EFFECT OF HOLE CLEARANCE ON BOLT LOADS IN PULTRUDED GRP TENSION JOINTS

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Abstract

A two-dimensional finite element (FE) model of a two-row single-column bolted tension joint in pultruded glass reinforced plastic (GRP) material is described. The bolt and hole diameters are nominally 10mm, i.e. there is zero clearance. In practice, however, the diameter of the bolt shank is 0.2mm smaller than that of the hole. Hence, one bolt may be out-of-contact with its hole edge when the joint starts to carry load. The FE model is used to analyse three initial bolt/hole contact states: Case 1 - both bolts initially in-contact, Case 2 - second bolt initially out-of-contact and Case 3 - first bolt initially out-of-contact. For Cases 2 and 3 the bolt load distributions are determined for various initial out-of-contact gaps and the tension loads at which the initially out-of-contact bolts start to carry load are evaluated. The implications of these results for joint design are also highlighted.

1 Introduction

Pultruded GRP structural grade profiles are being used with increasing frequency in infrastructure applications such as walkways, raised platforms, trusses and footbridges. In parallel with their increasing use, knowledge of their structural performance has also been increasing, principally through the efforts of researchers in the US and Europe.

One of the major barriers to the development and use of pultruded GRP structural grade profiles is the absence of design codes that are recognized by the authorities charged with regulating construction. Despite this, a number of code-like documents have been published which serve to guide structural engineers engaged in the design of pultruded and other composite structures. One of the most comprehensive and useful of these is the EUROCOMP design code [1] which was first published in 1996. Possibly the most useful sections of this code and its background document are those relating to the design of joints; not least because joints are generally the weakest parts of structures and often the most difficult to design.

In the EUROCOMP design code two methods – designated *simplified* and *advanced* – are presented for the design of concentrically and eccentrically loaded bolted joints. The simplified design method has been examined in detail by the authors [2] and several of its shortcomings have been highlighted. One of the principal shortcomings was shown to be the neglection of friction at the bolt-hole interface. Furthermore, it was shown that even a very small (nominally zero) hole clearance could have a very significant effect on the critical stress distributions around holes in single and multi-bolt tension joints. These shortcomings cast doubt on the validity and utility of the simplified method for bolted joint design in composites.

The present paper constitutes an extension of the earlier work by considering further the effect of the initial out-of-contact gap between the bolt shank and the hole edge on the behaviour of bolted joints with very small (nominally zero) hole clearances. The primary aim of the study is to explore how gap size affects the distribution of load between bolts in a pultruded GRP joint subjected to tensile loading. In order to reduce the size of the investigation to manageable proportions the simplest joint configuration was selected for analysis, namely a two-row single-column bolted tension joint.

Details of the elastic properties of the pultruded GRP material are presented first. This is followed by descriptions of the joint layout, range of out-of-contact gaps, load configuration etc. Details of a two-dimensional FE model of the two-row single-column bolted joint are then explained. Thereafter, FE analysis results are presented and discussed for the case of both bolts in-contact with the hole edge at the onset of loading – the zero gap situation commonly assumed for joint design - and for two extreme initial out-of-contact gap (hole clearance) cases. The paper is concluded by highlighting the principal results of the FE parameter study and their implications for the design of bolted joints in pultruded GRP materials.

2 Mechanical Properties of Pultruded GRP Plate

The authors have undertaken extensive experimental investigations of single and multi-bolt tension joints in pultruded GRP plate material. Several of these investigations have been reported over the past few years (see [3] – [5]). The pultruded GRP material used in the investigations was a composite formed from E-glass rovings and continuous filament mat (CFM) bound together by a matrix of polyester resin and a chalk or kaolin filler. The fibre volume percentage of the GRP plate material was about 30%.

