stainless steel beam-to-column connection, including those with flush endplates, extended endplates and top-and-seat angles with and without double-angle web cleats, and highlighted their higher ultimate moment capacities and better ductility compared to those of carbon steel beam-to-column connections. Similar experimental and numerical studies on austenitic stainless steel beam-to-column connections with top-and-seat angles and double-angle web cleats were also performed by Hasan et al. [11,12]. With regards to stainless steel beam-to-beam connections (i.e. plate-to-plate connections), there are four main types of failure mode, namely gross section yielding, net section fracture, bearing failure and block tearing. Kuwamura and Isozaki [13] and Kim and Kuwamura [14] conducted testing and numerical modelling of austenitic stainless steel bolted plate-to-plate connections, examined their net section fracture and bearing failure behaviour, and also highlighted the influence of curling on the resistances of bolted connections composed of thin stainless steel plates. Similar experimental studies on lean duplex and ferritic stainless steel bolted plate-to-plate connections were also reported in Cai and Young [15] and Talja and Torkar [16], respectively, where the established codified design provisions were assessed through comparisons against the experimental results, revealing undue conservatism. Salih et al. [17,18] proposed new design formulations for stainless steel bolted connections failing by net section fracture and bearing, based on a comprehensive numerical simulation programme, where a series of geometric parameters and bolt hole patterns were examined; the new proposals were shown to yield more accurate bearing and net section ultimate resistance predictions for stainless steel bolted connections. Salih et al. [19] also numerically studied the behaviour and resistances of stainless steel gusset plate connections and developed new efficient design rules. Cai and Young [20–22] carried out fire tests on austenitic and lean duplex stainless steel bolted connections to investigate their failure behaviour and resistances at elevated temperatures, and also concluded that the international standards established in

Europe, America and Australia/New Zealand (EN 1993-1-4 [23], SEI/ASCE-8 [24] and AS/NZS 4673 [25], respectively) all lead to conservative fire design of stainless steel bolted connections; improved design rules were hence proposed [26]. It is worth noting that previous studies mainly focused on stainless steel bolted connections with non-staggered bolt hole patterns, while the behaviour and capacity of stainless steel staggered bolted connections, particularly those prone to net section fracture between staggered bolt holes, remain unexplored. Staggered bolt hole arrangements are commonly used for bolted connections, where the connected plates or members are of small geometric sizes (due to space limitations) but subjected to large tension forces.

A comprehensive experimental study of stainless steel staggered bolted connections has been carried out and is reported in the present paper. The testing programme included a total of 31 stainless steel staggered bolted connection specimens, which were carefully designed to cover all three commonly used types of stainless steel, namely austenitic, duplex and ferritic stainless steels, two staggered bolt hole patterns and a wide spectrum of transverse and staggered pitches [27]. Tensile coupon tests were firstly carried out to acquire the material stress-strain responses of the connection specimens. Then, tension tests were carried out to derive their net section fracture modes and failure loads. The experimental setup, procedures and results are fully reported, and the influences of the staggered bolt hole patterns, as well as the transverse and staggered pitches, on the net section fracture modes and failure loads are discussed. The experimental failure loads and modes are also used to evaluate the accuracy of the existing design provisions for stainless steel staggered bolted connections, prescribed in EN 1993-1-4 [23], SEI/ASCE-8 [24] and AS/NZS 4673 [25]. Finally, new design rules are proposed.

2 Testing programme

2.1 Test specimens

A total of 31 stainless steel staggered bolted connection specimens were adopted in the present testing programme [27]. A double shear testing configuration, consisting of two collinear inner (directly loaded) plates and two outer splice plates, was employed for all the specimens, as shown in Fig. 1(a). The outer splice plates were 3 mm thick and made of three types of stainless steel – grade EN 1.4301 austenitic stainless steel, grade EN 1.4462 duplex stainless steel and grade EN 1.4016 ferritic stainless steel. The inner plates were made of grade S355 carbon steel, and were thicker (8 mm) and wider (by 40%) than the outer plates; this ensured that failure and the associated deformations were concentrated in the outer stainless steel plates. Two patterns of staggered bolt holes were examined – ‘Type A’ and ‘Type B’, as illustrated in Figs 1(b) and 1(c), respectively. Both of the two patterns included eight rows of bolt holes, with each row containing either one or two bolt holes, and the rows with one and two bolt holes were alternately arranged. For the Type A pattern, the row at the free end of the stainless steel plate contained one bolt hole, while for the Type B pattern, the end row included two bolt holes. Grade A490 high strength bolts, with a minimum tensile strength of 1034 MPa (150 ksi), were used for connecting the outer stainless steel plates with the inner carbon steel plates; the diameters of the employed A490 bolts d were all equal to 12.7 mm (0.5 inches), while the diameters of the bolt holes in the connected stainless steel and carbon steel plates d_0 were fixed at 14.3 mm (9/16 inch). For each staggered bolted connection specimen, the bolts were tightened to a snug tight condition, to minimise the effect of friction on the load transfer from the inner (loaded) carbon steel plates to the outer stainless steel plates.

Table 1 reports the material grade, staggered bolt hole pattern and geometric dimensions of each connection test specimen, where b is the width of the outer stainless steel plate, s is the longitudinal spacing (i.e. the staggered pitch) between the centrelines of two consecutive bolt holes measured parallel to the load transfer direction – see Fig. 1(b), p is the transverse spacing (i.e. the transverse pitch) between the centrelines of two consecutive holes measured perpendicular to the load transfer direction, and e_1 is the end distance measured from the centreline of the outermost bolt hole to the end of the stainless steel plate in the load transfer direction, while e_2 is the edge distance measured from the centreline of the outermost bolt hole to the edge of the stainless steel plate in the transverse direction; for the specimens tested herein, e_1 and e_2 are respectively fixed at 45 mm and 17.5 mm. The parameters s , p , e_1 and e_2 satisfy the relevant geometric requirements given in EN 1993-1-4 [23], SEI/ASCE-8 [24] and AS/NZS 4673 [25]. The austenitic and duplex stainless steel plates of the bolted connection specimens were cut from cold-rolled coils in the rolling direction and transverse to the rolling direction, while the ferritic stainless steel plates were cut only along the coil rolling direction. ‘PP’ and ‘PL’ in Table 1 signify stainless steel plates with the length directions (i.e. the load transfer directions) perpendicular and parallel to the coil rolling direction, respectively. The designation system of the connection specimens starts with the material grade (with ‘A’, ‘D’ and ‘F’ respectively referring to austenitic, duplex and ferritic stainless steels) and plate type (‘PP’ or ‘PL’), followed by the staggered and transverse pitches (in mm), and ends with the staggered bolt hole pattern (‘A’ or ‘B’), e.g., A-PL-23-55-A.

