THE STRUCTURAL BEHAVIOUR OF MONOCOQUE FIBRE COMPOSITE TRUSS JOINTS

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SUMMARY:

This paper presents early experimental results of an ongoing research project into the structural behaviour of monocoque fibre composite truss joints. The testing of three different types of joints will be discussed. Descriptions of the test procedures are presented as well as design and analysis of each jointing method.

KEYWORDS: truss, joints, monocoque, particulate filled resin, civil infrastructure, structures

INTRODUCTION

Trusses are amongst the most efficient structural forms available in terms of material and weight. History has shown that the popularity of trusses reached a maximum during the Great Railway era of the 19th century and subsequently died with the advent of suspension bridges and post-tensioned concrete. One factor that contributed to the waning popularity of truss structures was the increase in labour costs during manufacture. Truss joints are very labour intensive and require a large proportion of the manufacturing time. By the mid 20th century, labour costs had increased to such a level that material cost was no longer the governing component in structure choice.

The ingress of fibre composite materials into the field of civil engineering has created the opportunity for a new and innovative approach to conventional truss design. In particular the suitability of fibre composites to monocoque construction opens up many new possibilities, the elimination of expensive truss joints should result in more efficient structures.

A new and innovative two-dimensional monocoque fibre composite truss was recently proposed by Van Erp. In order to establish the merit of this approach a testing program was commenced at the University of Southern Queensland to investigate the local and overall behaviour of this type of truss. This paper presents the results of a series of joint tests that were conducted at USQ to increase the understanding of the behaviour of monocoque joints.

MONOCOQUE FIBRE COMPOSITE TRUSS

Truss Configuration

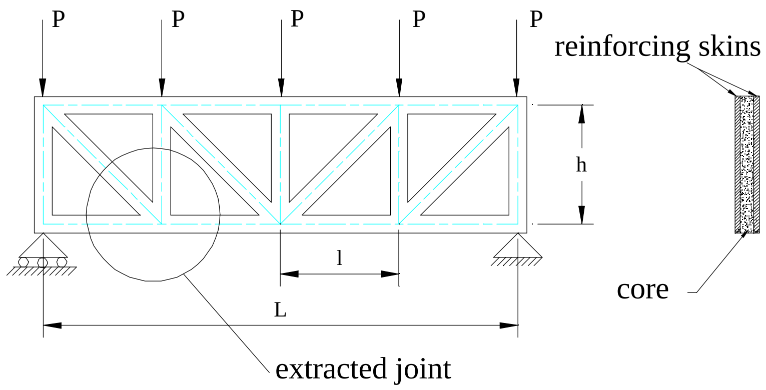


Figure 1 - Typical Truss and Cross Section

The truss consists of two external skins of glass and/or carbon fibre over a largely non-structural core material. One could think of the truss as a sandwich panel with triangular cut-outs. However, to save material and to make sure that the reinforcement in the different truss elements runs in the direction of the forces, the present truss is constructed from a cast core material molded in the form of the truss. The reinforcement is laid down on the core as individual strips that overlap at the joints.

The style of the truss from which the test joints have been extracted is planar and is commonly called a Pratt truss. The Pratt truss is most efficient for predominantly downward static loading.

The panel aspect (h/l) is chosen as 1:1 to produce a diagonal tension member at 45° to the horizontal. The reinforcement in the top and bottom chords of the truss are continuous making pullout of the diagonal tension members the critical failure mechanism. The geometry of the truss elements has been adopted to minimise materials and construction effort whilst maintaining a practical size and performance relevant to a larger structure. The exact joint dimensions are presented later in this paper.

Truss Behaviour

The classical method for analysing trusses is to treat them as perfect pin ended elements joined at nodes. In this type of structure the truss members will be subjected to axial forces only. However, it is not uncommon for trusses to have rigid joints, especially in the case of steel trusses. By fixing the joints bending moments and shear forces develop in the members (Figure 4) which result in 'secondary' stresses additional to the 'primary' stresses due to axial loads. In the case of steel trusses, the impact of these secondary stresses is very small due to the ability of steel to yield locally and redistribute stress concentrations. Consequently many steel designs ignore these secondary stresses all together.

