HIGH STRENGTH RIGHT ANGLE COMPOSITE JOINTS FOR CIVIL ENGINEERING APPLICATIONS

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SUMMARY: This paper presents initial results of an ongoing research project that is concerned with the development of strong right angle composite joints for civil engineering applications. Experimental, analytical and numerical results for four different types of monocoque right angle joints loaded in pure bending will be presented. It will be shown that a significant increase in load carrying capacity can be obtained through small changes to the inside corner of the joints. The test results also demonstrate that there is reasonable correlation between the failure mode of the joints and the location and severity of the stress concentrations predicted by the FE method.

KEYWORDS: Joining, Civil Application, Testing, Structures.

INTRODUCTION

Plane frames are common load carrying elements in buildings and civil engineering structures. These frames are combinations of beams and columns, rigidly jointed at right angles. The rigid joints transfer forces and moments between the horizontal and the vertical members (Fig. 1a) and play a major role in resisting lateral loads (Fig. 1b).

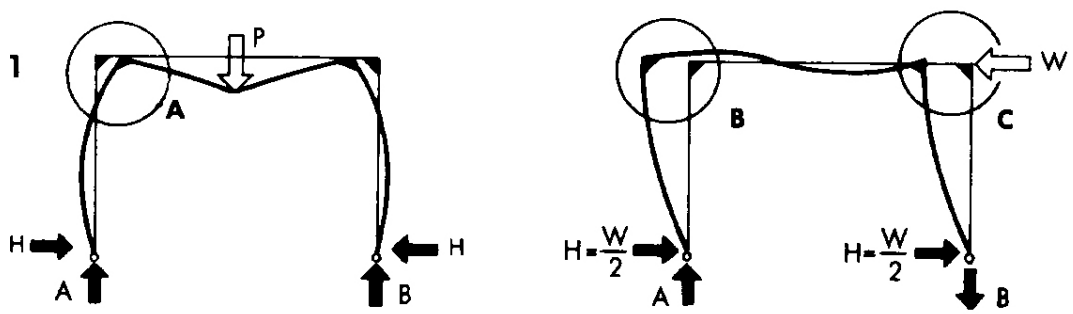


Figure 1a: Frame subjected to vertical loading b: Frame subjected to horizontal loading

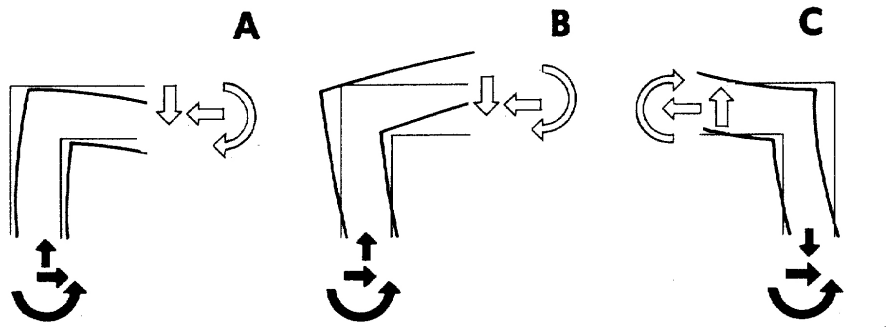


Figure 1c: Different types of loading on right angle joints

Depending on the type of loading and on the location of the joint in the frame, the joint will be subjected to a closing action (Fig. 1: case A and B) or an opening action (Fig. 1: case C). This paper will concentrate on joints with an opening action only.

Production of rigid right angle joints in fibre composites poses a major challenge. Linear elastic theory [1] predicts an infinite stress concentration in the inside corner of a right angle joint in bending. For ductile materials such as steel this is not a problem, localised yielding will alleviate the peak stress and the load carrying capacity of the cross section is hardly affected. However, this infinite stress creates a major problem for brittle materials such as fibre composites as it results in localised failure in the corner for very small loads. This failure will spread rapidly over the depth of the joint resulting in a significantly reduced load carrying capacity. Fortunately, real joints are never perfectly square resulting in a finite rather than an infinite stress. Nevertheless a large stress concentration remains.

Another problem with right angle joints is that fibres continuous around an internal corner will pull-out at relatively low loads when the joint is subjected to an opening action (the fibres tend to straighten). Research into this pull-out problem is still in progress at USQ and will not be considered here. This paper will concentrate on joints with laminates on the side surfaces (webs) of the members only. An example of this type of joint is shown in Figure 2. The purpose of the current study is to investigate the effects of small changes to the inside corner on the load carrying capacity of this joint.