2.2 Material tensile coupon tests

Prior to the connection tests, tensile coupon tests were carried out to derive the material properties of the connected stainless steel plates. Tensile coupons were extracted from the same

batch of material as used for the fabrication of the connection specimens. For each of the three stainless steel grades, three longitudinal coupons were extracted along the rolling direction of the corresponding coil, while three additional transverse coupons were also cut from each of the austenitic and duplex stainless steel coils perpendicular to the coil rolling direction. The dimensions of the tensile coupons complied with the geometric requirements specified in both the European code EN ISO 6892-1 [28] and American Standard ASTM E8M [29], with the width and parallel length of the necked portion equal to 12.5 mm and 75 mm, respectively. All the tensile coupon tests were carried out under displacement control, with the applied strain rates conforming to the requirements of EN ISO 6892-1 [28] and ASTM E8M [29]. Fig. 2 displays the experimental setup used for the tensile coupon tests, including an extensometer mounted onto the central 50 mm of the necked portion of the coupon and a pair of strain gauges attached to the two parallel wider faces of the coupon at mid-height. Figs 3–5 display the stress-strain curves measured from the longitudinal and transverse coupons for the three grades of stainless steels, while the key average measured material properties, including the Young's modulus E , the 0.2% and 1.0% proof stresses $\sigma_{0.2}$ and $\sigma_{1.0}$, the ultimate strength σ_u , the strain at the ultimate strength ε_u , the fracture strain measured over a gauge length of 50 mm ε_f , and the Ramberg–Osgood (R–O) coefficients n , $m_{1.0}$ and m_u [30–34], are reported in Table 2.

2.3 Staggered bolted connection tests

Tension tests were carried out on 31 stainless steel staggered bolted connection specimens, to investigate their net section fracture behaviour and failure loads. A hydraulic universal testing machine, driven by displacement-control at a constant speed of 2.25 mm/min, was adopted for all the connection tests. The testing machine was equipped with a pair of end clamps, allowing the far ends of the two collinear inner carbon steel plates of each connection specimen to be

securely gripped. Hence, the tension force from the testing machine was directly applied to the inner carbon steel plates and then transferred to the outer stainless steel splice plates through the bolts. Fig. 6 depicts the experimental setup for the tension tests on the stainless steel staggered bolted connections, which included two LVDTs mounted onto the connection specimens to measure the elongation of the stainless steel splice plates between the two innermost rows of bolt holes and three strain gauges attached to the centreline of the stainless steel splice plates in the load transfer direction to record the longitudinal strains.

Failure by net section fracture was observed in the outer stainless steel splice plates of all the bolted connection specimens upon testing. Specifically, for the stainless steel splice plates with the Type A staggered bolt hole pattern, the net section failure modes featured fracture paths passing through either the two innermost bolt holes (located in one row) or the three innermost consecutive staggered bolt holes (located in two rows), as depicted in Fig. 7, while the stainless steel splice plates with the Type B staggered bolt hole pattern exhibited net section failure with either the single innermost bolt hole or the three innermost consecutive staggered bolt holes on the fracture path, as shown in Fig. 8. It is also worth noting that the two outer stainless steel splice plates of each staggered bolted connection specimen displayed the same fracture modes, demonstrating proper alignment of the two inner (directly loaded) carbon steel plates and symmetric assembly of the two outer stainless steel splice plates for each connection specimen. Table 1 reports the net section failure mode and failure load for each stainless steel staggered bolted connection specimen, where P_{test} is the test failure load, and ‘1F’, ‘2F’ and ‘3F’ denotes the failure modes with fracture paths passing through one, two and three bolt holes, respectively. The failure load of each of the two stainless steel splice plates P_s is equal to half of the failure load of the corresponding connection specimen P_{test} .

3 Discussion of test results

3.1 Failure modes

The examined bolted connection specimens with the Type A and Type B staggered bolt hole patterns showed different modes of net section fracture in the stainless steel splice plates; this is explained as follows. Fig 9(a) illustrates the free body diagram of half of the stainless steel splice plate with the Type A staggered bolt hole pattern just prior to fracture, in which P_s is the failure force and $P_o=P_s/6$ is the force exerted by each bolt on the stainless steel splice plate. The resulting net forces on the potential fracture paths A-A, B-B and C-C, passing through one, two and three bolt holes, are then given as $2P_s/3$ (i.e. $P_s-2(P_s/6)$), P_s and P_s , respectively, as shown in Figs 9(b)–9(d), and the corresponding transmission ratios η , defined as the ratios of the net forces on the potential fracture paths to the overall failure force acting on the stainless steel splice plate, are equal to $2/3$, 1 and 1, as reported in Table 3. Compared with path A-A, containing one bolt hole, paths B-B and C-C, containing two and three bolt holes, have smaller net section areas and are under larger net forces (see Fig. 9). Hence, the stainless steel splice plates with the Type A staggered bolt hole pattern are more prone to fracture on paths B-B and C-C and should therefore be expected to feature fracture paths passing through either two bolt holes (located in one row) or three consecutive staggered bolt holes (located in two rows). Similarly, the free body diagram of half of the stainless steel splice plate with the Type B staggered bolt hole pattern just prior to fracture is depicted in Fig. 10(a); the resulting net forces on the three potential fracture paths A-A, B-B and C-C (see Figs 10(b)–10(d)) passing through one, two and three bolt holes are equal to P_s , $5P_s/6$ (i.e. $P_s-P_s/6$) and P_s , respectively, with the corresponding transmission ratios η of 1, $5/6$ and 1. The paths A-A and C-C, containing one and three bolt holes, are subjected to larger net forces and are thus generally expected to be

more critical than the path B-B, containing two bolt holes (though this does, of course, depend on the ratio of net forces to net areas, as discussed later), i.e. the net section failure modes of the stainless steel splice plates with the Type B staggered bolt hole pattern should be expected to feature fracture paths passing through either one bolt hole or three consecutive staggered bolt holes. For both staggered bolt hole patterns, the anticipated failure modes were indeed observed in the tests.

3.2 Influence of transverse and staggered pitches

The influence of the transverse and staggered pitches on the failure loads and net section fracture modes of the examined stainless steel staggered bolted connections are discussed in this section. Two transverse pitches of 36 mm and 55 mm were used for the stainless steel splice plates of the staggered bolted connection specimens. Given that the edge distance was fixed at 17.5 mm, the resulting widths of the stainless steel splice plates were 107 mm and 145 mm, as presented in Table 1. The failure loads of typical austenitic stainless steel connection specimens (A-PL-26-36-A and A-PL-26-55-A, with the same staggered pitch of 26 mm) and ferritic stainless steel connection specimens (F-PL-27-36-A and F-PL-27-55-A, with the same staggered pitch of 27 mm) are plotted against the corresponding transverse pitches in Fig. 11. The comparison indicates that an increase in the transverse pitch leads to enhanced failure loads and changes the failure modes from ‘2F’ (with the fracture path B-B passing through two bolt holes in one row – see Fig. 9(c)) to ‘3F’ (with the fracture path C-C passing through three consecutive staggered bolt holes – see Fig. 9(d)). The enhanced failure loads can be attributed to the enlarged plate widths (and thus net section areas) associated with the increasing transverse pitches; moreover, the net section area of path B-B increases more than that of path

C-C, and thus path C-C becomes more critical, i.e. the failure mode changes from ‘2F’ to ‘3F’, as the transverse pitch increases.