In the case of brittle materials such as fibre composites, the secondary stresses must be taken into account. Failure to do so could result in premature collapse of the structure.

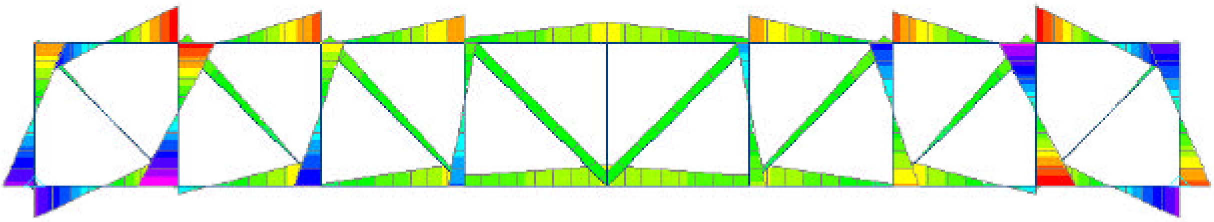


Figure 2 - Bending Moments in a Simply Supported Rigid Jointed Truss Under Uniform Nodal Loading

The relative dimensions and mechanical properties of each of the truss members in a joint will affect the degree of rigidity of the joint. In turn, the degree of rigidity will affect the amount of moment attracted to the joint and hence the level of secondary stress created in the members of that joint. The exact magnitude of the bending moment in each of the truss members can be determined using standard finite element software. Figure 2 shows that the bending moment in the diagonals decreases towards the supports, while the moment in the top and bottom chords and vertical web members increases towards the supports.

Another issue important to secondary stresses in trusses is the amount of eccentricity between the load lines of the truss members. Small eccentricities can result in significant moments in the members. In the present truss design, great care has been taken to eliminate these eccentricities.

Early truss tests using end grain balsa and polystyrene foam as core materials showed some deficiencies. The balsa tended to crush easily and required hard points in the vicinity of loads and supports. The foam core had insufficient shear strength and stiffness and crushed easily. To overcome these problems a hollow particulate filled resin (PFR) core was developed.

A schematic cross section of a typical member is presented in Figure 3. The members are comprised of a foam void former that has been wrapped with a unidirectional glass tape at 45° to the horizontal. The intention of the wrap is to contain the layer of PFR in which the foam core is encased. The reinforcing skins are hand laid onto the core and encased in a protective coating of PFR. The outer protective casing has been excluded in this series of tests to allow observation of the reinforcing fibres. Initial tests have shown that very strong and light trusses can be constructed in this way.

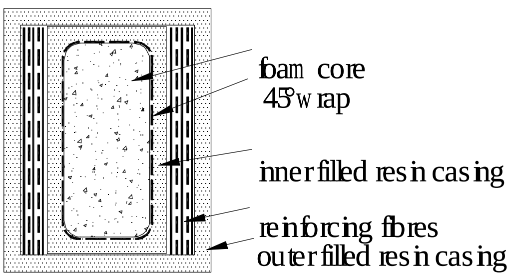


Figure 3 - Schematic of Typical Truss Member Cross Section

ADR246TX epoxy resin was used with ADH160 hardener from ATL Composites and fly-ash microspheres provided by Envirosphere to produce the PFR. The finished density of the filled resin is approximately 800 kg/m^3. Research into alternative filled resin formulations is continuing at USQ.

The reinforcing skins in this series of testing are unidirectional 450gsm E-glass heatset tape supplied by Colan Products Pty Ltd. The epoxy/glass reinforcement has been tested at USQ and has an ultimate tensile strength of 320 N/mm width per glass layer. Investigations into the performance of other fibres such as carbon and glass/carbon hybrids are underway.

JOINT TESTING

The aim of the testing program is to closely examine the failure mechanisms of different types of joints and to provide data for the validation of numerical models.

In the four panel Pratt truss shown in Figure 1, the most highly loaded tension members are the outer-most diagonals. Under load the diagonals tend to pull out of the top and bottom chord and a purpose built test rig was developed to model this type of behaviour. The test rig is shown in Figure 4.

