PIN-BEARING BEHAVIOR OF NOTCHED PULTRUDED PLATE

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ABSTRACT

Presented are the results of physical tests and a finite element analysis on the pin-bearing behavior of notched pultruded plate. In testing a steel bolt of diameter 9.8 mm and notch clearances of 0.2 and 1.2 mm were chosen. Test specimens were cut from a 6.35 mm (1/4 inch) EXTREN 625 flat sheet with material orientations of 0^o, 45^o and 90^o. Using a purpose-built test rig a pin-bearing load was applied until ultimate failure occurred. ABAQUS© finite element software was used to model the contact/friction problem with a 10 mm pin and two notch clearances of 0 and 1 mm. It was found that the presence of notch clearance and the friction/contact phenomenon was successfully simulated. The magnitude of the maximum minimum principal strain was found to increase with notch clearance. There was a reasonable comparison between simulation and experimental strains, especially when the notch clearance was present. The ABAQUS© results showed that the maximum compressive stress may not be located on the assumed bearing failure plane thereby bringing doubt on the appropriateness of existing bolted joint design procedures.

INTRODUCTION

Pultruded profiles are increasingly used in load-bearing structures for many reasons (Mottram and Turvey 1998). The pultrusion industry (Anon 1989, Anon 1995, Anon 1999) provides guidance for the design of simple braced frames that correspond to what is seen with conventional steelwork. This naturally leads to the joints between beam and column members having web cleats (Anon 1989 and 1995, Clarke 1996), and bolting as the main connection method. The bolts are of steel, often stainless, with no thread along their bearing length. Bolting has the principal advantage that appropriate joint dimensions lead to the strength (Mottram and Turvey 1998) being governed by a potentially benign mode of failure, known as bearing. Bearing failure is desirable since the other characteristic connection failure modes (Clarke 1996) are more brittle, and are therefore less acceptable.

One major disadvantage of bolting is that it is difficult to have a connection strength that is 50% of the material strength of the plates being joined (Mottram and Turvey 1998). When combined with other engineering uncertainties, the current factors of safety (Anon 1995, Anon 1999) lead to maximum working loads in bolted lap-joint connections which are < 15% of the material strength available.

Extensive research in the aircraft industry has shown that well-designed bolted connections for carbon fiber reinforced laminated plates possess damage tolerance. By harnessing such damage progression in strength predictions Camanho (1999) showed that the safe working load could be increased. In the aerospace industry a very small bolt clearance is often required (Camanho 1999). Since this is not practical in construction, research is required to determine how joint strength changes when the clearance is, say 10% of the hole diameter. In practice hole clearance for bolted joints with pultruded members can be 1 (Anon 1995) or 1.6 mm (Anon 1989 and Anon 1999) in size. Vangrimde (2000), who studied non-pultruded glass fiber laminated joints (for construction), recommended that future research priorities should include the determination of the laminate parameters which govern initial damage stress, and the need to understand the mechanisms of bearing failure.

With Lancaster University (see Turvey and Wang 2001) the authors are jointly working on a project for the structural integrity of bolted joints for pultruded profiles. Its objectives are:

- To test virgin/degraded bolted joints with practical details. Loading is concentric and eccentric and the main forms of degradation will be hot/wet conditioning.
- To understand the physical response and damage mechanisms in joints under normal/adverse conditions.
- To relate measured strengths and damage progression to predictions using advanced FEA (Finite Element Analysis) and simple lumped parameter (component method) techniques.
- To transform structural integrity methods, used with composite materials in the aerospace sector, into joint design guidance for use in construction, offshore, marine and transportation engineering.

EXTREN flat sheet of nominal thickness 6.35 mm (1/4 inch) is the single material used in this project (see Turvey and Wang 2001). This limitation in its scope was necessary to ensure that sufficient joint test data would be generated to meet the objectives listed above.

One important aspect of the research is to find out if FEA can be used to predict strains (and stresses) associated with the initiation, and growth, of progressive damage at the bolt/hole interface. Previously, Mottram and Padilla-Contreras (2001) completed a similar preliminary investigation to the one reported in this paper. Numerical analysis was by the SDRC I-DEAS simulation software. Their study used 9.35 mm thick web material (from a 203×203×9.53 mm wide flange profile) and notch clearances of 0, 1 and 2 mm for a 16 mm diameter pin. At a distance of 2.5 mm from the notch perimeter measurements of the radial and tangential strains were compared with strains obtained by FEA. The outcome of the comparison was not good. The FEA output was believed to be adversely affected by the performance of the I-DEAS contact algorithm. Strains were from single or cross-ply gauges and this made it difficult to establish, with accuracy, the specific strains used in the comparison. Mottram and Padilla-Contreras (2001) concluded that additional FE modeling (with other packages) and physical testing were required.