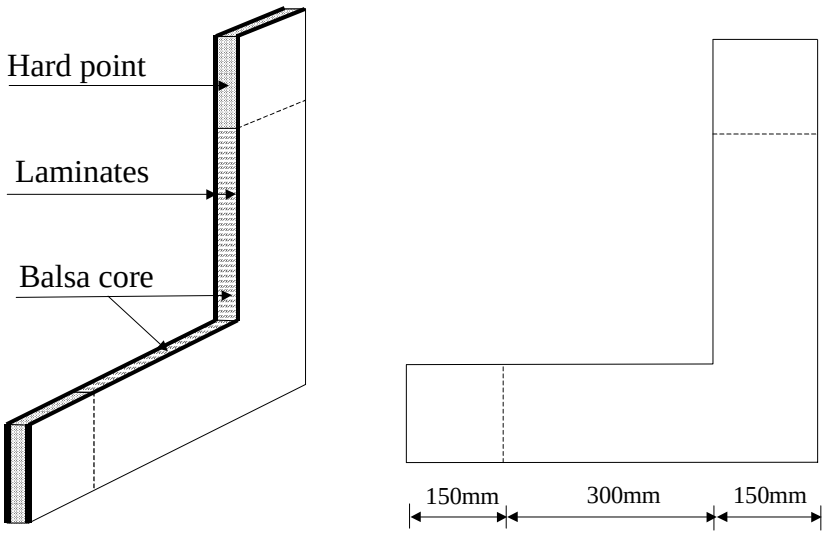


Figure 2: Investigated joint

PRODUCTION OF THE JOINTS

The joints were produced as a sandwich structure with two identical skins and a 25mm balsa core. The glass/epoxy laminates were made using standard hand lay-up techniques and were post cured for 8 hours at 60 degrees Celsius. The resin used is ADR246TX and the hardener ADH160, both from ATL Composites Pty Ltd in Australia. 450 g/m^2 unidirectional E-glass and 600 g/m^2 double bias E-glass were used as reinforcement. The same laminate was used on both sides of the balsa resulting in an overall symmetric lay-up. Details of the lay-up are presented in the next section. Hard points were included at the loading area to avoid crushing of the core.

NUMERICAL ANALYSES

Numerical analyses were conducted using MSC/NASTRAN. The maximum Tsai-Wu failure index [2] was used to compare the structural performance of the joints. Only static linear elastic analyses were conducted. The double bias was modelled as two unidirectional laminae at + and – 45 degrees with a thickness of 0.3 mm each. The unidirectional lamina is 0.5 mm thick. The material properties of the unidirectional lamina were determined through in-house testing and the values used in the analyses are as follows: UTS_1=600MPa, UTS_2=40MPa, UCS_1=400MPa, UCS_2=100MPa, USS=40MPa, E_1=30000MPa, E_2=10000MPa and G_{12}=4000MPa. The balsa was ignored in the numerical analyses and the joints were analysed as solid symmetric laminates.

TESTING PROGRAM AND NUMERICAL RESULTS

Four different types of joints were investigated (Figure 3).

1. A square right angle joint.
2. A right angle joint with a corner fillet.
3. A right angle joint with a circular cut-out at the inside corner.
4. A right angle joint with steel inserts.

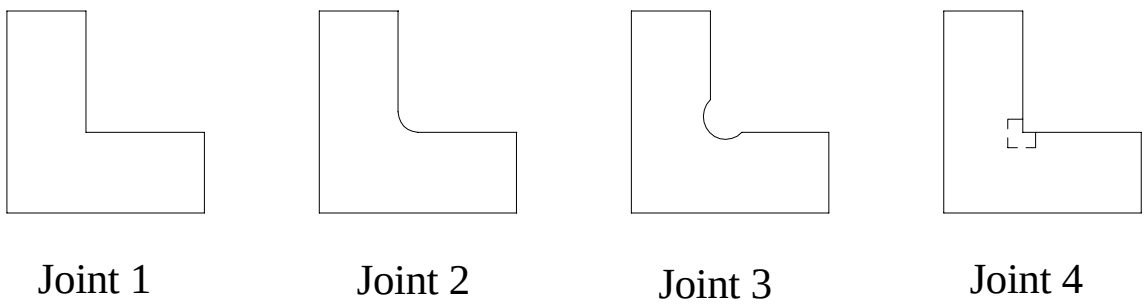


Figure 3: Types of joints investigated

Joint 1

The square right angle joint is used as a benchmark to assess the effects of the changes to the inside corner. The two different types of lay-up used for Joint 1 are shown in Figure 4 (the same 3-ply laminate is used on both sides of the balsa). Both lay-ups require the same amount of material. A total of six joints of type 1 were produced; 3 with lay-up type *a* (Joint 1a) and 3 with lay-up type *b* (Joint 1b). The load carrying capacity for both types of lay-up is

expected to be very similar for Joint 1 but is expected to lead to different results for some of the other joints.

