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Abstract

This paper investigates the effects of bolt threads on the initial and final stiffnesses of double-shear bolted connections through laboratory tests and finite element (FE) analyses. Nineteen specimens composed of 4.7 mm and 8.0 mm thick structural steel plates with bolt diameters of 20 mm and 30 mm having varying end distances are studied. The investigation, which involves shank and thread bolted connections, has found that the threads reduce the initial stiffness but increase the final stiffness. The FE analysis shows that the reduction in the initial stiffness is due to the bolt threads cutting into the connected plate, increasing the initial displacement. However, the same factor moderates the softening behaviour of a thread bolted connection as it approaches its ultimate capacity. The FE simulation shows that in certain cases this newly discovered phenomenon is caused by the threads restraining the crimping of the plate material downstream of it. The present modelling technique significantly improves the simulation results of bolted connections tested by independent researchers, compared to their own modelling techniques including that which attempts to simulate the thread effects by reducing the diameter of the bolt model. The "elastic" stiffness values obtained from the present laboratory tests are compared against the Eurocode's provision based on the ASTM definition, and ad hoc stiffness formulae are proposed for shank and thread bolted connections.

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Thread Effects on the Stiffness of Bolted Shear Connections

Aziz Ahmed¹ and Lip H. Teh²

Abstract:

This paper investigates the effects of bolt threads on the initial and final stiffnesses of double-shear bolted connections through laboratory tests and finite element (FE) analyses. Nineteen specimens composed of 4.7 mm and 8.0 mm thick structural steel plates with bolt diameters of 20 mm and 30 mm having varying end distances are studied. The investigation, which involves shank and thread bolted connections, has found that the threads reduce the initial stiffness but increase the final stiffness. The FE analysis shows that the reduction in the initial stiffness is due to the bolt threads cutting into the connected plate, increasing the initial displacement. However, the same factor moderates the softening behaviour of a thread bolted connection as it approaches its ultimate capacity. The FE simulation shows that in certain cases this newly discovered phenomenon is caused by the threads restraining the crimping of the plate material downstream of it. The present modelling technique significantly improves the simulation results of bolted connections tested by independent researchers, compared to their own modelling techniques including that which attempts to simulate the thread effects by reducing the diameter of the bolt model. The “elastic” stiffness values obtained from the present laboratory tests are compared against the Eurocode’s provision based on the ASTM definition, and ad hoc stiffness formulae are proposed for shank and thread bolted connections.

Author keywords: bearing deformation, bolted shear connection, bolt thread, connection stiffness, finite element analysis, thread modelling

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21 List of notations

22 ε = engineering strain

23 ε_{true} = true strain

24 ε_u = engineering strain at the ultimate stress

25 σ = engineering stress

26 σ_{true} = true stress

27 $\Delta_{0.40}$ = measured displacement corresponding to 40 percent of the ultimate test load