Strain gauge measurements recorded on pin loaded joints during one of these investigations were compared with strains predicted by FE analysis in which the GRP plate was modeled as a homogeneous orthotropic material. The measured and predicted strains were in sufficiently good agreement for it to be concluded that, for stiffness analyses at least, the GRP plate behaves as a homogeneous orthotropic material. In that investigation, the elastic constants of the GRP were derived from tests, conducted at ambient temperature, on coupons cut out of 6.4mm thick plate parallel and transverse to the roving direction. It was decided to use these elastic constants in the present FE analyses. Their particular values are given in Table 1.

Table 1. Elastic constants of pultruded GRP plate

Elastic Constants	Average Values
Longitudinal Modulus (E_L)	15.23 GPa
Transverse Modulus (E_T)	11.12 GPa
Major Poisson's Ratio (ν_{LT})	0.30
Minor Poisson's Ratio (ν_{TL})	0.22
Shear Modulus (G_{LT})	2.93 GPa

3 Tension Joint Geometry

As mentioned in the Introduction, only the simplest form of multi-bolt tension joint was considered. The overall joint geometry was defined in terms of the following three parameters: the bolt end distance (*E*), the bolt pitch distance (*P*) and the bolt side distance (*S*). Joint geometries are frequently defined in dimensionless terms by expressing the aforementioned quantities as ratios of the bolt diameter (*D*). For the simple two-row single-column tension joint, these geometric parameters are illustrated in Figure 1.

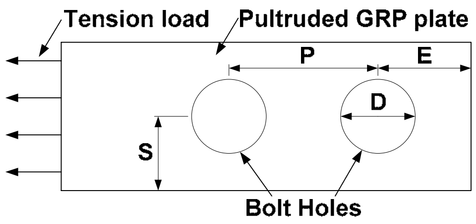

Fig. 1. Two-row single-column bolted tension joint showing geometric parameters

4 Finite Element Model of a Two-Row Single-Column Bolted Tension Joint

Because the GRP plate material could be considered as homogeneous and orthotropic, a two-dimensional FE model was adopted. The longitudinal centre-line of the joint was coincident with the geometric axis of symmetry and the major axis of orthotropy. Hence, symmetry was exploited and only one half of the joint was modeled.

The ANSYS software [6] was used to create the FE model of the two-row single-column bolted tension joint. An overall view of the FE mesh, which comprised of approximately five thousand elements, is shown in Figure 2.

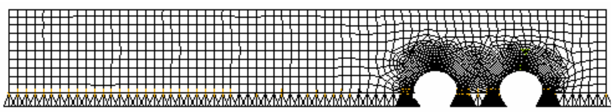

Fig. 2. FE mesh used to analyse a two-row single-column tension joint

Two types of plane quadrilateral element were used in the FE model. Around the bolt holes eight node elements with two translational degrees of freedom per node were used in a regular polar mesh, as shown in Figure 3. Remote from the holes four node elements with two degrees of freedom per node were used in order to reduce the overall size of the FE model to about fourteen thousand degrees of freedom.

In the tension tests on single and multi-bolt joints carried out by the authors, mild steel bolts were used with the smooth parts of their shanks in contact with the GRP plate material. Because mild steel is considerably stiffer than GRP, the bolts in the FE model of the joint were assumed to be rigid and fixed in position. Special contact pairs of elements were used to simulate surface to surface contact between the bolt shank and the edge of the hole with the shank identified as the target surface and the edge of the hole as the contact surface. Friction and sliding between these surfaces was also taken into account using a Coulomb friction model in which the friction coefficient was assumed equal to 0.2. Figure 3 shows an enlarged view of the regular polar FE mesh around the bolt holes (with each element subtending 3^o of arc at the centre of the hole).