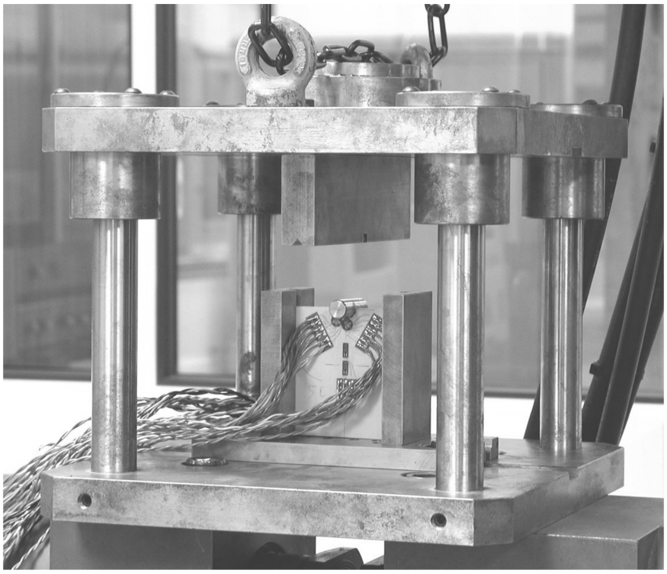
The work presented in this paper simulated a typical plate-to-plate bolted connection when there is no tightening torque (worse scenario). Both experimental and numerical results will be presented and general observations given in what follows.

PHYSICAL TEST PROGRAM

A series of short-term physical tests were conducted on 70×70 mm specimens cut from Strongwell's EXTREN Series 625 flat sheet of nominal thickness 6.35 mm (Anon 1989). Figures 1(a) and 1(b) show the experimental set-up. The plate specimen was supported in a holder so that buckling could not occur and load was imposed via a steel test rig that had a stiff top plate which moved freely on four pillars. The pillars provided the necessary horizontal stiffness.

Experimental problems identified by Mottram and Padilla-Contreras (2001) were lack of precise centering of the specimen and the non-cylindrical surface to their 16 mm single-piece indenter. These two factors meant the experiment's boundary conditions were physically different to those chosen in the I-DEAS FE modeling. To minimize these problems the indenter was now a 9.8 mm diameter steel bar of the same material and diameter as a standard grade 8.8 M10 bolt. This new indenter was restrained by a V-notch fixture, which had a central gap, equal to the thickness of the flat sheet material. The test rig was also modified such that the specimen holder allowed more accurate positioning for centering. These features can be seen in Figures 1(a) and 1(b).

Groups of two specimens had a semi-circular notch of 10 or 11 mm diameter at the top. The orientation of the undirectional roving reinforcement was either 0^o, 45^o or 90^o, with respect to the pultrusion direction being 0°. Label 1-10-00 is for specimen No. 1 with 10 mm notch and 0° material orientation, and label 2-11-90 is for specimen No. 2 with 11 mm notch and 90° material orientation. Strain rosettes of 2 mm length (type FRA-2-11) were located at 10° intervals from 0° to 60°, with their center 2.5 mm from the perimeter of the notch (Figure 1(b)). The distance of 2.5 mm was the minimum which a rosette could be located from the notch's perimeter.



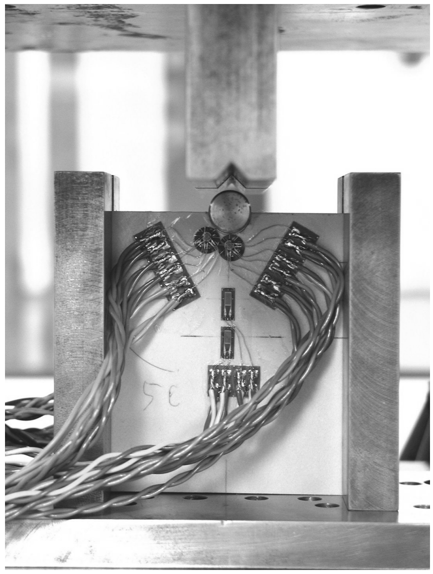


Figure 1. (a) Pin-bearing test rig with an unloaded specimen, (b) close-up of indenter, strain rosettes and anti-buckling support with a 0.2 mm clearance specimen.

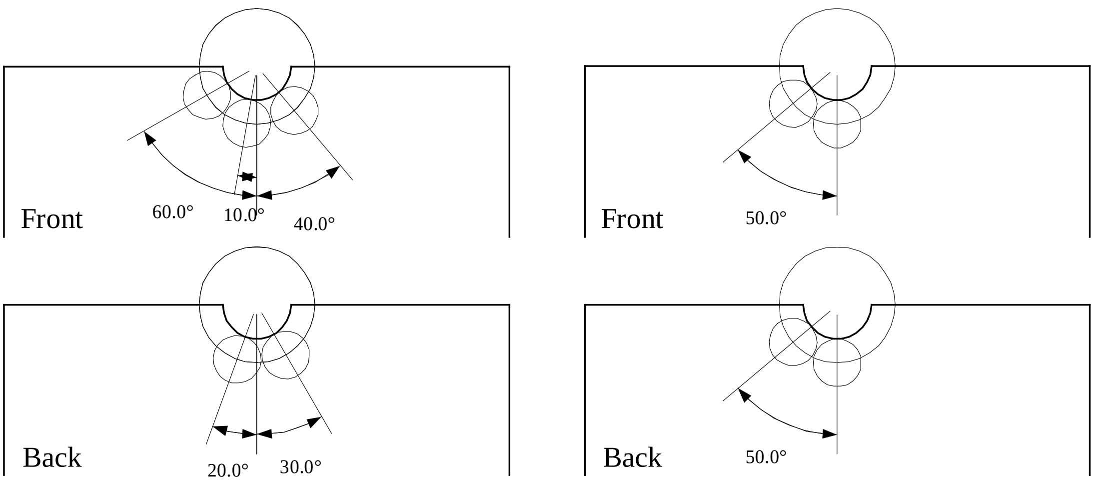


Figure 2. Locations of the 2 mm strain rosettes.