Fig. 12 depicts the variation in failure load with staggered pitch for two typical series of austenitic stainless steel bolted connection specimens with the Type A and Type B staggered bolt hole patterns. Each series contains test specimens with the same transverse pitch of 55 mm but different staggered pitches ranging from 23 mm to 60 mm; specifically, the specimen series with the Type A staggered bolt hole pattern includes connection specimens A-PL-23-55-A, A-PL-26-55-A, A-PL-30-55-A and A-PL-50-55-A, while the specimen series with the Type B staggered bolt hole pattern contains connection specimens A-PP-25-55-B, A-PP-40-55-B, A-PP-50-55-B and A-PP-60-55-B. The failure loads P_{test} can be seen generally to increase with increasing staggered pitch for both the two specimen series, while the net section failure modes change from ‘3F’ to ‘2F’ and ‘1F’ for the specimen series with the Type A and Type B staggered bolt hole patterns, respectively, as the staggered pitch increases. The explanation for this is as follows: for both types of stainless steel bolted connection specimen, when the staggered pitches are small, the net section areas of paths C-C (passing through three consecutive staggered bolt holes – see Figs 9(d) and 10(d)) are less than those of paths B-B (passing through two bolt holes – see Figs 9(c) and 10(c)) and A-A (passing through one bolt hole – see Figs 9(b) and 10(b)), indicating that paths C-C are the critical fracture paths. As the staggered pitch increases, the net section areas of paths C-C are also enlarged, leading to larger failure loads. However, once the staggered pitch reaches a particular value, the net section areas of paths C-C become higher than those of paths B-B and A-A for Type A and Type B stainless steel bolted connection specimens, respectively, leading to changes in failure modes from ‘3F’ to ‘2F’ and ‘1F’.

4 Assessment of international design standards

4.1 General

In this section, the established design provisions for stainless steel staggered bolted connections susceptible to net section fracture, as set out in the European code EN 1993-1-4 [23], American Specification SEI/ASCE-8 [24] and Australian/New Zealand Standard AS/NZS 4673 [25], are described. The accuracy of each design code is then evaluated by comparing the predicted failure modes and loads against the experimentally observed results – see Table 4. Finally, shortcomings of the existing codified design provisions for stainless steel staggered bolted connections are highlighted, and new, more efficient design rules are proposed.

4.2 European code EN 1993-1-4 (EC3)

For stainless steel bolted connections in tension, the design ultimate resistance of the connected plate to net section fracture $N_{u,EC3}$, as specified in the European code EN 1993-1-4 [23], is given by Eq. (1), in which σ_u is the material ultimate strength, k_r is a reduction factor determined from Eq. (2), where r is the ratio of the number of bolt holes on the examined fracture path n_e to the total number of bolt holes n_t and u is equal to $2e_2$ but not greater than p , A_{net} is the net section area of the examined fracture path calculated from Eq. (3) and $\gamma_{M2}=1.25$ is the partial safety factor for the resistance of cross-sections in tension to fracture.

$$N_{u,EC3} = \frac{k_r \sigma_u A_{net}}{\gamma_{M2}} \quad (1)$$

$$k_r = 1 + 3r \left(\frac{d_0}{u} - 0.3 \right) \leq 1 \quad (2)$$

$$A_{net} = A - t \left(n_e d_0 - \sum \frac{s^2}{4p} \right) \quad (3)$$

With regards to the outer stainless steel splice plates of the studied staggered bolted connection specimens, there are three potential fracture paths A-A, B-B and C-C passing through one, two and three bolt holes; the unfactored (i.e. with the partial safety factor γ_{M2} set to be equal to unity) EC3 net section ultimate resistances for the three potential fracture paths have been calculated and are presented in Table 5(a). EN 1993-1-4 [23] also specifies that stainless steel bolted connections in tension should be assessed for gross section yielding, with the resistance of the connected plate $N_{pl,EC3}$ defined by Eq. (4), where A is the gross section area of the plate, $\sigma_{0.2}$ is the 0.2% proof stress and $\gamma_{M0}=1.10$ is the partial safety factor for the resistance of cross-sections to yielding. The unfactored EC3 gross section plastic resistances of the stainless steel splice plates of the staggered bolted connection specimens have also been calculated and reported in Table 5(a).

$$N_{pl,EC3} = \frac{A\sigma_{0.2}}{\gamma_{M0}} \quad (4)$$

The design failure load of the stainless steel splice plate for each potential failure mode is then calculated as the design ultimate resistance on the examined failure path $N_{u,EC3}$ divided by the corresponding transmission ratio η , or the design plastic resistance $N_{pl,EC3}$, as presented in Table 6(a), while the minimum of the design failure loads calculated from all four potential failure modes is given as the final design failure load of the stainless steel splice plate $P_{s,EC3}$. The EC3 design failure load P_{EC3} for each stainless steel staggered bolted connection specimen is equal to $2P_{s,EC3}$, as reported in Table 4.

Evaluation of the EC3 design provisions for stainless steel staggered bolted connections susceptible to net section fracture was made herein by comparing the predicted failure modes and failure loads against the experimentally obtained results. As can be seen from Table 4, EN 1993-1-4 [23] yields rather conservative and scattered design failure load predictions with almost all the examined stainless steel staggered bolted connections deemed by EN 1993-1-4 [23] to fail due to gross section yielding. This is because of the high ultimate-to-yield stress ratio of stainless steel, particularly the austenitic grades, with $\sigma_u/\sigma_{0.2}$ being around 2 for the grade EN 1.4301 austenitic stainless steel specimens studied herein. This results in the net section ultimate resistances (calculated based on the material ultimate strength) typically being higher than the corresponding gross section plastic resistances (determined based on the material 0.2% proof yield stress), i.e. failure by gross section yielding is generally more critical.

4.3 American Specification SEI/ASCE-8 (ASCE) and Australian/New Zealand Standard AS/NZS 4673 (AS/NZS)

The American Specification SEI/ASCE-8 [24] and the Australian/New Zealand Standard AS/NZS 4673 [25] provide the same rules for the design of stainless steel bolted connections susceptible to net section fracture. The tension resistance of a connected plate is taken as the lesser of the ultimate and plastic resistances of the net section. The net section ultimate resistance $N_{u,a}$ is determined from Eq. (5), where $\phi_{net}=0.70$ is the resistance factor for cross-sections failing by tensile fracture, k_a is a reduction factor given by Eq. (6) and A_{net} is the net section area, determined using the same design formula (i.e. Eq. (3)) as that adopted in the European code EN 1993-1-4 [23].

$$N_{u,a} = \phi_{net} k_a \sigma_u A_{net} \quad (5)$$

$$k_a = 1 - r + \frac{2.5rd_0}{b} \leq 1 \quad (6)$$

The net section plastic resistance $N_{pl,a}$ is determined from Eq. (7), where $\phi_{pl}=0.85$ is the resistance factor for cross-sections failing by material yielding.

$$N_{pl,a} = \phi_{pl} A_{net} \sigma_{0.2} \quad (7)$$

Table 5(b) reports the unfactored design net section ultimate and plastic resistances along the three potential failure paths for the stainless steel splice plate of each connection specimen. The net section ultimate resistance along each potential failure path is divided by the corresponding transmission ratio, and defined as the design failure load for fracture along the examined failure path, as reported in Table 6(b), while the net section plastic resistances along the three failure paths are divided by the corresponding transmission ratios, with the minimum value listed in Table 6(b) as the design failure load for material yielding. The minimum of the design failure loads calculated from all four potential failure modes is given as the final design failure load of the stainless steel splice plate $P_{s,ASCE}$ (or $P_{s,AS/NZS}$). For each stainless steel staggered bolted connection specimen, the ASCE (or AS/NZS) design failure load P_{ASCE} (or $P_{AS/NZS}$) is then calculated as $2P_{s,ASCE}$ (or $2P_{s,AS/NZS}$), as shown in Table 4.