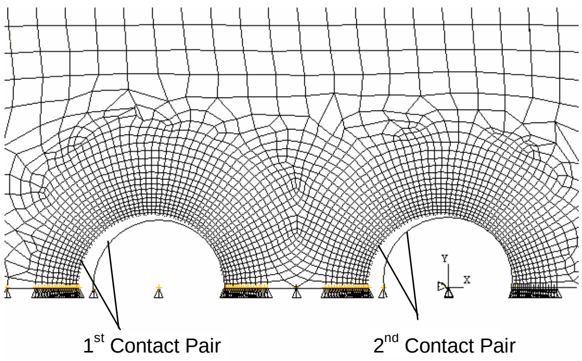

Fig. 3. Enlarged view of FE mesh around the bolt holes of a two-row single-column bolted tension joint

The pairs of contact surfaces are identified in Figure 3 which also shows the rigid bolts in clearance holes making simultaneous contact with the GRP at the hole edge.

The two-row single column joint was loaded by applying a uniform longitudinal tensile stress to each of the GRP elements at the left hand end of the joint (see Figures 1 and 2).

5 Effect of Initial Out-of-Contact Gap (Hole Clearance) on Load Distribution Between Bolts – Parametric Results

In order to limit the extent of the FE calculations, the scope of the study was restricted in a number of ways. The bolt diameter *D* was fixed at 10mm and only one joint geometry, corresponding to *E/D = 2*, *P/D = 2* and *S/D = 2* was considered. Furthermore, the maximum value of the tensile load applied to the joint was restricted to 10kN. This value was chosen because it represented about 40% of the failure load observed in many of the authors' single-bolt tension joint tests and, therefore, it could reasonably be assumed that the GRP plate material was behaving as an elastic material.

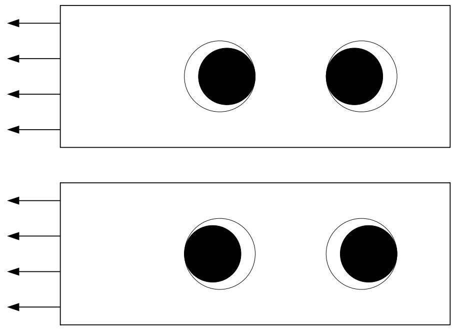

Fig. 4. Two-row single-column bolted tension joints: Case 2 (top sketch) - first bolt in-contact, second out-of-contact initially and Case 3 (bottom sketch) - first bolt out-of-contact, second in-contact initially. [Note: Hole clearances are drawn to an exaggerated scale.].

In the authors' single and multi-bolt joint tests the holes were 10mm in diameter and the smooth parts of the shanks of the mild steel bolts were 9.8mm in diameter. Thus, these nominally *snug* fitting bolts could, in fact, have initial out-of-contact gaps (hole clearances) varying from 0mm to a maximum of 0.2mm. Therefore, as the focus of the paper is on how the initial gap affects the load distribution between the two bolts in the tension joint, a range of gaps was considered for each bolt between these upper and lower limits. For this very simple joint configuration three limiting cases were considered: Case 1 - both bolts had 0mm gaps, i.e. both bolts were initially in-contact with the GRP at the hole edge, as shown in Figure 3 (Note: In Figure 3 the hole clearance is drawn to an exaggerated scale.), Case 2 - the first bolt had 0mm gap and the second bolt had an initial gap ranging from 0mm to 0.2mm, i.e. initially the first bolt was in-contact and the second was out-of-contact with the GRP at the hole edge and Case 3 - the first bolt had an initial gap ranging from 0mm to 0.2mm and the second bolt had a 0mm gap, i.e. initially the first bolt was out-of-contact and the second bolt was in-contact with the GRP at the hole edge. The latter two situations are depicted in Figure 4.

It is convenient to present the FE analysis results, obtained for the three limiting hole clearance cases, i.e. Cases 1 – 3 of the two-row single-column bolted tension joints, separately.

5.1 Case 1 – Both Bolts Initially In-Contact

For this case, even though the diameters of the bolt holes were 0.2mm larger than the diameters of the bolt shanks, the initial out-of-contact gap for both bolts was 0mm because their shanks were always in-contact with GRP material at the edge of the hole as the tension load was increased from 0kN to 10kN.