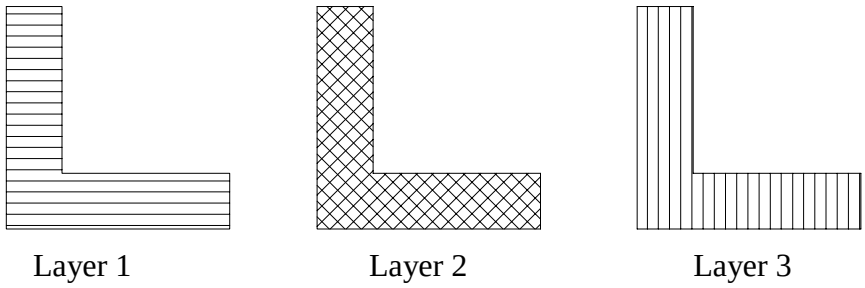


Figure 4a: Lay-up for Joint 1a

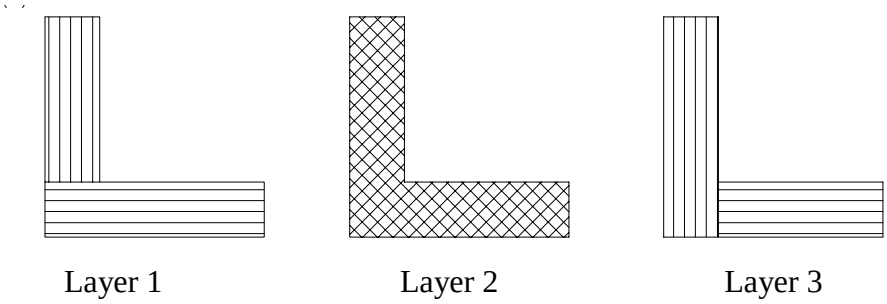


Figure 4b: Lay-up for Joint 1b

Numerical results

Finite element analyses show that the maximum stress in the corner of Joint 1a and Joint 1b continues to increase as the finite element mesh is refined, indicating an infinite stress in the corner of the joint. The analyses also reveal that, for the same finite element mesh, the maximum failure index for Joint 1a is approximately 15% higher than that of Joint 1b. This seems to indicate that the stress concentration in Joint 1a is slightly more severe than in Joint 1b. Figure 5 shows a contour plot of the Tsai-Wu failure index for Joint 1b.

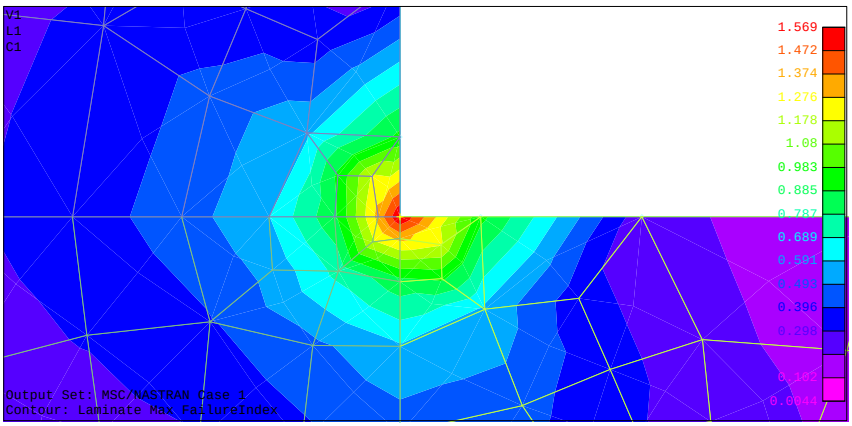
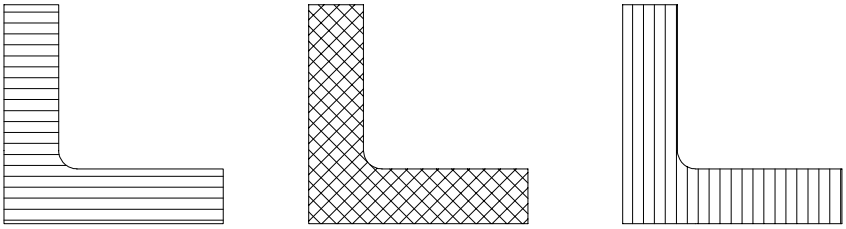


Figure 5: Contour plot for the Tsai-Wu failure index for Joint 1b.