28 d = bolt diameter

29 d_h = bolt hole diameter

30 d_{min} = minor diameter of a bolt

31 d_{M16} = nominal diameter of an M16 bolt

32 d_{M20} = nominal diameter of an M20 bolt

33 $d_{min,M20}$ = minor diameter of an M20 bolt

34 e_1 = end distance

35 e_2 = edge distance

36 n_b = number of bolts in shear

37 p = bolt pitch

38 t = plate thickness

39 t_d = thread depth

40 t_p = thread pitch

41 E = Young's modulus

42 F_u = tensile strength of the plate material

43 F_{ub} = tensile strength of the bolt material

- 44 F_y = yield stress of the plate material
- 45 G = shear modulus of elasticity
- 46 P_p = predicted ultimate capacity
- 47 P_t = ultimate test load
- 48 $P_{0.40}$ = 40 percent of the ultimate test load
- 49 S_b = plate bending stiffness
- 50 S_{br} = bearing stiffness of a plate (Rex & Easterling 2003)
- 51 S_{bs} = “elastic” stiffness of a bolt in shear (ECS 2010)
- 52 S_e = resultant stiffness of a double-shear bolted connection (present work)
- 53 S_{ei} = estimated stiffness of an inner plate (present work)
- 54 S_{eo} = estimated stiffness of an outer plate (present work)
- 55 $S_{e,eu}$ = equivalent spring stiffness of a double-shear bolted connection (ECS
56 2010)
- 57 $S_{e,re}$ = resultant stiffness of the connection (Rex and Sterling 2003)
- 58 $S_{e,shank}$ = estimated stiffness of a plate in a shank bolted connection (present work)
- 59 $S_{e,thread}$ = estimated stiffness of a plate in a thread bolted connection (present work)
- 60 S_{pi} = bearing stiffness of inner plate (ECS 2010)
- 61 S_{pj} = bearing stiffness of a plate (ECS 2010)
- 62 S_{po} = bearing stiffness of outer plate (ECS 2010)
- 63 S_t = measured “elastic” stiffness of a bolted shear connection
- 64 S_v = plate shear stiffness
- 65
- 66
- 67

68 Introduction

69 Bolted shear connections have been investigated experimentally and numerically by many researchers
 70 (Rex and Sterling 2003; Lim and Nethercot, 2004, Salih *et al.* 2011, Moze and Beg 2011, Vangaasbeek
 71 2015, Yang *et al.* 2015, D'Antimo *et al.* 2017). However, none modelled the bolt threads in their finite
 72 element (FE) analyses, and some (Moze and Beg 2011, Vangaasbeek 2015, Yang *et al.* 2015) used
 73 only shank bolted connections in their laboratory tests. Those who used threaded bolts in their
 74 laboratory tests reported significant differences in the initial stiffness between the test specimens and
 75 their FE models (Rex and Sterling 2003, Lim and Nethercot 2004, D'Antimo *et al.* 2017).

76 Lim and Nethercot (2004) shifted their original FE curve by an amount equal to the difference between
 77 the major and the minor diameters of the bolt, and obtained excellent agreement halfway through the
 78 complete response. On the other hand, D'Antimo *et al.* (2017) attributed the more flexible
 79 experimental response mainly to the geometrical imperfections around the bolt holes, and used an
 80 artificially smaller bolt diameter to match the experimental initial stiffness. However, their method
 81 resulted in a significant underestimation of the ultimate strength. In both cases (Lim and Nethercot
 82 2004, D'Antimo *et al.* 2017), there are still some differences between the improved FE curves and the
 83 experimental curves, as described later in this paper.

84 It is also noteworthy that in some laboratory tests where the bolt shank bearing on the connected plate
 85 did not have threads (Yang *et al.* 2015), the FE model responses were still found to be significantly
 86 stiffer than the experimental ones. In order to confirm whether the more flexible behaviour is due to
 87 the presence of threads in a bolted shear connection, this paper compares the laboratory test results of
 88 nineteen specimens that are either thread bolted or shank bolted against each other.

89 The present work also compares the laboratory test results against the predictions of Eurocode (ECS
 90 2010) and Rex and Sterling (2003). Ad hoc stiffness formulae will be proposed for shank and thread
 91 bolted connections.

92 The present work includes the development of FE models that closely replicate the experimental
 93 responses of shank and thread bolted connections. The developed FE models will be verified against
 94 the present and independent laboratory test results (Lim and Nethercot 2004, Yang *et al.* 2015,
 95 D'Antimo *et al.* 2017). The FE analysis results will be used to demonstrate the reason for the more
 96 flexible experimental responses. They will also be used to explain the “stiffening” behaviour of thread
 97 bolted connections as they approach their ultimate limit state.

It may be noted that Haidar *et al.* (2011), Hu *et al.* (2016) and Zhang *et al.* (2016) modelled the bolt threads explicitly in their FE analyses, but they only investigated bolted connections under tension and the interaction between the bolt and the nut. They were not concerned with bolted shear connections, which is the topic of this paper.

Fracture analysis is beyond the scope of this paper, which focuses on accurate simulation of the load-displacement response of a bolted shear connection up to the ultimate limit load. The post-ultimate load-displacement path is therefore not relevant to this paper.

Specimen configurations and test set-up

Two types of steel plates were used in the present experimental program, being 4.7 mm thick plate with a measured yield stress F_y of 470 MPa and a measured tensile strength F_u of 540 MPa, and 8 mm thick plate with a measured yield stress of 285 MPa and a measured tensile strength of 425 MPa. Threaded and shank bolts having nominal diameters of 20 mm and 30 mm were used. Most of the plates were 100 mm in width, with a few being 130 mm wide.