The bypass load is carried by the second bolt, i.e. the bolt which is nearer the unloaded end of the GRP plate (see Figure 2). This load was determined by integrating the longitudinal stresses over the width of a transverse cross-section of the GRP plate between the two bolts. Once the bypass load was determined, the load on the first bolt was calculated by subtracting the bypass load from the applied tension.

The load distribution for the case of both bolts initially in-contact, i.e. 0mm gap, is shown in Figure 5 for loads between 0.1kN and 10kN.

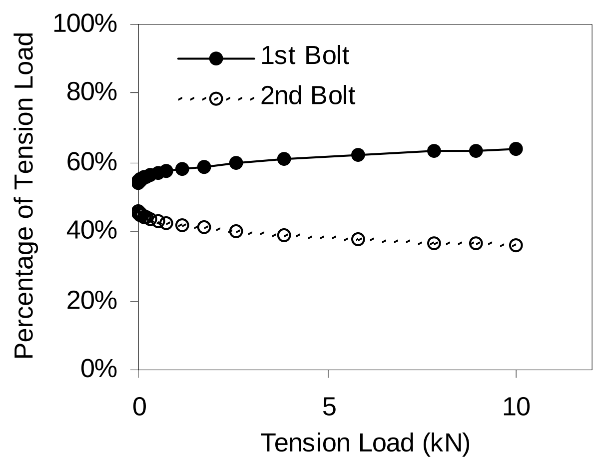

Fig. 5. Load distribution between bolts when both bolts are initially in-contact (0mm gap)

Figure 5 shows that the load on the first bolt increases as the tension load on the joint increases and, at the same time, the load on the second bolt decreases. At a tension load of 0.1kN 55.2% of the load is taken by the first bolt and 44.8% by the second bolt, whereas at a load of 10kN these percentages change to 63.8% and 33.2% respectively. The load share results depicted in Figure 5 indicate that the common assumption (also advocated in [1]) that the load is distributed equally between both bolts is incorrect.

5.2 Case 2 – First Bolt Initially In-Contact and Second Bolt Out-of-Contact

This situation is depicted in the top sketch of Figure 4, i.e. the shank of the first bolt is initially in-contact with its hole edge and starts to carry load as soon as the tension is applied; the second bolt, being initially out-of-contact with its hole edge does not carry load immediately. The load at which the latter bolt starts to carry load depends on the magnitude the initial out-of-contact gap. The effect of the second bolt’s initial out-of-contact gap on the load distribution between the two bolts is shown in Figure 6.

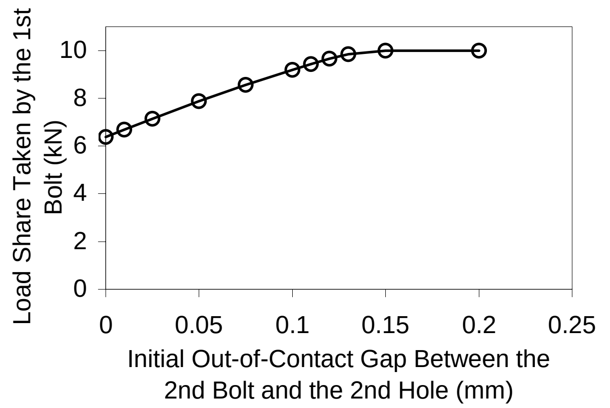

Fig. 6. Effect of second bolt’s initial out-of-contact gap on the load carried by the first bolt (tension load = 10kN)

Examination of Figure 6 shows that provided the initial out-of-contact gap between the second bolt and the hole edge is less than 0.15mm the second bolt will make contact with the hole edge and share some of the applied tension before it reaches its maximum value of 10kN. Moreover, the load carried by the first bolt appears to increase linearly with the second bolt’s out-of-contact gap up to a gap size of 0.13mm. For larger gaps, the second bolt does not contact its hole edge and the first bolt carries the whole of the applied tension. Thus, the two-row single-column bolted joint behaves as a single bolt tension joint.