By having two specimens per group, with the gauging shown in Figure 2, it was practical to position rosettes such that the seven stations from 0° to 60° could be included, with positions 0° and 50° twice. Specimen No. 1 had single-sided gauges at 10°, 20°, 30°, 40° and 60° while specimen No. 2 had, on its front and back, 0° and 50° gauges. Strain and load readings were taken in real time using a datalogger.

The pin-bearing load was applied by way of a DARTEC 9500 hydraulic testing machine at a constant stroke rate of 0.01 mm/s. Strains were recorded during the short-term tests at 1 s intervals. In all tests the load-stroke characteristic was linear to failure and there was no indication of ‘bearing’ failure, such as acoustic emission, prior to ultimate failure at the final load. Table 1 presents final loads from 12 physical tests. The loads are compressive. Within each notch diameter and orientation group there can be significant load variation. It is clear from the final loads in Table 2 that there is a considerable drop (25%) in load when there is 1.2 mm clearance. Transverse splitting (delamination) between the roving and mat layers was the ultimate mode of failure.

Table 1. Physical test results.

Specimen	Final load (kN)	Specimen	Final load (kN)
1-10-00	20.3	2-10-00	17.0
1-10-45	17.7	2-10-45	16.5
1-10-90	16.4	2-10-90	19.0
1-11-00	11.8	2-11-00	16.0
1-11-45	10.8	2-11-45	12.2
1-11-90	12.0	2-11-90	12.5

Mottram and Padilla-Contreras (2001) also obtained a considerable variation in failure load (from three specimens) and put this down to the non-homogeneity of pultruded thin-walled profiles, which has statistically large reinforcement areas of unidirectional roving bundles dispersed between the more uniform mat layers. Contrary to the findings of Pierron *et al.* (1999) and Mottram and Padilla-Contreras (2001) the new physical tests, when there was a 1.2 mm clearance (i.e. the 11 mm diameter notch), did not show material failure at a load below the final load. The new pin-bearing tests did not give a damage tolerance behavior.

FINITE ELEMENT ANALYSIS

The software used was ABAQUS© (http://www.abaqus.com). All analyses were linear elastic with the load taken to 25 kN (above the final loads in Table 1). Features of the final model for the 10 mm notch, with its mirror symmetry when the material orientation was 0^o and 90^o, are shown in Figure 3. The figure on the left gives the model’s dimensions. The orthotropic plate model was 70 mm high by 35 mm wide. Because symmetry is not present when the roving reinforcement is not oriented at 0^o or 90^o, the full-plate specimen (70 $\times$ 70 mm) had to be meshed for the 45^o material orientation situation. Advantage was taken of Vangrimde (2000) observation that there was no benefit in a three dimensional model. For the half-specimen model shown in Figure 3 there were 3550 linear CPS4R plane stress elements of 6.4 mm thickness. Hourglass control was employed since element integration was reduced. The mesh specification was chosen so that:

- It was very fine close to the contacting surfaces (Figure 3 right hand side).
- It had symmetry about the centerline, when acceptable.
- Nodal output was obtained at the center of the 2 mm strain gauges (Figure 4).

One possible reason for the unacceptable strain comparison in the preliminary study by Mottram and Padilla-Contreras (2001) was a mesh lacking adequate refinement. The mesh used here (Figure 3) had four times more elements and this refinement will be shown later to be acceptable.

The elastic constants for the EXTREN 625 flat sheet were assumed to be 16.2 GPa for the longitudinal modulus, 11.3 GPa for the transverse modulus, 4.5 GPa for the inplane shear modulus, and 0.3 for the major Poisson’s ratio. The steel indenter was modeled as a rigid body of 10 mm diameter. It was linked to a reference node on the plate model. Analyzing with the indenter as a deformable body gave no discernable difference in strain (or stress) output. The displacement boundary conditions were such that the centerline nodes (Figure 3) had their horizontal displacement fixed to maintain symmetry. At the vertical free edge the nodal displacements were all free. The nodes along the base of plate had their displacements set to zero.