The ASCE (or AS/NZS) design failure loads and modes were assessed through comparisons against their experimental counterparts, with the results of the assessment presented in Table 4. Overall, SEI/ASCE-8 [24] and AS/NZS 4673 [25] can be seen to yield even more conservative failure load predictions for the stainless steel staggered bolted connection specimens than EN 1993-1-4 [23], with the mean ratio of P_{test}/P_{ASCE} (or $P_{test}/P_{AS/NZS}$) equal to 1.74 and the corresponding COV of 0.19. It is also evident from Table 4 that the failure modes,

as predicted by SEI/ASCE-8 [24] and AS/NZS 4673 [25], are material yielding for all the stainless steel staggered bolted connection specimens.

4.4 New design approach

The European code EN 1993-1-4 [23] currently prescribes that the design gross section resistance of the connected plates of stainless steel bolted connections is calculated based on material yielding, i.e. through the use of the material 0.2% proof stress in the resistance calculation without considering the pronounced strain hardening exhibited by stainless steel. Given that stainless steels have high material ultimate-to-0.2% proof stress ratios, the calculated gross section resistances are generally less than the corresponding net section ultimate resistances (calculated based on the material ultimate strengths), and hence govern the design. Improved design rules for stainless steel bolted connections may thus be sought through the employment of a more suitable expression for determining the gross section resistance. The continuous strength method (CSM) [35–39] is a deformation-based design approach, which relates the resistance of a cross-section to its deformation capacity and utilises, for hand calculations, a bi-linear material model to take account of strain hardening. The method has been shown to lead to a high level of accuracy and consistency in predicting the resistances of stainless steel cross-sections in compression [35–37], bending [35–38] and shear [39]. The key aspects of the CSM are introduced below; extension of the method to the case of cross-sections in tension is then presented.

The use of the CSM firstly requires calculating the limiting strain of the cross-section ϵ_{csm} under the applied loading condition. The limiting strain reflects the susceptibility of the cross-section to local buckling and is determined from the CSM base curve, which defines the relationship

between the normalised limiting strain $\varepsilon_{csm}/\varepsilon_y$ and the cross-section slenderness $\bar{\lambda}_p$, as given by Eq. (8) [35,36,40], where $\varepsilon_y = \sigma_{0.2}/E$ is the yield strain and $\bar{\lambda}_p$ is calculated as $\sqrt{\sigma_{0.2}/\sigma_{cr}}$, in which σ_{cr} is the cross-section elastic local buckling stress under the applied loading condition [41].

$$\frac{\varepsilon_{csm}}{\varepsilon_y} = \begin{cases} \frac{0.25}{\bar{\lambda}_p^{3.6}} \leq \min\left(15, \frac{C_1 \varepsilon_u}{\varepsilon_y}\right), & \text{for } \bar{\lambda}_p \leq 0.68 \\ \left(1 - \frac{0.222}{\bar{\lambda}_p^{1.050}}\right) \frac{1}{\bar{\lambda}_p^{1.050}}, & \text{for } \bar{\lambda}_p > 0.68 \end{cases} \quad (8)$$

For hand calculations, the CSM adopts a bi-linear stress-strain model [37], which is linear elastic up to the material 0.2% proof stress, followed by a linear hardening response, as shown in Fig. 13. Note that for design by second-order inelastic analysis [42,43], the two-stage Ramberg–Osgood material model is recommended [32–34,44]. Four coefficients C_1 , C_2 , C_3 and C_4 are used to define the CSM bi-linear material model. Specifically, C_1 is used to define a cut-off strain $C_1 \varepsilon_u / \varepsilon_y$ to prevent overestimation of the design stress; C_2 is utilised in Eq. (9) to define the strain hardening slope E_{sh} ; C_3 and C_4 are employed to predict the strain at the material ultimate stress $\varepsilon_u = C_3(1 - \sigma_{0.2}/\sigma_u) + C_4$. Table 7 provides the values of the four coefficients for different grades of stainless steel [37]. The design stress calculated from the CSM bi-linear material model is given by Eq. (10); it is worth noting that the calculated CSM design stress is higher than the 0.2% proof stress for non-slender cross-sections with $\varepsilon_{csm} / \varepsilon_y \geq 1$, allowing the beneficial material strain hardening to be exploited.

$$E_{sh} = \frac{\sigma_u - \sigma_{0.2}}{C_2 \varepsilon_u - \varepsilon_y} \quad (9)$$

$$\sigma_{csm} = \begin{cases} \sigma_{0.2} + E_{sh} (\varepsilon_{csm} - \varepsilon_y), & \text{for } \varepsilon_{csm} \geq \varepsilon_y \\ E \varepsilon_{csm}, & \text{for } \varepsilon_{csm} < \varepsilon_y \end{cases} \quad (10)$$

408

409 For plates or members in tension, which are not susceptible to local buckling, it is proposed
 410 that the normalised limiting strain $\varepsilon_{csm}/\varepsilon_y$ be taken as the upper limit of Eq. (8), i.e. the minimum
 411 of 15 and $C_1\varepsilon_u/\varepsilon_y$. The CSM design stress for plates or members in tension can then be
 412 determined by substituting $\varepsilon_{csm}=\min(15\varepsilon_y, C_1\varepsilon_u)$ into Eq. (10), with the final expression shown
 413 by Eq. (11), while the CSM gross section resistance in tension is calculated from Eq. (12).

$$414 \quad \sigma_{csm,t} = \sigma_{0.2} + 14E_{sh}\varepsilon_y \quad \text{but} \leq \sigma_{0.2} + E_{sh}(C_1\varepsilon_u - \varepsilon_y) \quad (11)$$

$$415 \quad N_{csm,t,Rd} = \frac{A\sigma_{csm,t}}{\gamma_{M0}} \quad (12)$$

416

417 The CSM gross section resistance of the stainless steel splice plates of each staggered bolted
 418 connection specimen has been calculated and is reported in Table 5(c), together with the EC3
 419 net section ultimate resistances for the three potential fracture paths. The design failure load of
 420 the stainless steel splice plate for each potential failure mode is then calculated as the CSM
 421 gross section resistance $N_{csm,t,Rd}$ or the EC3 design net section ultimate resistance on the
 422 examined failure path $N_{u,EC3}$ divided by the corresponding transmission ratio η , as reported in
 423 Table 6(c), while the minimum of the design failure loads calculated from all four potential
 424 failure modes is given as the final design failure load of the stainless steel splice plate $P_{s,p}$. For
 425 each stainless steel staggered bolted connection specimen, the design failure load $P_p=2P_{s,p}$, as
 426 well as the corresponding failure mode, are shown in Table 4, in which ‘G’ denotes gross
 427 section failure. Note that γ_{M0} has been taken equal to unity for the presented comparisons but
 428 has a recommended value of 1.1 for design purposes. The mean test to design failure load ratio
 429 P_{test}/P_p is equal to 1.09, with the COV equal to 0.09, indicating that the new design approach,
 430 with the gross section resistances calculated based on the CSM design stress (instead of the
 431 material 0.2% proof stress), yields substantially more accurate and consistent failure load

predictions for stainless steel staggered bolted connection specimens. Moreover, accurate predictions of failure modes for the duplex and ferritic stainless steel staggered bolted connection specimens were also generally obtained by using the new design approach.