All specimens were single bolted double-shear connections where the bolt head and nut were finger tightened only, as shown in Figure 1. The inner plate was by far the critical component since each of the two outer plates was 9 mm thick with a measured yield stress of 585 MPa. The 20-mm bolts had 1 mm clearance, while the 30-mm bolts had 2 mm clearance.

It should be noted that, due to the thickness and yield stress of the two outer plates, the bolt hole deformation in each of them was negligible compared to that of the tested inner plate. Furthermore, previous testing had established that, for a single bolted connection failing in shear out, the stroke displacement of the Instron 8033 universal testing machine used was virtually due to the bolt hole deformation only once full contact was made between the bolt and the plates.

The plate thickness t , bolt hole diameter d_h , end distance e_1 , width w and bolt diameter d are provided in Table 1. The geometric variables of the present specimens are defined in Figure 2. An empty cell in the tables indicates that the value in the above cell applies.

The initials SP and ST in the specimen labels denote shank bolted and thread bolted specimens, respectively. The connections were designed such that the governing failure mode was shear-out. The specimens were loaded at a stroke rate of 2 mm per minute.

Laboratory test results and discussions

The shear-out capacities of the specimens in Table 1 were predicted using the equation proposed by Teh and Uz (2015)

$$P_p = 1.2 L_{av} t F_u \quad (1)$$

in which

$$L_{av} = e_1 - d_h / 4 \quad (2)$$

The ratios of the ultimate test load P_t to the prediction P_p obtained using Equation (1), called the professional factors, are provided in Table 1.

Figure 3 shows some of the tested specimens. As can be seen from Table 1, Specimens ST3 and ST4 had similar variables to SP3 and SP4 except for the bolt threads, respectively. Rugged damage to the threaded bolt holes is evident in the photographs. A subtle difference in the elongated shapes of the bolt holes can also be seen between the shank and the thread bolted specimens, in that the diameter at the elongated end of a threaded bolt hole is slightly smaller than the shank counterpart.

Figure 4 shows the load-displacement graphs of the shank bolted specimens, grouped according to their plate and bolt. The only variable in each group is the end distance e_1 , except that in Figure 4(c) the specimens had different plate widths as given in Table 1. It can be seen from the figure that the shear-out capacity increased with the end distance. However, there was virtually no difference in the initial stiffness between the specimens within each group. It therefore appears that the end distance e_1 does not have any significant effect on the initial stiffness of a shank bolted shear connection, at least within the range of practical bolted connections. A similar observation can be made for the thread bolted specimens, whose load-displacement graphs are shown in Figure 5 where the specimens are grouped according to their plate and bolt. It can also be observed from Figures 4(c) and 5(c) that the plate width, and hence the edge distance e_2 , does not have significant effects on the initial stiffness of the specimens tested in the present work.

Figure 6 shows the load-displacement graphs of threaded and shank bolted specimens that are comparable (or almost comparable) to each other in each group. The ultimate shear-out capacity of Specimen ST2 was 12% higher than that of Specimen SP1 even though the measured end distance e_1

of the thread bolted specimen was only 3% longer, as shown in Table 1. However, the initial stiffness of the thread bolted specimen was much lower than that of the shank bolted one. A similar observation regarding the difference in the initial stiffness can be made for the thicker specimens in Figures 6(b) through 6(d), although to a lesser extent.

Interestingly, the thread bolted specimens exhibited less softening behaviour as they approached their respective ultimate limit loads, compared to the shank bolted ones. This phenomenon is investigated through finite element analysis later in this paper.

Verification of existing equations for “elastic” stiffness

Following the recommendation of ASTM E2126-11 in Section 9.1.3 (ASTM 2018), the measured “elastic” stiffness S_t of a bolted shear connection is defined as:

$$S_t = \frac{P_{0.40}}{\Delta_{0.40}} \quad (3)$$

where $P_{0.40}$ is 40 percent of the ultimate test load P_t , and $\Delta_{0.4}$ is the measured displacement corresponding to $P_{0.40}$.