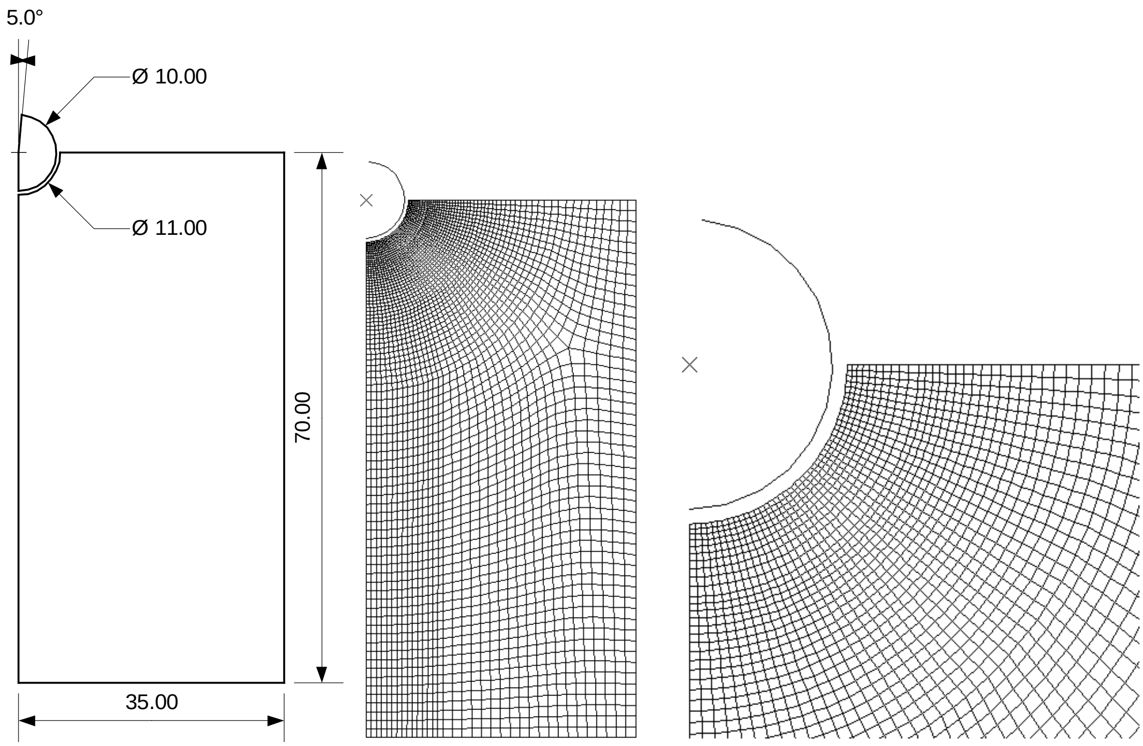


Figure 3. Dimensions and mesh specification for plate specimen.

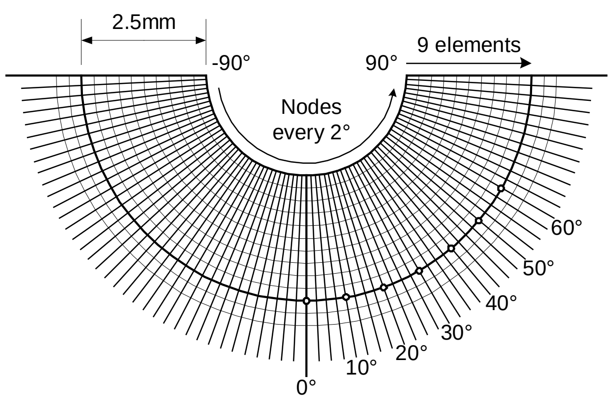


Figure 4. Local mesh refinement.

Account of contact and friction between steel and the pultruded material was achieved using the ABAQUS© master-slave contact algorithm. The coefficient of friction was assumed to be 0.2 (from Hyer *et al*. 1987). Notch clearances of 0 and 1 mm were modeled. Loading was applied by vertically displacing downwards the center of the pin-indenter towards the fixed base of the plate. Run times were up to 15 minutes on a standard PC. To cope with the contact and friction phenomenon the number of increments were between 8 and 40.

RESULTS AND DISCUSSION

Finite element results are given at loads of 10 and 15 kN. There is not space in this paper to present all relevant results. It was found that by lowering the shear modulus from 4.5 GPa to 3 GPa the strains were little changed. At the 15 kN load level Figure 5 shows, close to the mating surfaces, the minimum principal strain contour plots for the no clearance and clearance situations.

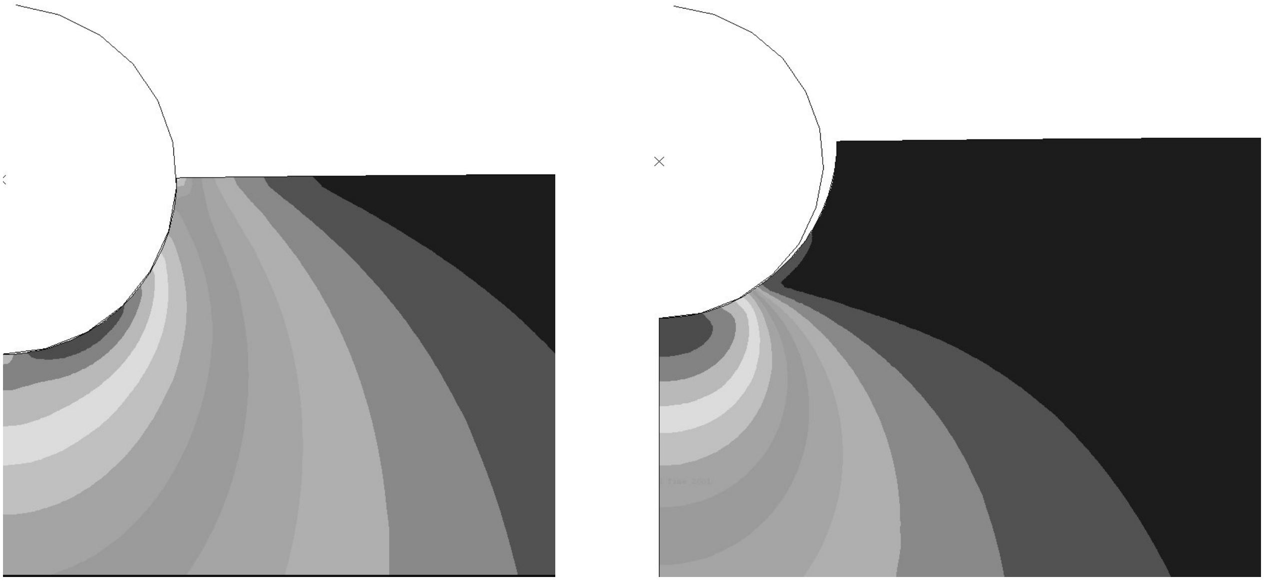


Figure 5. Minimum principal strain contour plots; left figure no clearance, right figure 1 mm clearance.