5 Conclusions

A comprehensive testing programme has been conducted to investigate the net section fracture behaviour and capacity of stainless steel staggered bolted connections in tension. The experimental programme comprised tensile coupon tests and a total of 31 stainless steel staggered bolted connection tests. Three material grades and a range of geometric variations, including the transverse and staggered pitches and the staggered bolt hole pattern, were studied. Three different net section fracture modes, with straight failure paths passing through one or two bolt holes and staggered failure paths passing through three bolt holes, were observed in the experiments. Analysis of the test results was conducted, and the influence of the transverse and staggered pitches as well as the staggered bolt hole patterns on the net section fracture modes and failure loads of the connection specimens were discussed. The experimental failure loads and modes were then used to evaluate the accuracy of the existing codified design provisions for stainless steel staggered bolted connections, as set out in EN 1993-1-4 [23], SEI/ASCE-8 [24] and AS/NZS 4673 [25]. The three international standards specify that the design failure load should be taken as the minimum value calculated for all potential net section fracture paths and gross section yielding. Comparisons of the predicted failure loads and modes against the corresponding experimental results generally revealed that all three considered international standards result in rather conservative and scattered failure load predictions as well as inaccurate failure mode predictions for the stainless steel staggered bolted connection specimens. A new improved design method was then developed through the use of the CSM

[35–39] to calculate the gross section resistances, and shown to yield substantially more accurate and consistent predictions of both failure modes and failure loads.

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Table 1 Material grade, bolt hole pattern, geometric dimensions and key results for stainless steel staggered bolted connection specimens

Grade	Specimen	Direction	Staggered pattern	b (mm)	s (mm)	p (mm)	e_1 (mm)	e_2 (mm)	Failure mode	P_{test} (kN)
Austenitic	A-PL-22-36-A	PL	Type A	107	22	36	45	17.5	3F	327.4
	A-PL-24-36-A	PL	Type A	107	24	36	45	17.5	2F	319.4
	A-PL-26-36-A	PL	Type A	107	26	36	45	17.5	2F	328.3
	A-PL-23-55-A	PL	Type A	145	23	55	45	17.5	3F	436.0
	A-PL-26-55-A	PL	Type A	145	26	55	45	17.5	3F	442.0
	A-PL-30-55-A	PL	Type A	145	30	55	45	17.5	2F	460.8
	A-PL-50-55-A	PL	Type A	145	50	55	45	17.5	2F	480.0
	A-PL-55-55-B	PL	Type B	145	55	55	45	17.5	1F	509.6
	A-PL-60-55-B	PL	Type B	145	60	55	45	17.5	1F	494.4
	A-PP-18-36-A	PP	Type A	107	18	36	45	17.5	3F	290.1
	A-PP-23-36-A	PP	Type A	107	23	36	45	17.5	2F	312.3
	A-PP-20-55-A	PP	Type A	145	20	55	45	17.5	3F	446.4
	A-PP-25-55-A	PP	Type A	145	25	55	45	17.5	2F	442.3
	A-PP-25-55-B	PP	Type B	145	25	55	45	17.5	3F	472.9
	A-PP-30-55-B	PP	Type B	145	30	55	45	17.5	1F	451.8
	A-PP-40-55-B	PP	Type B	145	40	55	45	17.5	1F	496.3
	A-PP-50-55-B	PP	Type B	145	50	55	45	17.5	1F	515.0
	A-PP-60-55-B	PP	Type B	145	60	55	45	17.5	1F	550.9
Duplex	D-PL-24-36-A	PL	Type A	107	24	36	45	17.5	3F	327.3
	D-PL-28-36-A	PL	Type A	107	28	36	45	17.5	2F	327.0
	D-PL-27-55-A	PL	Type A	145	27	55	45	17.5	3F	457.7
	D-PL-30-55-A	PL	Type A	145	30	55	45	17.5	2F	439.6
	D-PP-40-55-B	PP	Type B	145	40	55	45	17.5	3F	519.0
	D-PP-50-55-B	PP	Type B	145	50	55	45	17.5	3F	525.8
	D-PP-60-55-B	PP	Type B	145	60	55	45	17.5	1F	541.2
Ferritic	F-PL-24-36-A	PL	Type A	107	24	36	45	17.5	3F	218.2
	F-PL-27-36-A	PL	Type A	107	27	36	45	17.5	2F	226.2
	F-PL-27-55-A	PL	Type A	145	27	55	45	17.5	3F	311.4
	F-PL-30-55-A	PL	Type A	145	30	55	45	17.5	2F	314.8
	F-PL-50-55-B	PL	Type B	145	50	55	45	17.5	3F	330.4
	F-PL-55-55-B	PL	Type B	145	55	55	45	17.5	1F	333.3

Table 2 Summary of key measured material properties from tensile coupon tests

Grade	Direction	E (GPa)	$\sigma_{0.2}$ (MPa)	$\sigma_{1.0}$ (MPa)	σ_u (MPa)	ε_u (%)	ε_f (%)	R–O coefficients		
								n	$m_{1.0}$	m_u
Austenitic (EN 1.4301)	PL	199.5	350.6	386.5	710.3	48.8	54.0	5.3	1.9	2.4
	PP	201.3	348.3	401.4	748.3	43.9	48.9	9.3	1.2	2.3
Duplex (EN 1.4462)	PL	198.6	494.7	546.7	716.5	28.6	32.3	5.8	1.4	2.9
	PP	202.3	538.7	591.3	760.4	21.6	27.9	8.8	2.2	3.0
Ferritic (EN 1.4016)	PL	198.4	352.3	393.7	471.2	17.3	25.0	13.5	3.0	3.1

Table 3 Transmission ratio η

Staggered pattern	Failure mode		
	1F	2F	3F
Type A	2/3	1	1
Type B	1	5/6	1

Table 4 Predicted failure modes and loads from design codes and new design approach