The absolute maximum radial and tangential stresses at the edge of the first bolt hole and the absolute maximum shear stress within the joint are presented in Figure 7 as a function of the initial out-of-contact gap at the second bolt for the maximum tensile load of 10kN. It is evident that all three stress components increase gradually as the initial out-of-contact gap at the second bolt increases up to a value of 0.13mm. For larger gaps these stresses remain constant because the second bolt does not carry any of the 10kN tensile load.

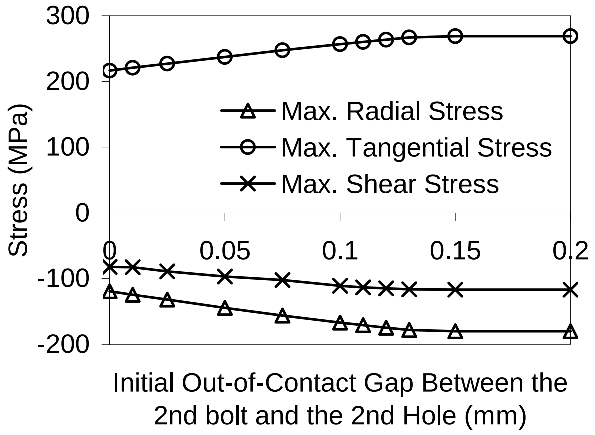

Fig. 7. Maximum radial and tensile stresses at the edge of the first bolt hole and the maximum shear stress within the joint versus the initial out-of-contact gap at the second bolt

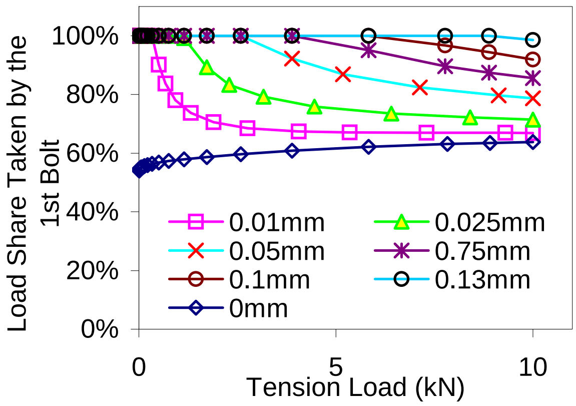

Fig. 8. Percentage of load carried by the first bolt versus applied tension for a range of initial out-of-contact gaps at the second bolt

It is of interest to determine the tension load at which the second bolt makes contact with the hole edge and how the load is re-distributed between the two bolts for a range of initial out-of-contact gaps at the second bolt. This information is presented in Figure 8.

Figure 8 indicates that when the initial out-of-contact gap at the second bolt is 0mm, i.e. both bolts are initially in-contact with their respective hole edges, the load carried by the first bolt increases with increasing tension, as previously shown in Figure 5. However, when the initial out-of-contact gap at the second bolt is 0.05mm, i.e. 0.5% of the hole diameter, the second bolt only starts to carry load when the tension reaches 2.58kN. As the tension is gradually increased to 10kN the load taken by the first bolt reduces to 7.9kN and the load in the second bolt increases to 3.1kN. Likewise, when the initial out-of-contact at the second bolt is 0.13mm or 1.3% of the hole diameter, the second bolt does not begin to carry any load until the tension reaches 9.54kN. At the maximum tension of 10kN the second bolt only carries 0.1kN. The values of the tension at which the second bolt begins to carry load for seven initial out-of-contact gap sizes are listed in Table 2.