Joint 2

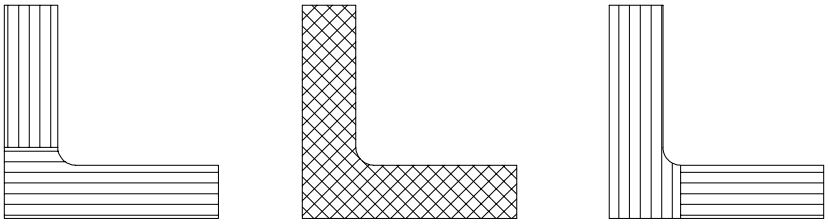
Inclusion of a fillet at the inside corner will result in a reduced stress concentration which should significantly increase the load carrying capacity of the joint. The larger the fillet, the smaller the stress concentration. However, as the size of the fillet increases it becomes more expensive and less practical. For the present series of tests a corner fillet with a radius of

50mm was selected. The lay-ups used for Joint 2 are shown in Figure 6 and 7. These lay-ups are based on the lay-ups of Joint 1a and 1b, but are slightly adjusted to incorporate the fillet. Six joints were tested, three of type 2a and three of type 2b.



Layer 1 Layer 2 layer 3

Figure 6: Lay up for Joint 2a



Layer 1 Layer 2 layer 3

Figure 7: Lay up for Joint 2b

Numerical results

The maximum Tsai-Wu failure index for both types of lay-up is almost identical; 0.28 for Joint 2a and 0.279 for Joint 2b. According to this result the influence of the different lay-ups on the load carrying capacity of Joint 2 is negligible. A contour plot for the Tsai-Wu failure index for Joint 2b is shown in Figure 8.

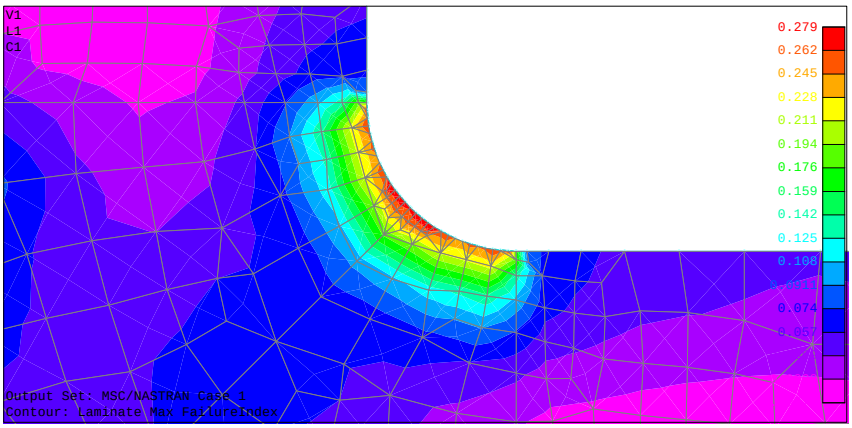


Figure 8: Contour plot for Tsai-Wu failure index for Joint 2b

Joint 3

Incorporation of a corner fillet is an effective way to reduce the stress concentration at the inside corner of a right angle joint. However, this solution cannot be used for structures which require a square inside corner. For this situation Joint 3 has been developed. The circular cut-out has the same effect as drilling a hole at the tip of a crack and will result in a reduction of the stress concentration in the inside corner. Filling the cut-out with a standard

non-structural filler will create the square corner. Figure 9 shows that the cut-out has been made such that the diagonal from the outside to the inside corner is not reduced in size.

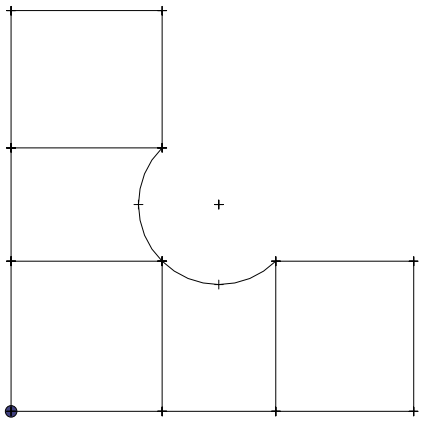


Figure 9: Geometry of the circular cut out

Two different types of lay-up (Joint 3a and 3b) were considered. The lay-up of Joint 3a is identical to that of Joint 1a and the lay up of Joint 3b to that of Joint 1b. A series of computer analyses was conducted for joints with different size cut-outs. The results show that as the radius of the cut-out is increased the stress concentration in the corner reduces. However, a new stress concentration appears where the material of the cross section has been cut away. As the stress concentration moves away form the corner to a position inside the adjoining members the influence of the different types of lay-up becomes very distinct. For example, in the case of Joint 3b the stress concentration moves into a region that has double the unidirectional reinforcement of Joint 3a.