Specimen	EN 1993-1-4			SEI/ASCE-8 (or AS/NZS 4673)			New design approach		
	Failure mode	P_{EC3} (kN)	P_{test}/P_{EC3}	Failure mode	P_{ASCE} (or $P_{AS/NZS}$) (kN)	P_{test}/P_{ASCE} (or $P_{test}/P_{AS/NZS}$)	Failure mode	P_p (kN)	P_{test}/P_p
A-PL-22-36-A	Yielding	225.2	1.45	Yielding	149.1	2.20	G	297.0	1.10
A-PL-24-36-A	Yielding	225.2	1.42	Yielding	151.7	2.11	G	297.0	1.08
A-PL-26-36-A	Yielding	225.2	1.46	Yielding	154.7	2.12	G	297.0	1.11
A-PL-23-55-A	Yielding	305.0	1.43	Yielding	225.0	1.94	G	402.2	1.08
A-PL-26-55-A	Yielding	305.0	1.45	Yielding	227.8	1.94	G	402.2	1.10
A-PL-30-55-A	Yielding	305.0	1.51	Yielding	232.1	1.99	G	402.2	1.15
A-PL-50-55-A	Yielding	305.0	1.57	Yielding	244.9	1.96	G	402.2	1.19
A-PL-55-55-B	Yielding	305.0	1.67	Yielding	272.8	1.87	G	402.2	1.27
A-PL-60-55-B	Yielding	305.0	1.62	Yielding	274.9	1.80	G	402.2	1.23
A-PP-18-36-A	Yielding	223.6	1.30	Yielding	143.5	2.02	G	297.8	0.97
A-PP-23-36-A	Yielding	223.6	1.40	Yielding	149.4	2.09	G	297.8	1.05
A-PP-20-55-A	Yielding	303.0	1.47	Yielding	221.0	2.02	G	403.6	1.11
A-PP-25-55-A	Yielding	303.0	1.46	Yielding	225.3	1.96	G	403.6	1.10
A-PP-25-55-B	Yielding	303.0	1.56	Yielding	225.3	2.10	G	403.6	1.17
A-PP-30-55-B	Yielding	303.0	1.49	Yielding	230.6	1.96	G	403.6	1.12
A-PP-40-55-B	Yielding	303.0	1.64	Yielding	243.9	2.03	G	403.6	1.23
A-PP-50-55-B	Yielding	303.0	1.70	Yielding	260.9	1.97	G	403.6	1.28
A-PP-60-55-B	Yielding	303.0	1.82	Yielding	273.2	2.02	G	403.6	1.36
D-PL-24-36-A	3F	310.2	1.06	Yielding	214.1	1.53	3F	310.2	1.06
D-PL-28-36-A	Yielding	317.6	1.03	Yielding	222.7	1.47	3F	322.6	1.01
D-PL-27-55-A	Yielding	430.4	1.06	Yielding	322.8	1.42	3F	467.6	0.98
D-PL-30-55-A	Yielding	430.4	1.02	Yielding	327.4	1.34	3F	474.2	0.93
D-PP-40-55-B	Yielding	468.6	1.11	Yielding	377.2	1.38	3F	532.4	0.97
D-PP-50-55-B	Yielding	468.6	1.12	Yielding	403.5	1.30	1F	536.4	0.98
D-PP-60-55-B	Yielding	468.6	1.15	Yielding	422.5	1.28	1F	536.4	1.01
F-PL-24-36-A	3F	204.0	1.07	Yielding	152.5	1.43	3F	204.0	1.07
F-PL-27-36-A	3F	210.0	1.08	Yielding	157.0	1.44	3F	210.0	1.08
F-PL-27-55-A	Yielding	306.4	1.02	Yielding	229.9	1.35	3F	307.6	1.01
F-PL-30-55-A	Yielding	306.4	1.03	Yielding	233.2	1.35	3F	312.0	1.01
F-PL-50-55-B	Yielding	306.4	1.08	Yielding	263.9	1.25	1F	332.4	0.99
F-PL-55-55-B	Yielding	306.4	1.09	Yielding	274.1	1.22	1F	332.4	1.00
Mean			1.33			1.74			1.09
COV			0.19			0.19			0.09

Table 5 Net and gross section resistance predictions from design codes and new design approach

(a) EN 1993-1-4

Specimen	$N_{u,EC3}$ (kN)			$N_{pl,EC3}$ (kN)
	Fracture path A-A	Fracture path B-B	Fracture path C-C	
A-PL-22-36-A	181.1	167.1	151.0	112.6
A-PL-24-36-A	181.1	167.1	153.7	112.6
A-PL-26-36-A	181.1	167.1	156.7	112.6
A-PL-23-55-A	250.5	248.1	227.9	152.5
A-PL-26-55-A	250.5	248.1	230.7	152.5
A-PL-30-55-A	250.5	248.1	235.1	152.5
A-PL-50-55-A	250.5	248.1	266.1	152.5
A-PL-55-55-B	250.5	248.1	276.2	152.5
A-PL-60-55-B	250.5	248.1	287.4	152.5
A-PP-18-36-A	190.8	176.1	154.1	111.8
A-PP-23-36-A	190.8	176.1	160.5	111.8
A-PP-20-55-A	263.9	261.4	237.4	151.5
A-PP-25-55-A	263.9	261.4	242.0	151.5
A-PP-25-55-B	263.9	261.4	242.0	151.5
A-PP-30-55-B	263.9	261.4	247.6	151.5
A-PP-40-55-B	263.9	261.4	261.9	151.5
A-PP-50-55-B	263.9	261.4	280.3	151.5
A-PP-60-55-B	263.9	261.4	302.7	151.5
D-PL-24-36-A	182.7	168.6	155.1	158.8
D-PL-28-36-A	182.7	168.6	161.3	158.8
D-PL-27-55-A	252.6	250.2	233.8	215.2
D-PL-30-55-A	252.6	250.2	237.1	215.2
D-PP-40-55-B	268.2	265.6	266.2	234.3
D-PP-50-55-B	268.2	265.6	284.8	234.3
D-PP-60-55-B	268.2	265.6	307.7	234.3
F-PL-24-36-A	120.2	110.9	102.0	113.1
F-PL-27-36-A	120.2	110.9	105.0	113.1
F-PL-27-55-A	166.2	164.6	153.8	153.2
F-PL-30-55-A	166.2	164.6	156.0	153.2
F-PL-50-55-B	166.2	164.6	176.5	153.2
F-PL-55-55-B	166.2	164.6	183.3	153.2

(b) SEI/ASCE-8 (or AS/NZS 4673)