Formulae for estimating the elastic stiffness of a bolted shear connection are provided by Huth (1986) and Eurocode 3 (ECS 2010). The Eurocode formulation is the most recent and was specifically developed for structural steel connections, and is therefore compared against the present test results.

Eurocode 3

Table 6.11 of Eurocode 3 (ECS 2010) provides formulae for two components of a double-shear bolted connection. For a bolt in shear, the “elastic” stiffness S_{bs} is

$$S_{bs} = \frac{16 n_b d^2 F_{ub}}{d_{M16}} \quad (4)$$

where d_{M16} is the nominal diameter of an M16 bolt, n_b is the number of bolt rows in shear and F_{ub} is the tensile strength of the bolt material. The geometric variables are defined in Figure 7.

For a plate in bearing, the “elastic” stiffness S_{pj} is

$$S_{pj} = 24 n_b k_b k_t d F_u \quad (5)$$

in which

$$\begin{aligned} k_b &= \min(k_{b1}, k_{b2}) \\ k_{b1} &= \min(1.25, 0.25 e_1 / d + 0.5) \\ k_{b2} &= \min(1.25, 0.25 p / d + 0.375) \end{aligned} \quad (6)$$

$$k_t = \min(2.5, 1.5 t / d_{M16}) \quad (7)$$

where e_1 is the end distance of the downstream bolt, and p is the bolt pitch defined in Figure 7.

Eurocode (ECS 2010) considers the two components to act as springs in series. For a double-shear bolted connection, there are three springs acting in series: one for the bolt in shear (S_{bs}); one for the two outer plates in bearing (S_{po}) acting in parallel and another for the inner plate in bearing (S_{pi}). The equivalent spring stiffness $S_{e,eu}$ of the double-shear bolted connection is

$$S_{e,eu} = \frac{1}{\frac{1}{S_{bs}} + \frac{1}{2S_{po}} + \frac{1}{S_{pi}}} \quad (8)$$

Eurocode 3 (ECS 2010) does not distinguish between shank and thread bolted connections. However, the present laboratory test results plotted in Figure 6 show significant differences in the elastic stiffness between comparable shank and thread bolted connections. The ratios of the measured S_t to the estimated $S_{e,eu}$ are given in Table 1. For the shank bolted specimens, the mean ratio is 0.57 with a coefficient of variation equal to 0.199. The corresponding values for the thread bolted specimens are 0.42 and 0.119. It should be noted that the Eurocode provision may be based on a different definition of “elastic” stiffness from the one represented by Equation (3).

195 *Rex and Easterling (2003)*

196 Rex and Sterling (2003) proposed another set of formulations to predict the initial stiffness of a single
 197 bolted shear connection. They defined the initial stiffness as the stiffness corresponding to a
 198 deformation of 0.102 mm. They considered that the initial stiffness had three components, being the
 199 bearing, bending and shear stiffnesses of the plate only. The plate stiffnesses are determined using
 200 Equations (9) through (11).

201 Bearing stiffness (Rex and Sterling 2003):

$$202 \quad S_{br} = 120 \, t \left(\frac{d}{25.4} \right)^{0.8} F_y \quad (9)$$

203 where d is in mm. This equation is unit dependent.

204 Plate bending stiffness (Rex and Sterling 2003):

$$205 \quad S_b = 32 \, t \left(\frac{e_1}{d} - \frac{1}{2} \right)^3 E \quad (10)$$

206 in which E is the Young's modulus.

207 Plate shear stiffness (Rex and Sterling 2003):

$$208 \quad S_v = 6.67 \, t \left(\frac{e_1}{d} - \frac{1}{2} \right) G \quad (11)$$

209 in which G is the shear modulus of elasticity.

210 The resultant stiffness of the connection $S_{e, re}$ is determined using Equation (12)

$$211 \quad S_{e, re} = \frac{1}{\frac{1}{S_{br}} + \frac{1}{S_b} + \frac{1}{S_v}} \quad (12)$$

212 The ratios of the elastic stiffness S_t , measured according to ASTM E2126-11 (ASTM 2018), to the
 213 estimated $S_{e, re}$ are given in Table 1. For the shank bolted specimens, the mean ratio is 0.26 with a

214 coefficient of variation equal to 0.114. The corresponding values for the thread bolted specimens are
 215 0.18 and 0.047.