The material orientation was 0^o. The continuous smooth contour lines indicate that the mesh had adequate refinement. In the two plots the same gray shades represent the same level of strain and, as expected, there was strain concentration towards the bearing plane (i.e. the symmetry or 0^o plane) when clearance was present. At the notch perimeter the highest compressive strains were located away from the bearing plane for the no clearance case. This indicates the existence of the stick/slip phenomenon (Mottram and Turvey 1998). The two contour plots show the usual pin-bearing behavior which has been observed using FEA by others (Vangrimde 2000, Mottram and Padilla-Contreras 2001).

Figures 6 to 11 present minimum principal strain plots from the ABAQUS© analysis. The load was 15 kN for the strain results in Figures 6 to 8. Final load in the physical tests was below 15 kN (Table 1) when the clearance was 1.2 mm. The comparison in Figures 9 to 11 was therefore made when the load was 10 kN. The plots range from -90^o to $+90^o$ with the 0^o corresponding to the bearing plane (Clarke 1996). The unfilled symbols are for the 10 mm notch (no clearance) and the filled symbols are for the 11 mm notch (1 mm clearance). The three different symbols are for the three material orientations, with 0^o given by ◇ and ◆, 45^o by □ and ■ and 90^o by ○ and ●.

Figure 6 gives the strains at 2.5 mm from the notch perimeter and Figure 7 gives the same strains on the perimeter. Plots in Figure 6 are given because strains were measured along the 2.5 mm arc. The curves are smooth and, except for the 45^o material orientation, the maximum values in Figure 6 occurs on 0^o (the assumed bearing plane). The results in Figure 7 are for strains that are more closely associated with the onset of pin-bearing failure. They show that the strain will be much higher at the notch perimeter, and that, only for the 0^o material orientation and clearance situation, will the maximum value be at the bearing plane. Figures 6 and 7 clearly show that the maximum minimum principal strain increased significantly when clearance (filled symbols) was present. From the FEA salient point strains at 15 kN load are collected in Tables 2 to 4.

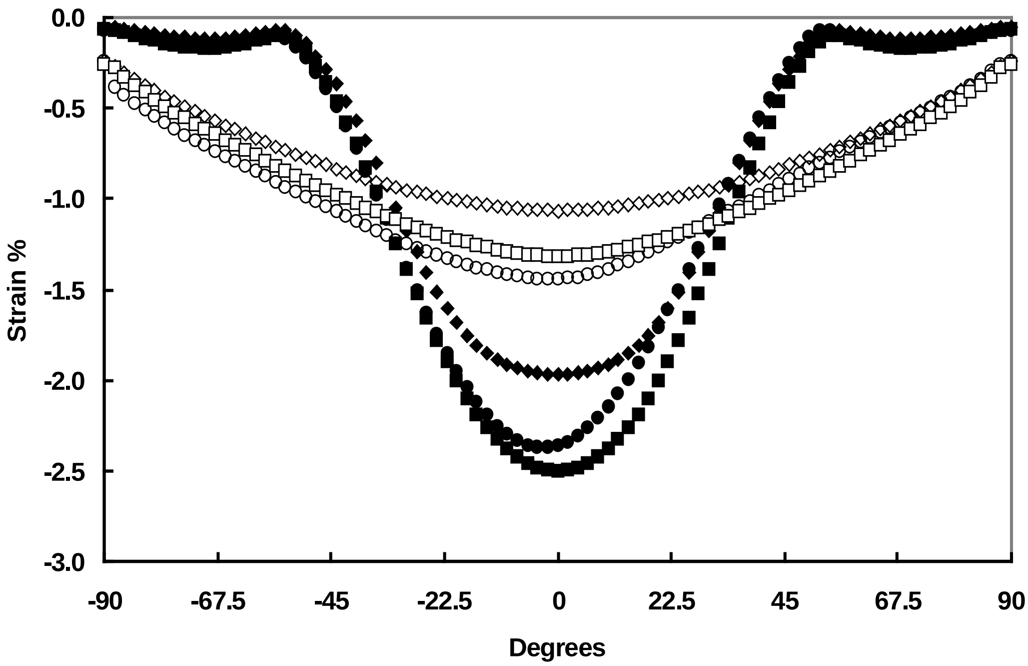


Figure 6. FEA minimum principal strains at 2.5 mm from notch perimeter.