Specimen	Fracture path A-A		Fracture path B-B		Fracture path C-C	
	$N_{u,a}$ (kN)	$N_{pl,a}$ (kN)	$N_{u,a}$ (kN)	$N_{pl,a}$ (kN)	$N_{u,a}$ (kN)	$N_{pl,a}$ (kN)
A-PL-22-36-A	175.6	97.5	166.7	82.5	150.4	74.5
A-PL-24-36-A	175.6	97.5	166.7	82.5	153.1	75.8
A-PL-26-36-A	175.6	97.5	166.7	82.5	156.1	77.3
A-PL-23-55-A	243.5	137.4	219.1	122.5	187.9	112.5
A-PL-26-55-A	243.5	137.4	219.1	122.5	190.3	113.9
A-PL-30-55-A	243.5	137.4	219.1	122.5	193.9	116.0
A-PL-50-55-A	243.5	137.4	219.1	122.5	219.4	131.4
A-PL-55-55-B	243.5	137.4	219.1	122.5	227.8	136.4
A-PL-60-55-B	243.5	137.4	219.1	122.5	237.0	141.9
A-PP-18-36-A	185.0	96.8	175.6	81.9	153.5	71.7
A-PP-23-36-A	185.0	96.8	175.6	81.9	159.8	74.7
A-PP-20-55-A	256.6	136.6	230.8	121.6	195.8	110.5
A-PP-25-55-A	256.6	136.6	230.8	121.6	199.6	112.7
A-PP-25-55-B	256.6	136.6	230.8	121.6	199.6	112.7
A-PP-30-55-B	256.6	136.6	230.8	121.6	204.2	115.3
A-PP-40-55-B	256.6	136.6	230.8	121.6	216.0	122.0
A-PP-50-55-B	256.6	136.6	230.8	121.6	231.2	130.4
A-PP-60-55-B	256.6	136.6	230.8	121.6	249.7	140.9
D-PL-24-36-A	177.1	137.6	168.1	116.4	154.4	107.1
D-PL-28-36-A	177.1	137.6	168.1	116.4	160.6	111.3
D-PL-27-55-A	245.7	194.0	221.0	172.8	192.8	161.4
D-PL-30-55-A	245.7	194.0	221.0	172.8	195.6	163.7
D-PP-40-55-B	260.7	211.2	234.6	188.2	219.5	188.6
D-PP-50-55-B	260.7	211.2	234.6	188.2	234.9	201.8
D-PP-60-55-B	260.7	211.2	234.6	188.2	253.7	218.0
F-PL-24-36-A	116.5	98.0	110.6	82.8	101.6	76.3
F-PL-27-36-A	116.5	98.0	110.6	82.8	104.6	78.5
F-PL-27-55-A	161.6	138.1	145.3	123.0	126.8	115.0
F-PL-30-55-A	161.6	138.1	145.3	123.0	128.6	116.6
F-PL-50-55-B	161.6	138.1	145.3	123.0	145.6	131.9
F-PL-55-55-B	161.6	138.1	145.3	123.0	151.1	137.0

(c) New design approach

Specimen	$N_{u,EC3}$ (kN)			$N_{csm,t,Rd}$ (kN)
	Fracture path A-A	Fracture path B-B	Fracture path C-C	
A-PL-22-36-A	181.1	167.1	151.0	148.5
A-PL-24-36-A	181.1	167.1	153.7	148.5
A-PL-26-36-A	181.1	167.1	156.7	148.5
A-PL-23-55-A	250.5	248.1	227.9	201.1
A-PL-26-55-A	250.5	248.1	230.7	201.1
A-PL-30-55-A	250.5	248.1	235.1	201.1
A-PL-50-55-A	250.5	248.1	266.1	201.1
A-PL-55-55-B	250.5	248.1	276.2	201.1
A-PL-60-55-B	250.5	248.1	287.4	201.1
A-PP-18-36-A	190.8	176.1	154.1	148.9
A-PP-23-36-A	190.8	176.1	160.5	148.9
A-PP-20-55-A	263.9	261.4	237.4	201.8
A-PP-25-55-A	263.9	261.4	242.0	201.8
A-PP-25-55-B	263.9	261.4	242.0	201.8
A-PP-30-55-B	263.9	261.4	247.6	201.8
A-PP-40-55-B	263.9	261.4	261.9	201.8
A-PP-50-55-B	263.9	261.4	280.3	201.8
A-PP-60-55-B	263.9	261.4	302.7	201.8
D-PL-24-36-A	182.7	168.6	155.1	201.9
D-PL-28-36-A	182.7	168.6	161.3	201.9
D-PL-27-55-A	252.6	250.2	233.8	273.6
D-PL-30-55-A	252.6	250.2	237.1	273.6
D-PP-40-55-B	268.2	265.6	266.2	292.4
D-PP-50-55-B	268.2	265.6	284.8	292.4
D-PP-60-55-B	268.2	265.6	307.7	292.4
F-PL-24-36-A	120.2	110.9	102.0	127.4
F-PL-27-36-A	120.2	110.9	105.0	127.4
F-PL-27-55-A	166.2	164.6	153.8	172.6
F-PL-30-55-A	166.2	164.6	156.0	172.6
F-PL-50-55-B	166.2	164.6	176.5	172.6
F-PL-55-55-B	166.2	164.6	183.3	172.6

Table 6 Design failure loads of stainless steel splice plate of each connection specimen for different potential failure modes

(a) EN 1993-1-4

Specimen	$N_{u,EC3}/\eta$ or $N_{pl,EC3}$ (kN)				$P_{s,EC3}$ (kN)
	1F	2F	3F	Yielding	
A-PL-22-36-A	271.7	167.1	151.0	112.6	112.6
A-PL-24-36-A	271.7	167.1	153.7	112.6	112.6
A-PL-26-36-A	271.7	167.1	156.7	112.6	112.6
A-PL-23-55-A	375.7	248.1	227.9	152.5	152.5
A-PL-26-55-A	375.7	248.1	230.7	152.5	152.5
A-PL-30-55-A	375.7	248.1	235.1	152.5	152.5
A-PL-50-55-A	375.7	248.1	266.1	152.5	152.5
A-PL-55-55-B	250.5	297.7	276.2	152.5	152.5
A-PL-60-55-B	250.5	297.7	287.4	152.5	152.5
A-PP-18-36-A	286.2	176.1	154.1	111.8	111.8
A-PP-23-36-A	286.2	176.1	160.5	111.8	111.8
A-PP-20-55-A	395.8	261.4	237.4	151.5	151.5
A-PP-25-55-A	395.8	261.4	242.0	151.5	151.5
A-PP-25-55-B	263.9	313.6	242.0	151.5	151.5
A-PP-30-55-B	263.9	313.6	247.6	151.5	151.5
A-PP-40-55-B	263.9	313.6	261.9	151.5	151.5
A-PP-50-55-B	263.9	313.6	280.3	151.5	151.5
A-PP-60-55-B	263.9	313.6	302.7	151.5	151.5
D-PL-24-36-A	274.0	168.6	155.1	158.8	155.1
D-PL-28-36-A	274.0	168.6	161.3	158.8	158.8
D-PL-27-55-A	379.0	250.2	233.8	215.2	215.2
D-PL-30-55-A	379.0	250.2	237.1	215.2	215.2
D-PP-40-55-B	268.2	318.7	266.2	234.3	234.3
D-PP-50-55-B	268.2	318.7	284.8	234.3	234.3
D-PP-60-55-B	268.2	318.7	307.7	234.3	234.3
F-PL-24-36-A	180.2	110.9	102.0	113.1	102.0
F-PL-27-36-A	180.2	110.9	105.0	113.1	105.0
F-PL-27-55-A	249.2	164.6	153.8	153.2	153.2
F-PL-30-55-A	249.2	164.6	156.0	153.2	153.2
F-PL-50-55-B	166.2	197.5	176.5	153.2	153.2
F-PL-55-55-B	166.2	197.5	183.3	153.2	153.2

(b) SEI/ASCE-8 (or AS/NZS 4673)