Eight joints in total were tested and all joints were loaded in static tension using an Avery universal testing machine. The joints were tested to destruction and the ultimate failure load of each joint was recorded as well as the failure mode.

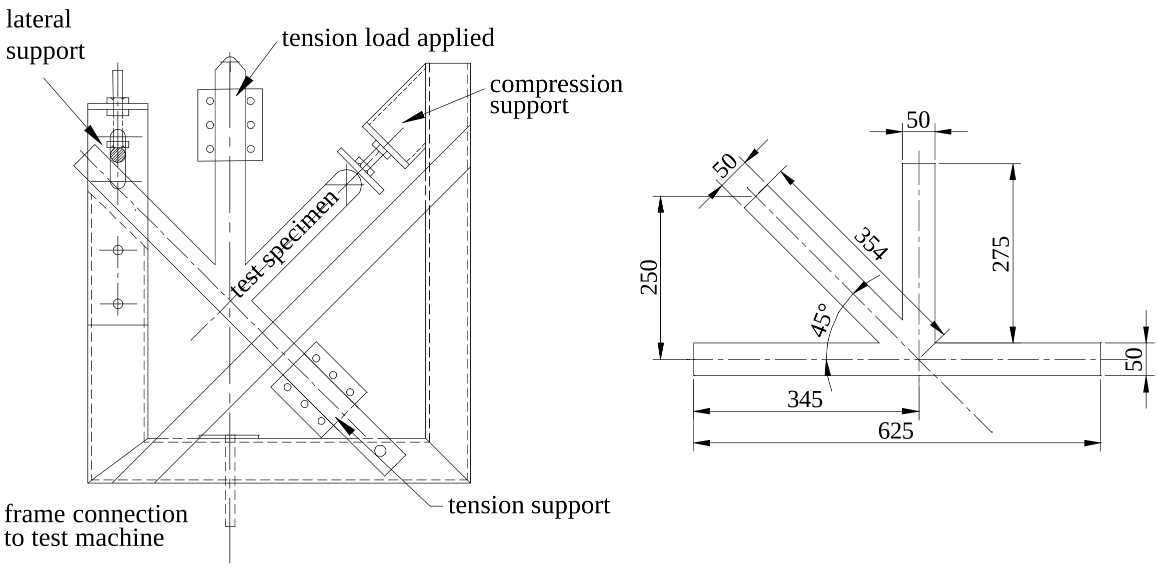
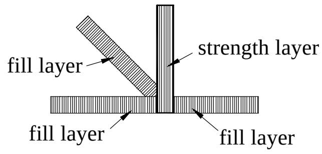
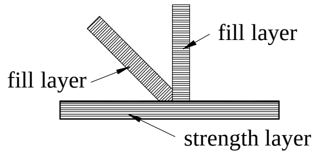
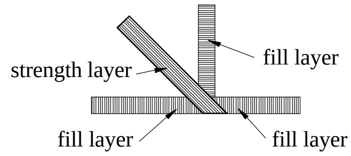
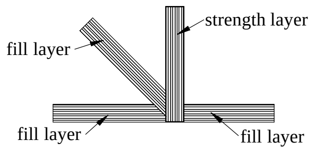
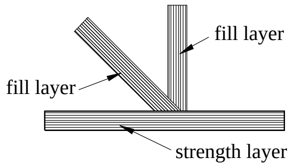
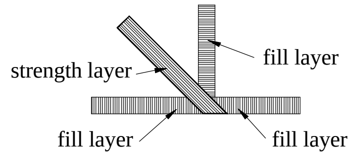
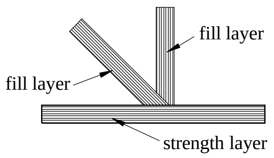
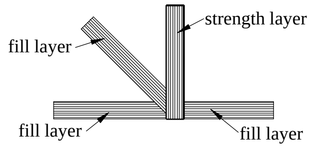
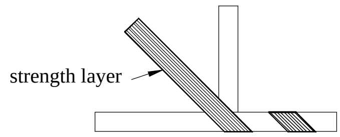
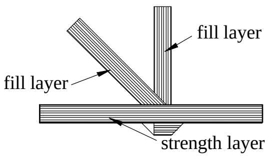
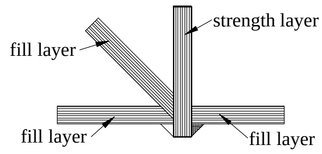
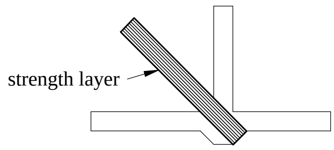