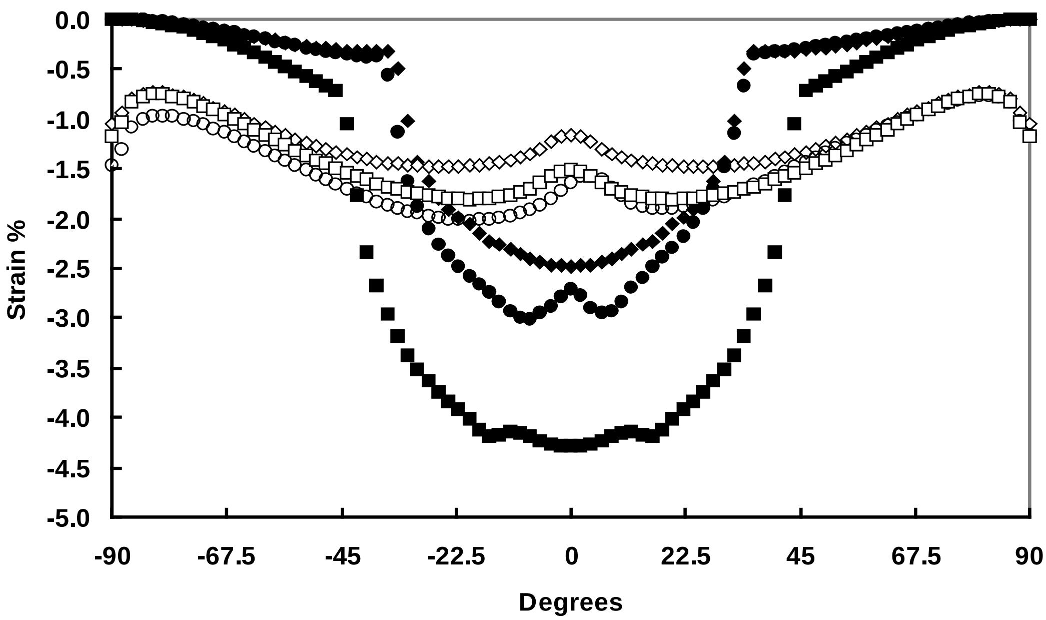


Figure 7. FEA minimum principal strains on notch perimeter.

The tables show a significant change in strain with the three material orientations and the two clearance values. By introducing the 1 mm clearance, which is the minimum used in practice (Anon 1989, Anon 1995, Anon 1999), the maximum compressive strain was increased by at least 65%. For the simulation load of 15 kN the strain was little changed with material orientation when there was no clearance, and significantly when there was 1 mm clearance. The 90^o material orientation was most sensitive to the presence of the clearance.

Prior to giving plots showing strain comparison between physical testing and ABAQUS© analysis it is relevant to show how the minimum principal strain changes with distance from the notch perimeter. Figure 8 gives, for the 0^o material orientation, two such curves along the bearing plane. The centers of the 2 mm long strain gauges are 2.5 mm from the notch perimeter (Figure 1(b)). For both the 0 mm (◇) and 1 mm (◆) clearance cases the change in slope of their strain curve at ±1 mm from the gauge's center indicates that the average strain can be assumed to be at the center.

Table 2. Minimum principal strain at 0^o and 2.5 mm from notch perimeter.

Material orientation	**Strain % 0.2 mm clearance**	**Strain % 1.2 mm clearance**	**% strain increase with clearance**
0^o	-1.06	-1.97	86
45^o	-1.44	-2.37	65
90^o	-1.32	-2.50	89

Table 3. Minimum principal strain at 0^o on notch perimeter.

Material orientation	**Strain % 0.2 mm clearance**	**Strain % 1.2 mm clearance**	**% strain increase with clearance**
0^o	-1.17	-2.48	86
45^o	-1.64	-2.70	65
90^o	-1.52	-4.29	89

Table 4. Maximum minimum principal strain at notch perimeter.

Material orientation	**Strain % and location 0.2 mm clearance**	**Strain % and location 1.2 mm clearance**
0^o	-1.48% @ ±26^o	-2.48 @ 0^o
45^o	-2.01% @ -20^o	-2.70 @ -8^o
90^o	-1.80% @ -20^o	-4.29 @ 0^o

This finding supports a comparison being made between theory and practice. A second finding from Figure 8 is that, when there was no clearance, the maximum strain was not at the notch perimeter; it was about 0.7 mm distance from the surface. This observation might be useful when developing improved procedures for the design of bolted joints.

Figures 9 to 11 present a comparison with point experimental strains, which were measured using the test procedure described earlier. Strain measurements with the 0.2 mm and 1.2 mm notch clearances are given by symbols × and +. These point strains are therefore to be compared with numerical strains at 10 kN load given by the unfilled and filled symbols, respectively.

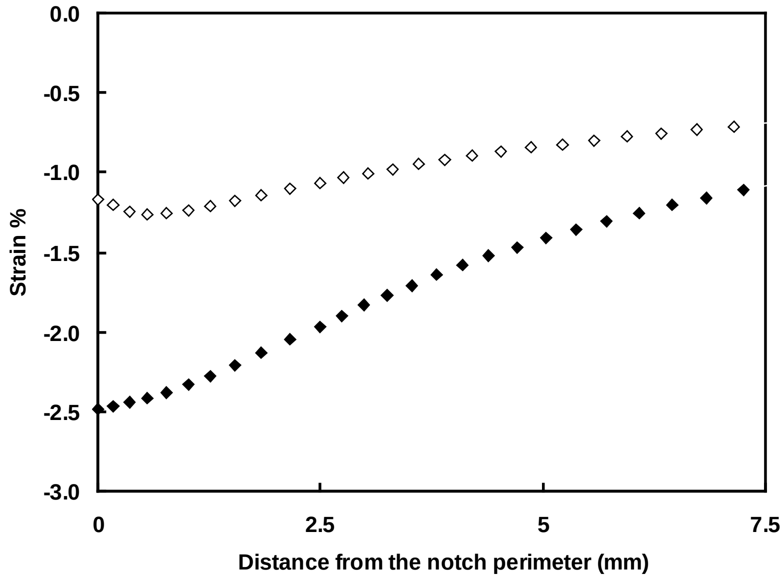


Figure 8. Minimum principal strains on bearing plane from notch perimeter.