216 *Proposed formula*

217 It can be seen from Figures 4 and 5 that the end distance e_1 does not affect the elastic stiffness of the
 218 tested connections meaningfully. The authors have also observed that the connection displacements
 219 were almost entirely due to the bolt hole's deformations. On the other hand, Figure 6 shows that there
 220 are significant differences in the elastic stiffness between comparable shank and thread bolted
 221 connections.

222 Based on the definition of the elastic stiffness in Section 9.1.3 of ASTM E2126-11 (ASTM 2018)
 223 as represented by Equation (3), and the present laboratory test observations, ad hoc formulae are
 224 proposed for shank and thread bolted connections in Equations (13) and (14), respectively. It is
 225 logically expected that the stiffness varies linearly with the number of bolts n_b , the plate thickness t
 226 and the material tensile strength F_u . The relationship between the stiffness and the bolt diameter d has
 227 to be determined empirically, using the M20 bolt specimens as the reference. Likewise, the constants
 228 of 24 and 15 in Equations (13) and (14) have been determined empirically based on the test results
 229 plotted in Figures 4 and 5.

$$230 \quad S_{e,\text{shank}} = 24 n_b t \left(\frac{d}{d_{\text{M20}}} \right)^{0.3} F_u \quad (13)$$

$$231 \quad S_{e,\text{thread}} = 15 n_b t \left(\frac{d_{\text{min}}}{d_{\text{min,M20}}} \right)^{0.3} F_u \quad (14)$$

232 in which d_{min} is the minor diameter determined from

$$233 \quad d_{\text{min}} = d - 2t_d \quad (15)$$

234 The minor diameter d_{min} and the thread depth t_d are defined in Figure 8.

235 In the present work, the resultant stiffness of a double-shear bolted connection is computed from

$$236 \quad S_e = \frac{1}{\frac{1}{2S_{eo}} + \frac{1}{S_{ei}}} \quad (16)$$

237 where S_{eo} and S_{ei} are the stiffnesses of the outer and inner plates, respectively, determined using
 238 Equations (13) and/or (14) as appropriate.

239 Equation (16) does not include the bolt shear component found in Equation (8). The authors believe
 240 that the definition of the elastic stiffness represented by Equation (3) means that the bolt shear
 241 component is negligible compared to the bolt hole deformation.

242 The ratios of the measured stiffness S_t to the present estimated stiffness S_e are given in the last column
 243 of Table 1. For the shank bolted specimens, the mean ratio is 1.00 with a coefficient of variation equal
 244 to 0.080. The corresponding values for the thread bolted specimens are 1.00 and 0.088.

245 **Finite element simulation**

246 The present finite element (FE) model used the hexahedral eight-node reduced integration brick
 247 element C3D8R available in ABAQUS 6.14 Standard (2014) to model the plate and the shank bolt,
 248 and tetrahedral ten-node brick element (C3D10) for the threaded bolt. Displacement controlled quasi-
 249 static movement of the bolt was used to simulate loading of the inner plate by the bolt, which was set
 250 to be a rigid body in the Interaction module of the analysis software. The plasticity of the steel material
 251 was handled through the von Mises yield criterion and the Prandtl-Reuss flow rule with isotropic
 252 hardening. The elastic modulus was taken as 200 GPa, and the Poisson's ratio was 0.3.

253 The Ramberg-Osgood power model (Ramberg and Osgood 1943) was used to define the engineering
 254 stress-strain curve based on the elastic modulus, the yield stress, the tensile strength and the
 255 engineering strain at the ultimate stress as shown in Equations (17) through (19).

$$256 \quad \varepsilon = \frac{\sigma}{E} + 0.002 \left(\frac{\sigma}{F_y} \right)^n \quad (17)$$

257 where ε is engineering strain, σ represents engineering stress. The power term n is determined from

$$258 \quad n = \frac{\ln(\varepsilon_{us}/0.2)}{\ln(F_u/F_y)} \quad (18)$$

259 where ε_{us} is defined as

$$260 \quad \varepsilon_{us} = 100 \left[\varepsilon_u - (F_u/E) \right] \quad (19)$$

with the variable ε_u being the engineering strain at the ultimate stress.