Figure 4 - Test Rig and Joint Dimensions

Joint Configuration

The monocoque truss joints use a combination of fill layers and strength layers to ensure load is transferred from member to member whilst minimising the generation of out of plane forces. Three types of joints were chosen for investigation, differing mainly in the termination of the diagonal tensile reinforcement. Table 1 shows the fibre orientation for each of the joint types, including a detailing modification between joint 1a and joint 1b to increase the lap area of diagonal layers without additional material.

Table 1 - Schematic Fibre Orientation

Joint 1a	 layers 1 & 5	 layers 2 & 4	 layer 3
Joint 1b	 layers 1 & 5	 layers 2 & 4	 layer 3
Joint 2	 layers 1 & 2	 layers 3 & 4	 layer 5
Joint 3	 layers 1 & 2	 layers 3 & 4	 layer 5

The main diagonal tensile reinforcement of joint 1 laps onto the reinforcing fibres of the bottom chord and force is transmitted from member to member through inter-laminar shear. As shown in Table 1, five layers of reinforcement are required to complete joints 1a and 1b. Consideration was given to the stacking sequence of the layers and it was decided that the reinforcing fibres of the diagonal tension member (layer 3) should reside at the mid-layer of the laminate. In order to provide the most direct load path from the tension member to the bottom chord member it was located between layers 2 and 4 which contain the bottom chord reinforcement. Finally the compression reinforcement of layers 1 and 5 was applied completing the symmetric layup.

The stacking sequence of joint 1b is identical to that of joint 1a. The difference is the length of overlap of fill material onto the compression member from the diagonal tension member. Stress concentrations were identified at the junction of the members using finite element analysis and the extra lap length provided by the fill layers of the diagonal member (layers 1, 2, 4 and 5) is used to increase the total contact area onto the bottom chord and compression member.

Joint 2 uses a spiral wrap to terminate the main tensile reinforcement around the bottom chord. The stacking sequence differs from that of joint 1 as the two bottom chord reinforcing layers are laid first, followed by the vertical compression web member layers. Consequently the amount of fill material is reduced.
Joint 3 terminates the main diagonal reinforcement by looping the fibres beneath the bottom chord and compression member to lap back on the diagonal tension member. The force in the joint is carried completely by the fibres and the joint has less fill material than joints 1a and 1b.

The ultimate load carrying capacity of joints 1a and 1b relies heavily on the interlaminar shear strength developed between the tensile diagonal strength layer and the adjacent layers in the joint. Failure of the resin in the joint would most likely produce ultimate failure of the joint. Joints 2 and 3 rely on positive termination of the reinforcing fibres away from the joint, and in the case of joint 2 around a member. In both of these latter cases the failure of the resin would not necessarily produce ultimate failure of the joint.

Fabrication of Test Joints

The core of each joint was cast in a flat open mould shown in Figure 5. Lengths of foam were cut, shaped and wrapped with unidirectional tape then wet out by hand rolling. Once cured the inserts were cut to length and located in the pre-waxed and assembled mould. The mould was then filled with PFR and the foam was fixed in position and prevented from floating. After the joints were cured at room temperature for 24hrs, they were removed from the mould, cleaned and thicknessed in preparation for application of the reinforcing skins.

The unidirectional tape skins were hand laid and wet-out by manual rolling. The skins were applied to each side of the joint on consecutive days and were allowed to room temperature cure for 24hrs after which time they were post-cured at 60 degrees centigrade for 8 hrs.