When plotting the point experimental strains in Figures 9 to 11 it has been assumed that there is symmetry about the 0^o plane, even though this is known to be incorrect when rovings are oriented at 45^o to the line-of-action of the load. The mean of front and back gauges at 0^o and 50^o (see Figure 2) are given in the figures. There was but a small strain difference between the paired gauges on the six specimens covering the full range of material orientations and notch clearance sizes. This observation suggests that the load was not too unevenly distributed through the plate thickness.

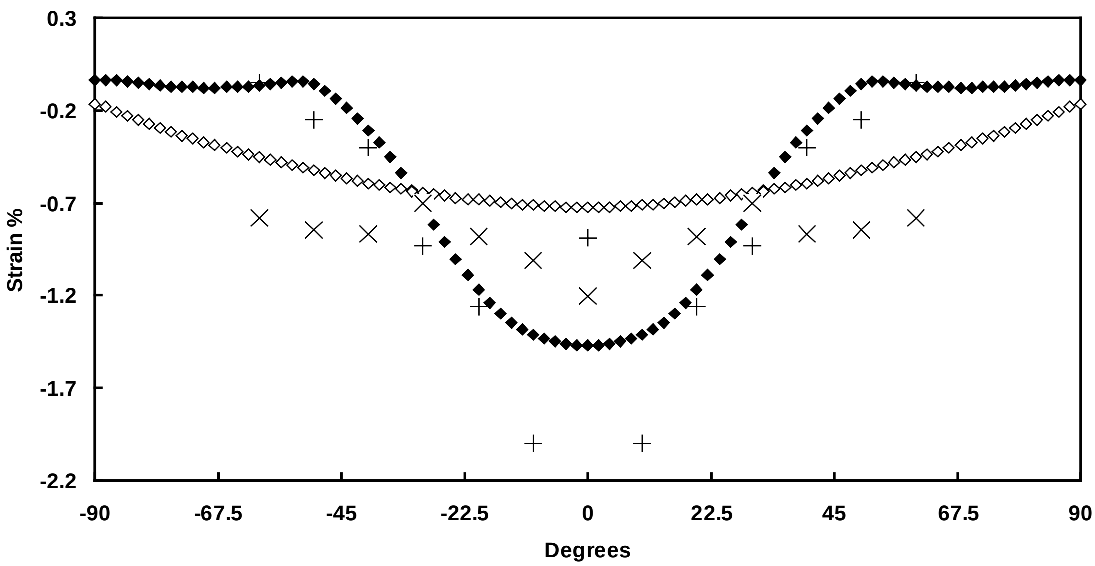


Figure 9. Comparison of strains for 0^o material orientation.

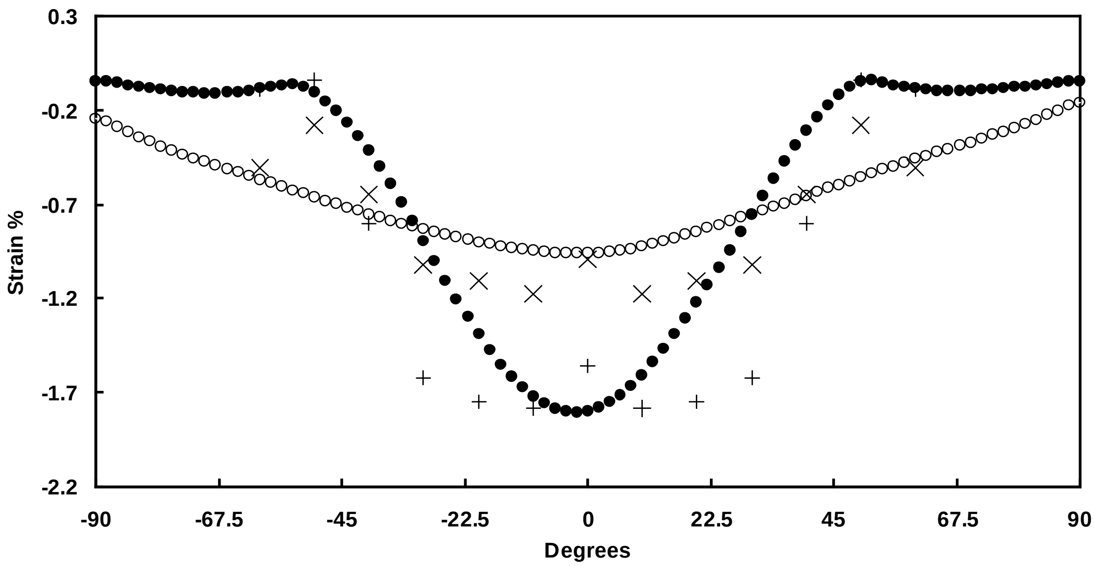


Figure 10. Comparison of strains for 45^o material orientation.