Table 2. Load at which second bolt starts to carry load and load share percentage for first bolt for different values of the second bolt's out-of-contact gap

Second Bolt's Initial Out-Of-Contact Gap (mm)	Tension At Which Second Bolt Starts To Carry Load (kN)	First Bolt's Load Share at 10kN Tension (%)
0.000	0.00	63.7
0.010	0.33	66.8
0.025	1.14	71.4
0.050	2.58	78.7
0.075	3.88	85.5
0.100	5.83	92.0
0.130	9.54	98.5
0.150	------	100.0
0.200	------	100.0

5.3 First Bolt Initially Out-Of-Contact and Second Bolt In-Contact

For this case, the second bolt of the joint makes contact with its hole edge as soon as the tension load is applied. The out-of-contact gap at the first bolt is varied between 0mm and 0.2mm. The load carried by the first is presented as a function of its out-of-contact gap in Figure 9 for the case that the tensile load equals 10kN. As expected when the gap is 0mm, i.e. the first bolt is in-contact, the load carried by the first bolt equals about 6.4kN. However, as the out-of-contact gap increases the load carried by the first bolt reduces linearly with gap size until the gap reaches 0.2mm when the second bolt carries all of the 10kN applied tension.

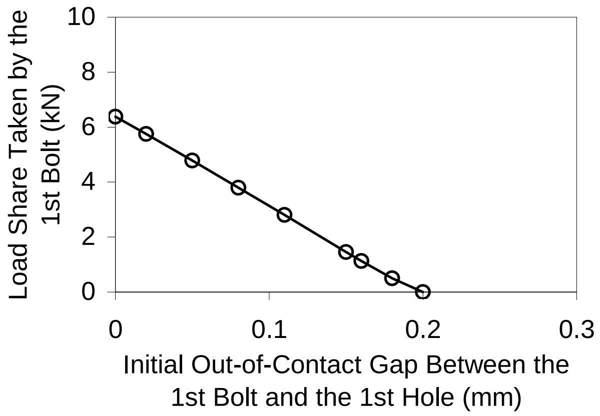

Fig. 9. Load carried by the first bolt versus initial out-of-contact gaps at the first bolt for a tensile load of 10kN

The FE results show that the size of the out-of-contact gap at the first bolt greatly influences whether the first or the second bolt carries the greater portion of the tensile load applied to the joint. Consequently, the maximum radial and tensile stresses do not necessarily arise at the edge of the first bolt hole. Hence, the maximum stresses around the edges of both bolt holes have been determined in order to quantify the situation. These stresses are plotted as a function of the initial out-of-contact gap at the first bolt hole, as shown in Figure 10.

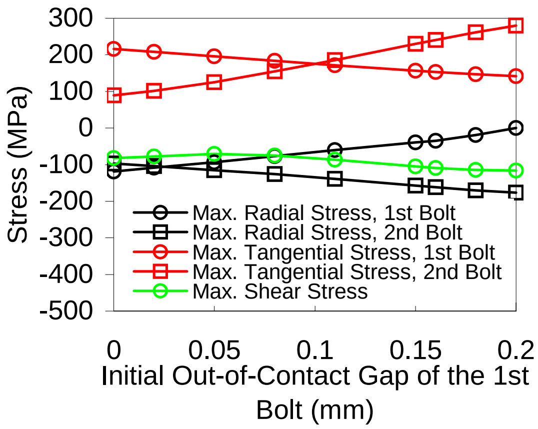

Fig. 10. Maximum stresses around bolt holes versus the first bolt's initial out-of-contact gap when the tensile load equals 10kN

It is evident from Figure 10 that when the initial out-of-contact gap is 0.02mm and the first bolt carries 57% of the tensile load the maximum radial compressive (negative) stresses around both hole edges are almost equal. As the out-of-contact gap at the first bolt increases above 0.02mm, so the maximum radial compressive stress occurs at the edge of the second bolt's hole. Likewise, for the tangential stresses at the hole edges, the maximum value occurs at the edge of the second hole when the out-of-contact gap of the first bolt exceeds about 0.11mm. Also, from Figure 10 it is clear that the maximum shear stress in the joint is not very sensitive the size of the first bolt's out-of-contact gap.

The load carried by the first bolt, expressed as a percentage of the tensile load applied to the joint, is shown in Figure 11 for a range of initial out-of-contact gaps at the first bolt.