Having defined the engineering stress-strain relationship as given by Equation (17), the true stress-strain curve is plotted using Equations (20) and (21).

$$\varepsilon_{true} = \ln[1 + \varepsilon] \quad (20)$$

$$\sigma_{true} = \sigma[1 + \varepsilon] \quad (21)$$

The present work took advantage of the symmetry of a double-shear connection, with only a quarter of the inner plate of a double-shear lap connection being explicitly modelled using appropriate boundary conditions in ABAQUS, as shown in Figure 9(a). The nodes on the in-plane symmetry plane were restrained from translating in the x -axis direction, while the nodes on the through thickness symmetry plane were restrained from translating in the y -direction. Rotational degrees of freedom are not relevant to the C3D8R element employed in the present work.

Around the bolt hole, 1 mm mesh was used based on the authors' sensitivity analyses. Contact was modelled in the manner described by Clements & Teh (2013). However, the present models included the bolt threads as described below.

ISO (1998) defines the basic profile and available thread sizes for a range of bolt diameters. There are typically two types of threads, coarse and fine threads with an intermediate thread size available for some bolts. The thread pitch t_p and the thread depth t_d are related to each other through the following equation

$$t_d = \frac{\sqrt{3}}{2} t_p \quad (22)$$

In the Part module of ABAQUS (2014), a threaded bolt was modelled using 3D deformable solid with revolution and pitch. In the Interaction module, node to surface discretization was used for surface to surface contact definition. The tangential behaviour was defined using penalty formulation, and friction coefficients of 0.3 and zero were assumed for a threaded bolt and a shank bolt, respectively.

Bolted shear connections through a square hollow section

D'Antimo *et al.* (2017) tested double-shear bolted connections of square hollow sections such as that illustrated in Figure 10 that is copied from their paper, and found that the responses obtained from their

tests were much more flexible than those predicted by their “ideal” finite element models. They attributed the more flexible experimental responses to geometrical imperfections related to the manufacturing process, and to the “net” diameter of the bolts. They improved the agreement in the initial stiffness between the experimental and the finite element results by using bolt models with artificially reduced diameters. However, on average the resulting ultimate limit loads were 13% lower than the ultimate tests loads.

The present study analysed Specimen HX-2-M-12 (Test 6) reported by D’Antimo *et al.* (2017) using two models, one incorporating the bolt threads and the other neglecting them. In the latter case, the major diameter was used. The specimen was a 2 mm thick square hollow section (SHS) having a 12 mm bolt passing through two sides with a clearance of 0.5 mm. The coarse thread pitch of a 12 mm bolt was 1.75 mm. The end distance was 40 mm. The present FE simulation used the measured material properties and dimensions provided by D’Antimo *et al.* (2017). Figure 11 shows the true stress-strain curve used in the simulation, generated using an engineering yield stress of 400 MPa, a tensile strength of 500 MPa, and a strain at the ultimate engineering stress of 0.4.

Figure 12 shows the deformed shapes of the threaded and shank bolted models at an applied load of 30 kN. At this point, the displacements of the threaded and the shank models were 1.3 mm and 0.4 mm, respectively. It is evident in Figure 12(a) that the bolt threads cut into the side wall of the SHS tube, reducing the initial stiffness of the connection.

Figure 13 compares the load-displacement graphs obtained from the laboratory test against those obtained from the two FE analyses with and without a threaded bolt model, respectively. The FE model incorporating bolt threads gave a much better agreement with the experimental response than the other model.

Interestingly, while up to a load of about 55 kN the model with bolt threads is more flexible than the one without, it is the opposite afterwards. This phenomenon is consistent with the present laboratory test results, plotted in Figure 6. Figure 14 compares the deformed shapes between the two FE models at a load of 65 kN. It can be seen that there is much less crimpling of the connected side wall in the thread bolted model as the threads penetrate into it.

The necessity of modelling the bolt threads explicitly is evident in Figure 15, which compares the load-displacement graphs obtained from the various FE models against the laboratory test result. The present model with bolt threads produced a better agreement with the experimental curve than the modified model of D’Antimo *et al.* (2017), where a reduced diameter of the bolt was used.