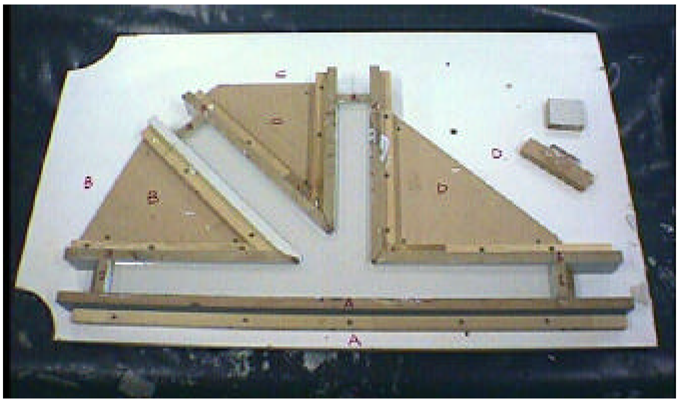


Figure 5 - Cured Joint in Casting Bed

The total number of joints fabricated for this series of tests was eleven, 2 of joint 1a and three each of joint types 1b, 2 and 3.

RESULTS

The table below shows the ultimate failure loads of the eleven tests carried out on the joints. A predicted load is given for each joint as well as the achieved load from the test. The predicted load was obtained using values of ultimate tensile load carrying capacity of a single layer of glass reinforcement, gathered from tests carried out at USQ.

Table 1 – Predicted Capacity and Test Results

Joint	Predicted Load (kN)	Attained Load (kN)

1a-1	27.2	52.3
1a-2	27.2	60.9
1b-1	27.2	64.7
1b-2	27.2	60.6
1b-3	27.2	62.2
2-1	27.2	55.2
2-2	27.2	70.7
2-3	27.2	53.5
3-1	27.2	59.4
3-2	27.2	56.8
3-3	27.2	60.7

Using the ultimate failure strength of the epoxy/glass material, the ultimate load carrying capacity of the tension member was estimated as:

$$F_U = \phi . f_U . w . n \qquad (1)$$

Where
F_U = ultimate failure load of member
f_U = ultimate failure load of laminate (per mm width)
w = width of laminate
n = number of strength layers
ϕ = reduction factor for secondary stresses determined using finite element analysis (0.85)

With an ultimate tensile failure strength of the epoxy/glass material of 320N/mm width and one 50mm wide layer of diagonal tensile reinforcement on each side of the truss, the total ultimate failure load is:

$$F_U = 0.85 \times 320 \times (50 \times 2)$$
$$= 27200\text{N}$$

The load carrying capacity of the compression web member (ignoring buckling) and bottom chord is 2 x 27.2kN = 54.4kN.

Figure 6 below illustrates typical failure modes of each joint type obtained during the tests.

<u>Joint 1a</u>
The failure mode was tensile failure of the diagonal strength layer at the face of the joint (see Figure 6). The failure line was very distinct and coincided with the position were all the fill layers were terminated.

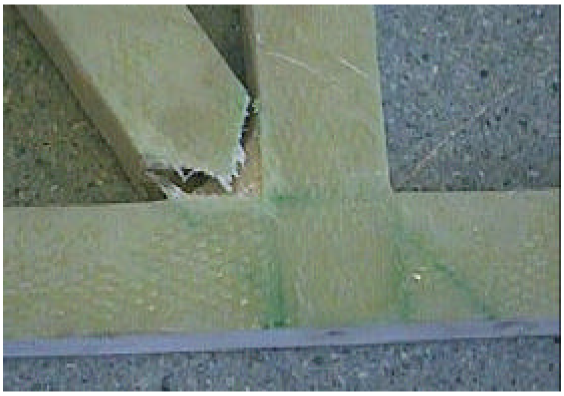
<u>Joint 1b</u>
This joint also failed through tensile failure of the diagonal strength layer at the face of the joint. In this case however, the different way of terminating the fill layers appeared to disrupt the failure mode. The line of failure was less distinct and included some pull out of the fill layers.

<u>Joint 2</u>
Joint 2 did not fail in the diagonal member which at first was unexpected. On closer examination it was obvious that the omission of two fill layers in the bottom chord was the cause of this behaviour. This reduced number of fill layers combined with the significantly increased failure load of the diagonal has created a new critical area in the bottom chord.

Failure is initiated in this member by a combination of tension and bending moment. The results of an additional finite element analysis confirmed this type of behaviour.