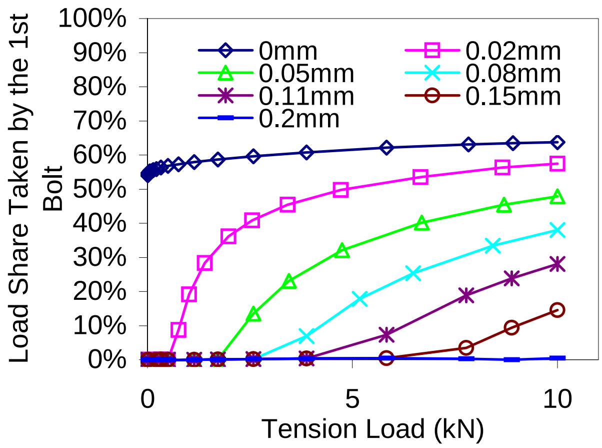

Fig. 11. Percentage of the tensile load carried by the first bolt versus tensile load for a range of initial out-of-contact gaps at the first bolt

It is immediately obvious that when the initial out-of-contact gap at the first bolt is 0mm, i.e. the bolt is initially in-contact, the percentage of the applied tension carried by the first bolt increases from about 55% to 64%. This is in agreement with the corresponding curves in Figures 5 and 8. However, when the initial out-of-contact gap at the first bolt is 0.05mm, i.e. 0.5% of the hole diameter, the first bolt comes into contact with its hole edge at a load of 1.72kN and when the tensile load reaches 10kN the loads carried by the first and second bolts are 4.8kN and 5.2kN respectively. Likewise, when the initial out-of-contact gap is much larger, say 0.2mm, the load carried by the first bolt is very small – only 0.4KN – when the tensile load reaches its maximum value of 10kN. Finally the loads at which the first bolt begins to carry load and the loads carried by the same bolt when the applied tension reaches 10kN are given in Table 3 for seven values of the initial out-of-contact gap at the first bolt.

Table 3. Load at which first bolt starts to carry load and load share percentage for first bolt for different values of the first bolt's out-of-contact gap

First Bolt's Initial Out-of-Contact Gap(mm)	Tension At Which First Bolt Starts To Carry Load (kN)	First Bolt's Load Share at 10kN Tension (%)
0.000	0.00	63.7
0.020	0.50	57.5
0.050	1.72	47.9
0.080	2.58	38.0
0.110	3.88	28.0
0.150	5.83	14.6
0.200	10.00	0.4

6 Concluding Remarks

An FE parameter study of a simple two-row single-column bolted joint in pultruded GRP plate has been undertaken. The joint was loaded in tension with the tension and pultrusion axes coincident. The diameters of the smooth shanks of the bolts were 0.2mm smaller than the 10mm diameter bolt holes. The difference between the shank and hole diameters implied that for each bolt the initial out-of-contact gap could vary between 0mm and 0.2mm. Three extreme cases of initial out-of-contact gap were investigated to quantify how the load was distributed between the bolts as the tensile load was increased to its maximum value of 10kN. It was shown that when both bolts were in-contact with the hole edge at the onset of loading, the load in the first bolt gradually increased and the load in the second bolt gradually decreased until, at the maximum tension of 10kN, the load share was 63.8% and 44.2% respectively. In the other two cases investigated, i.e. when either the first or the second bolt was initially out-of-contact at the onset of loading, the load distribution was much more complex. Indeed, when the initial out-of-contact gap was relatively large (~0.15mm) then just one of the bolts carried the entire load, so that the two-row single-column joint behaved essentially as a single-bolt tension joint. This has implications for design, because designers often assume that when hole clearances are nominally zero bolts share the applied load equally. The results of the present parameter study show that this is clearly not so and, moreover, they quantify the loads at which the initially out-of-contact bolt starts to carry load as a function of the initial gap size.

7 Acknowledgements

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