318 *Double-shear lap connections in cold-reduced steel sheets*

319 Lim & Nethercot (2004) tested double-shear lap connections each of which had a single bolt that was
 320 either threaded or not. Their P1 specimen (the inner plate) was 2.99 mm thick with a measured bolt
 321 hole diameter of 17.7 mm, connected with a shank bolt having a diameter of 15.6 mm. The threaded
 322 counterpart (Specimen T1) was 2.95 mm thick with a hole diameter of 17.8 mm, connected with a bolt
 323 having a major diameter of 15.8 mm and a nominal coarse thread pitch of 2 mm. The end distance of
 324 each specimen was 80 mm.

325 Figure 16 shows the true stress-strain curve used in the present simulation. The figure also shows the
 326 engineering yield stress, the tensile strength and the strain at the ultimate engineering stress.

327 Figures 17(a) and 17(b) compare the load-displacement graphs obtained from the laboratory tests
 328 against those obtained from the present FE analyses, for the shank bolted and thread bolted specimens,
 329 respectively. It can be seen that there are good agreements in both cases.

330 *Double-shear lap connections in stainless steel plates*

331 Yang *et al.* (2015) tested double-shear bolted connections where only the unthreaded shank portion of
 332 the bolts came into contact with the 6 mm thick austenitic stainless steel plates. However, despite the
 333 absence of thread effects, their FE load-displacement graphs are significantly stiffer than the
 334 experimental ones. This outcome indicates that there is another reason for the stiffer responses of their
 335 FE models.

336 The present work simulated Specimens S-2 and S-5 tested by Yang *et al.* (2015), which had a bolt
 337 diameter of 20 mm and 24 mm, respectively. The bolt hole clearance was 2 mm. The end distances of
 338 S-2 and S-5 were 40 mm and 60 mm, respectively.

339 Figure 18 shows the true stress-strain curve used for the present analysis as provided by Yang *et al.*
 340 (2015). Figures 19(a) and 19(b) compare the load-displacement graphs obtained from the laboratory
 341 tests against those obtained by the authors and Yang *et al.* (2015) for the shank bolted S-2 and S-5
 342 specimens, respectively. It can be seen that the present models were able to match the experimental
 343 responses closely.

344 One likely reason for the significantly stiffer behaviour of the FE model by Yang *et al.* (2015) is the
 345 much coarser mesh used in their analyses as evident from a figure given in their paper. The present
 346 mesh is shown in Figure 20. Another possible reason could be the use of a high friction coefficient in

the contact property definition. The present study used zero friction coefficient in modelling Specimens S-2 and S-5, each of which was connected with the unthreaded shank portion of the bolt.

Conclusions

The paper has presented laboratory test and finite element analysis results of threaded and shank bolted shear connections. The threaded specimens have been found to possess significantly lower initial stiffnesses than those of the comparable shank specimens due to the threads cutting into the plates. However, the same factor can reduce the crimping of the plate material downstream of the bolt in the case of a bolted hollow section, increasing the final stiffnesses of the thread bolted connections as they approached their respective ultimate loads.

The end and edge distances did not have significant effects on the elastic stiffness of the bolted connections tested in the present work, as the connection displacements were almost entirely due to the bolt hole deformation. For the same reason, each connection's stiffness was largely independent of the bolt deformation. Ad hoc stiffness formulae have been proposed separately in this paper for thread and shank bolted shear connections, based solely on the bolt hole deformation.

The present finite element model, which incorporates the bolt threads explicitly, mimicked the load-displacement behaviour up to the ultimate test load of an independent specimen better than a published model employing an artificially smaller bolt, which resulted in a significant underestimation of the ultimate test load. The present approach of modelling the threads explicitly is also better than shifting the curve obtained using a model ignoring the threads, which cannot provide the initial stiffness.