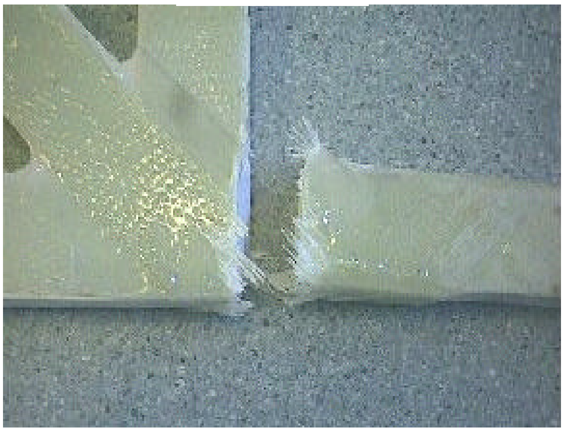
Joint 3

Joint 3 failed at the junction of the bottom chord and the compression member in a mode similar to that of joint 2. Failure was due to tensile failure of the bottom chord reinforcement possibly because of secondary stresses.

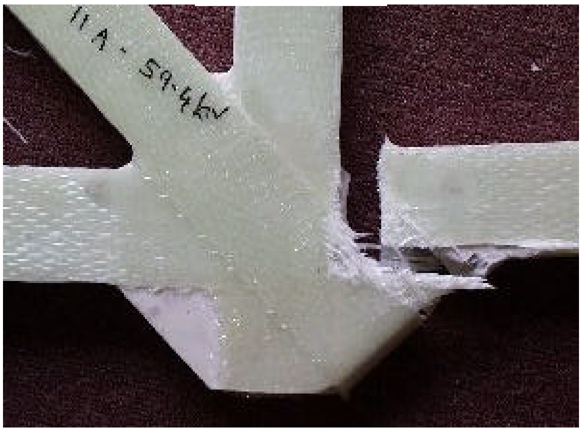


Joint 1a

Joint 1b



Joint 2



Joint 3

Figure 6 - Joint Failure Modes

The location of first and second noise for all of the joints is shown in Figure 9. During loading the joint displaces which results in the PFR core becoming over-strained at the corners eventually leading to failure. Second noise occurred at the opposite internal corner with the same result.

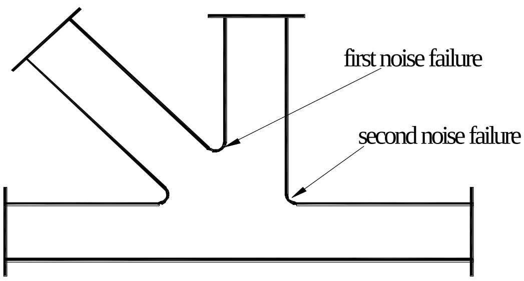


Figure 7 - Location of First and Second Noise Failure

CONCLUSIONS

A number of monocoque fibre composite truss joints have been tested at the University of Southern Queensland to determine their structural behaviour. The joints were subjected to static loading of the diagonal tension member and the ultimate load carrying capacity of each joint was recorded.

The experimental ultimate load carrying capacity of the joints was compared with the predicted load carrying capacity of each joint. The predicted load carrying capacity was based on equation (1) and ignored the contribution of the core material. The experimental load carrying capacity of each joint was found to be significantly higher than the predicted capacity.

The test results confirm the potential of the present truss joints. In all cases failure was initiated by fibre failure in the member rather than joint pullout. All failure loads were significantly above the predicted loads. It also appears that joint 1b fails at a higher average load than joint 1a, however more testing is required to confirm this.

Replacement of the balsa core by a filled resin core has almost doubled the load carrying capacity. It is tempting to include the contribution of the filled resin in the design but at this stage to many questions remain regarding the creep and temperature behaviour of the core. Also, the effects of the different failure strains of the core and glass laminate needs further investigation. Testing of the present joints at higher temperature is one of the next steps. These tests should show the difference between the lap joints, the spiral wrap joint and the sling joint.

From the results presented, it can be seen that strong monocoque fibre composite trusses can be produced using the present approach. However, further research is required in order to fully understand the fundamental structural behaviour of these trusses.

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ACKNOWLEGMENTS

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