Specimen	$N_{u,a}/\eta$ or $N_{pl,a}/\eta$ (kN)				$P_{s,ASCE}$ (or $P_{s,AS/NZS}$) (kN)
	1F	2F	3F	Yielding	
A-PL-22-36-A	263.4	166.7	150.4	74.5	74.5
A-PL-24-36-A	263.4	166.7	153.1	75.8	75.8
A-PL-26-36-A	263.4	166.7	156.1	77.3	77.3
A-PL-23-55-A	365.3	219.1	187.9	112.5	112.5
A-PL-26-55-A	365.3	219.1	190.3	113.9	113.9
A-PL-30-55-A	365.3	219.1	193.9	116.0	116.0
A-PL-50-55-A	365.3	219.1	219.4	122.5	122.5
A-PL-55-55-B	243.5	262.9	227.8	136.4	136.4
A-PL-60-55-B	243.5	262.9	237.0	137.4	137.4
A-PP-18-36-A	277.5	175.6	153.5	71.7	71.7
A-PP-23-36-A	277.5	175.6	159.8	74.7	74.7
A-PP-20-55-A	384.9	230.8	195.8	110.5	110.5
A-PP-25-55-A	384.9	230.8	199.6	112.7	112.7
A-PP-25-55-B	256.6	277.0	199.6	112.7	112.7
A-PP-30-55-B	256.6	277.0	204.2	115.3	115.3
A-PP-40-55-B	256.6	277.0	216.0	122.0	122.0
A-PP-50-55-B	256.6	277.0	231.2	130.4	130.4
A-PP-60-55-B	256.6	277.0	249.7	136.6	136.6
D-PL-24-36-A	265.7	168.1	154.4	107.1	107.1
D-PL-28-36-A	265.7	168.1	160.6	111.3	111.3
D-PL-27-55-A	368.5	221.0	192.8	161.4	161.4
D-PL-30-55-A	368.5	221.0	195.6	163.7	163.7
D-PP-40-55-B	260.7	281.5	219.5	188.6	188.6
D-PP-50-55-B	260.7	281.5	234.9	201.8	201.8
D-PP-60-55-B	260.7	281.5	253.7	211.2	211.2
F-PL-24-36-A	174.8	110.6	101.6	76.3	76.3
F-PL-27-36-A	174.8	110.6	104.6	78.5	78.5
F-PL-27-55-A	242.4	145.3	126.8	115.0	115.0
F-PL-30-55-A	242.4	145.3	128.6	116.6	116.6
F-PL-50-55-B	161.6	174.4	145.6	131.9	131.9
F-PL-55-55-B	161.6	174.4	151.1	137.0	137.0

(c) New design approach

Specimen	$N_{u,EC3}/\eta$ or $N_{csm,t,Rd}$ (kN)				$P_{s,p}$ (kN)
	1F	2F	3F	G	
A-PL-22-36-A	271.7	167.1	151.0	148.5	148.5
A-PL-24-36-A	271.7	167.1	153.7	148.5	148.5
A-PL-26-36-A	271.7	167.1	156.7	148.5	148.5
A-PL-23-55-A	375.7	248.1	227.9	201.1	201.1
A-PL-26-55-A	375.7	248.1	230.7	201.1	201.1
A-PL-30-55-A	375.7	248.1	235.1	201.1	201.1
A-PL-50-55-A	375.7	248.1	266.1	201.1	201.1
A-PL-55-55-B	250.5	297.7	276.2	201.1	201.1
A-PL-60-55-B	250.5	297.7	287.4	201.1	201.1
A-PP-18-36-A	286.2	176.1	154.1	148.9	148.9
A-PP-23-36-A	286.2	176.1	160.5	148.9	148.9
A-PP-20-55-A	395.8	261.4	237.4	201.8	201.8
A-PP-25-55-A	395.8	261.4	242.0	201.8	201.8
A-PP-25-55-B	263.9	313.6	242.0	201.8	201.8
A-PP-30-55-B	263.9	313.6	247.6	201.8	201.8
A-PP-40-55-B	263.9	313.6	261.9	201.8	201.8
A-PP-50-55-B	263.9	313.6	280.3	201.8	201.8
A-PP-60-55-B	263.9	313.6	302.7	201.8	201.8
D-PL-24-36-A	274.0	168.6	155.1	201.9	155.1
D-PL-28-36-A	274.0	168.6	161.3	201.9	161.3
D-PL-27-55-A	379.0	250.2	233.8	273.6	233.8
D-PL-30-55-A	379.0	250.2	237.1	273.6	237.1
D-PP-40-55-B	268.2	318.7	266.2	292.4	266.2
D-PP-50-55-B	268.2	318.7	284.8	292.4	268.2
D-PP-60-55-B	268.2	318.7	307.7	292.4	268.2
F-PL-24-36-A	180.2	110.9	102.0	127.4	102.0
F-PL-27-36-A	180.2	110.9	105.0	127.4	105.0
F-PL-27-55-A	249.2	164.6	153.8	172.6	153.8
F-PL-30-55-A	249.2	164.6	156.0	172.6	156.0
F-PL-50-55-B	166.2	197.5	176.5	172.6	166.2
F-PL-55-55-B	166.2	197.5	183.3	172.6	166.2

Table 7 Summary of CSM material model coefficients for each stainless steel grade.

Material	C_1	C_2	C_3	C_4
Austenitic stainless steel	0.10	0.16	1.00	0
Duplex stainless steel	0.10	0.16	1.00	0
Ferritic stainless steel	0.40	0.45	0.60	0

(a) Elevation view

(b) Plan view of Type A staggered bolt hole pattern

(c) Plan view of Type B staggered bolt hole pattern

Fig. 1. Configuration of stainless steel staggered bolted connections

Fig. 2. Tensile coupon test setup

Fig. 3. Measured stress-strain curves for grade EN 1.4301 austenitic stainless steel from longitudinal (PL) and transverse (PP) coupons

Fig. 4. Measured stress-strain curves for grade EN 1.4462 duplex stainless steel from longitudinal (PL) and transverse (PP) coupons

Fig. 5. Measured stress-strain curve for grade EN 1.4016 ferritic stainless steel from longitudinal (PL) coupons

Fig. 6. Experimental setup for tension tests on stainless steel staggered bolted connection specimens

(a) 2F failure mode (fracture path passing through two innermost bolt holes)

(b) 3F failure mode (fracture path passing through three innermost consecutive staggered bolt holes)

Fig. 7. Net section failure modes of stainless steel staggered bolted connection specimens with Type A staggered bolt hole pattern.

(a) 1F failure mode (fracture path passing through single innermost bolt hole)

(b) 3F failure mode (fracture path passing through three innermost consecutive staggered bolt holes)

Fig. 8. Net section failure modes of stainless steel staggered bolted connection specimens with Type B staggered bolt hole pattern.

(a) At middle face

(b) On fracture path A-A

(c) On fracture path B-B

(d) On fracture path C-C

Fig. 9. Free body diagrams of stainless steel splice plate with Type A staggered bolt hole pattern

(a) At middle face

(b) On fracture path A-A

(c) On fracture path B-B

(d) On fracture path C-C

Fig. 10. Free body diagrams of stainless steel splice plate with Type B staggered bolt hole pattern

Fig. 11. Influence of transverse pitch on failure load and mode of stainless steel staggered bolted connection specimens

Fig. 12. Influence of staggered pitch on failure load and mode of stainless steel staggered bolted connection specimens

Fig. 13. CSM bi-linear (elastic, linear hardening) material model