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411 Table 1: Specimen dimensions, laboratory test results and comparison against predictions

Specimen	F_y (MPa)	F_u (MPa)	d (mm)	d_h (mm)	e_1 (mm)	t (mm)	w (mm)	P_t/P_p	$S_t/S_{e,eu}$	$S_t/S_{e,re}$	S_t/S_e
SP1	470	540	20	20.8	49.1	4.7	100	0.95	0.69	0.27	1.10
SP2				20.9	53.9			0.95	0.71	0.28	1.16
SP6				20.9	59.7			0.94	0.60	0.25	1.03
SP3	285	425		20.9	40.4	8.0		1.05	0.69	0.29	0.98
SP4				20.8	49.6			1.01	0.69	0.30	1.04
SP5				21.0	59.2			0.92	0.61	0.28	0.97
SP7			30	31.7	50.2			1.05	0.48	0.23	0.95
SP8				31.4	61.1			1.05	0.50	0.25	1.04
SP9				31.6	76.8			0.85	0.42	0.23	0.95
SP10				31.7	50.1		130	1.09	0.46	0.22	0.90
SP11				31.7	61.5			1.04	0.43	0.22	0.91
Shank bolted							Mean	0.99	0.57	0.26	1.00
							COV	0.075	0.200	0.114	0.080
ST1	470	540	20	20.8	41.8	4.7	100	1.14	0.45	0.17	1.08
ST2				21.0	50.6			1.03	0.33	0.13	0.85
ST5	285	425		20.9	32.4	8.0		1.06	0.45	0.18	0.96
ST3				20.9	41.8			1.03	0.42	0.18	0.97
ST4				21.0	52.6			0.94	0.45	0.20	1.09
ST6			30	31.8	45.9			1.10	0.31	0.15	0.95
ST7				31.8	60.5			1.02	0.31	0.15	1.01
ST8				31.5	69.6		130	0.91	0.32	0.17	1.11
Thread bolted							Mean	1.03	0.38	0.16	1.00
							COV	0.069	0.178	0.130	0.088

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Figure 1. Test set-up

Figure 2. Geometric variables of a single bolted connection

Figure 3. Shear-out failure mode: (a) SP3; (b) SP4; (c) ST3; (d) ST4

(a)

(b)

(c)

Figure 4. Experimental load-displacement graphs: (a) SP1, SP2 & SP6; (b) SP3, SP4 & ST5; (c) SP7, SP8, ST9, SP10 & ST11

Figure 5. Experimental load-displacement graphs: (a) ST1 & ST2; (b) ST3, ST4 & ST5; (c) ST6, ST7 & ST8

Figure 6. Comparisons between shank and thread bolted specimens: (a) SP2 & ST1; (b) SP3 & ST3; (c) SP4 & ST4; (d) SP8 & ST7

Figure 7. Geometric variables of a double-row bolted connection

Figure 8. Dimensions of shank and threaded bolts

Figure 9. Boundary conditions of quarter models in ABAQUS: (a) inner plate of a double-shear lap connection; (b) bolted shear connections through a square hollow section

Figure 10. Schematic diagram of a bolted shear connection through a square hollow section (from D'Antimo *et al.* 2017)

Figure 11. True stress-strain curve of 2 mm thick HX420LAD steel tested by D'Antimo *et al.* (2017)

(a)

(b)

Figure 12. Deformed FE models of Specimen HX-2-M12 at an applied load of 30 kN: (a) with threads; (b) without threads

Figure 13. Comparison of FE models with and without bolt threads

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(a)

(b)

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Figure 14. Deformed shape of HX-2-M12 at an applied load of 65 kN: (a) with threads; (b) without threads

Figure 15. Comparison of FE load-displacement graphs for specimens tested by D'Antimo *et al.* (2017)

Figure 16. True stress-strain curve of 3 mm thick cold-formed steel tested by Lim and Nethercot (2004)

(a)

(b)

Figure 17. Comparisons between present FE and experimental results of Lim and Nethercot (2004):
 (a) shank bolted; (b) thread bolted

Figure 18. True stress-strain curves of 6 mm thick austenitic stainless steel tested by Yang *et al.* (2015)

(a)

(b)

Figure 19 Comparison of FE load-displacement graphs for specimens tested by Yang *et al.* (2015):
 (a) S-2; (b) S-5

Figure 20. Present FE mesh for Specimen S-5 tested by Yang *et al.* (2015)