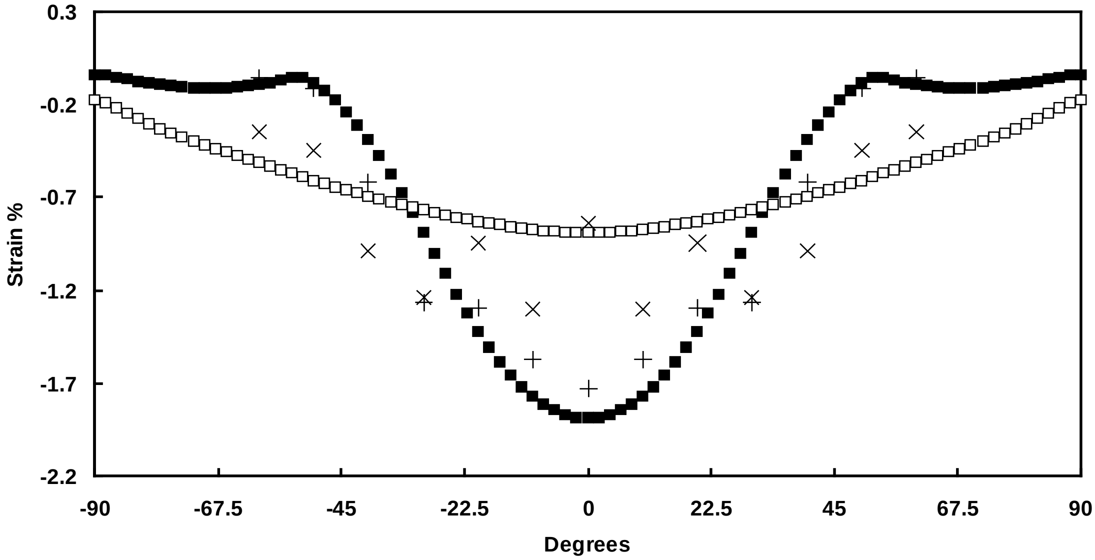


Figure 11. Comparison of strains for 90^o material orientation.

Comparing the FEA and experimental strains in Figures 9 to 11 it has to be assumed that the elastic constants used in the FEA are those of the test specimens. In modeling the pultruded material it had to been assumed that the material was homogeneous with orthotropic properties. In reality the material's macrostructure deviates considerably from homogeneity. The construction takes the form of alternate reinforcement layers of continuous filament mat and undirectional rovings (Anon 1989). Outer reinforcement layers are of mat. The thickness of the layers is not constant since the roving reinforcement is unevenly spaced between the mats. It takes the form of elongated ellipsoidal bundles with matrix rich regions between the bundles that are spaced between 4 and 10 mm. Strains measured at the surface will be governed by the local material stiffness beneath. This could change depending on whether a roving bundle is under a gauge or not. This potential difficulty when measuring strains in pultruded materials is neglected when making the following observations on the preliminary results presented in Figures 9 to 11.

The characteristics of the strain profiles from the physical test series suggest that the 0.2 mm notch clearance was significant. By joining the ×s in the figures and observing the trends it appears that the measured strains, 2.5 mm from the notch perimeter, take a similar form to the FE strains on the notch perimeter (see Figure 7). Since it would be impractical on site to have bolted joints with zero hole clearance it is recommended (if required) to develop a design procedure for joints with 'no' clearance using the FE results from a model with 1 mm clearance. This approach would guarantee that the maximum FE stresses (or strains) used in the design procedure will always be higher than experienced in practice, assuming 'no' clearance is equivalent to a clearance of, say 0.2 mm.

There is a closer correlation between numerical (filled) and measured (+'s) minimum principal strains when the clearance was 1 and 1.2 mm, respectively.

The six sets of results in Figure 9 to 11 indicate that in practice the load is distributed over a longer arc and that the FEA often predicts a maximum strain which is equal of higher than that measured. The exception to this was with material orientation 0^o and notch clearance. From Figure 9 it can be seen that the maximum strain in the test was 2% (at the angle of 10^o). This strain was > 25% higher than given by the FEA. Further physical tests are required to establish the importance of this result by way of its potential link to the non-homogeneity of the plate's fiber reinforcement arrangement.

CONCLUSIONS

1. A simple physical test method has been developed to study the pin-bearing behavior of pultruded materials for the design of steel bolted connections.
2. Because there was no material failure prior to the final pin-bearing load the physical tests with EXTREN Series 625 flat sheet (of 6.35 mm thickness) and notch clearance show that there was no damage tolerance. This observation contradicts what was found by Mottram and Padilla-Contreras (2001) when the pin-bearing tests used the web material of a 203×203×9.35 mm wide flange profile, a pin of 16 mm diameter and clearances of 1 and 2 mm.
3. The ABAQUS© FE modeling was successful, providing strain curves at the notch perimeter which were smooth and do not appear to be adversely affected by the contact algorithm. Comparison with strains measured at 10 kN indicates that the FEA is concentrating the load over a narrower arc of the notch perimeter. There is a need to rigorously assess the numerical behavior of the contact algorithm.
4. The minimum principal strains at the notch perimeter were influenced by friction; confirming that there are slip and no slip regions. When there is no clearance the highest FE strain is at 20^o, rather than at 0^o (i.e. the bearing plane). Maximum compressive strain does not always coincide with the assumed plane for bearing failure. And it is the maximum compressive stress on the 0^o plane which existing design procedures for the 'no' clearance case (Clarke 1996) use to make predictions for a bolted joint's bearing strength.
5. FE analysis shows that the maximum minimum principal strain increased with material orientation and with notch clearance.
6. Comparison with experimental strains shows that a small clearance of 0.2 mm in the physical tests has a noticeable affect on the strain distribution near the notch. The six sets of strain results that make up the comparison show that the FEA output is reasonably accurate when the notch clearance of 1 mm is present.

7. For the safe design of bolted joints, FEA output from a model with 1 mm hole clearance should often provide the strains (or stresses) required to establish joint strength (with or without clearance to 1 mm).
8. Additional physical test data and further FE simulation results are needed to establish if the strains (and stresses) associated with the initiation, and growth, of progressive damage at the bolt/hole can be predicted with sufficient accuracy for their employment in a damage tolerant design procedure.

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