For the present series of joints the maximum load carrying capacity is obtained for Joint 3b and a cut-out with a radius of 110mm. Figure 10a shows the stress concentration for this size cut-out for Joint 3a and Figure 10b shows the stress concentration for the same size cut out for Joint 3b.

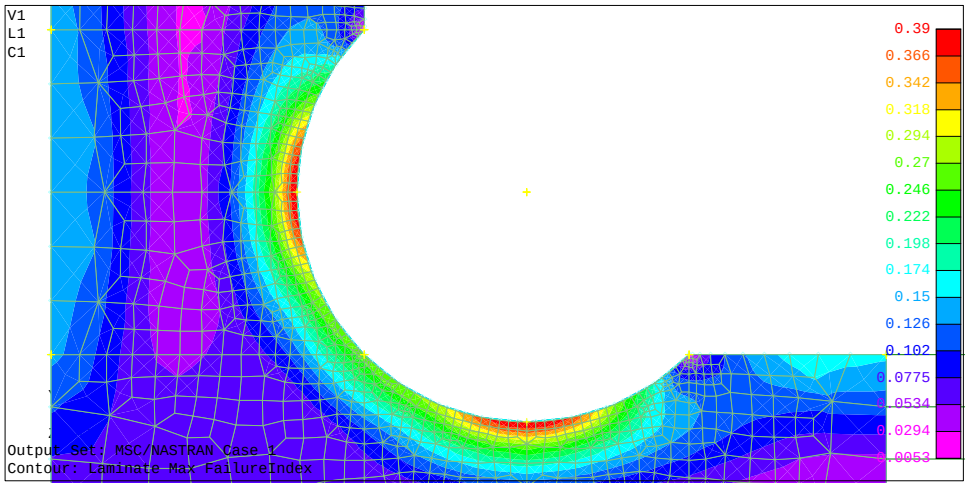


Figure 10a: Stress concentrations in Joint 3a with a 110mm radius cut-out

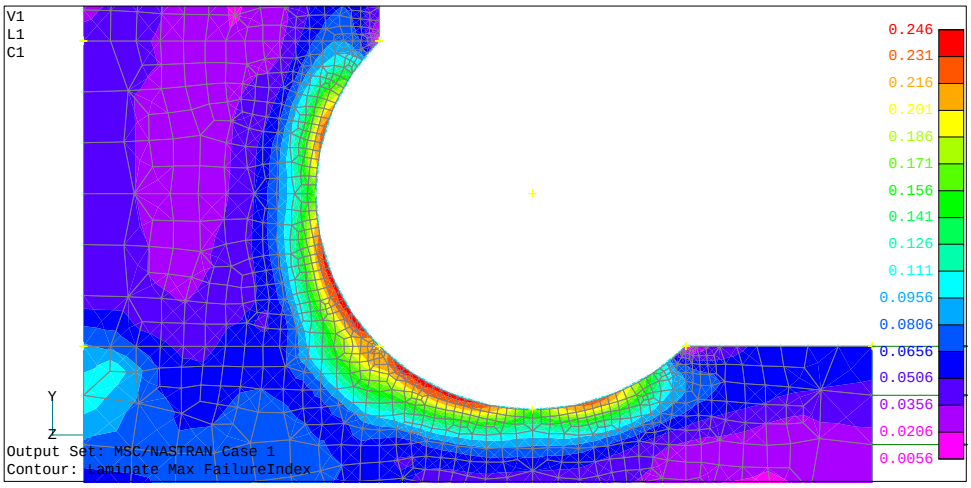


Figure 10b: Stress concentrations in Joint 3b with a 110mm radius cut-out

In the case of Joint 3a the maximum stress concentration occurs at the position of the maximum cut-out. In Joint 3b there are distinct regions of stress concentration, one on each side of the points of maximum cut-out. The Tsai-Wu failure index for Joint 3a is approximately 50% higher than that of Joint 3b, indicating that first ply failure in Joint 3a will occur at a load which is 50% lower than that of Joint 3b. The maximum failure index of Joint 3b (0.246) is very similar to that of Joint 2 (0.279). Accordingly, the load carrying capacity of Joint 3b should also be very similar to that of the joint with the corner fillet.

Joint 4

The inclusion in Joint 4 of two 1 mm thick mild steel inserts under the laminate (one on each side, embedded in the balsa) is expected to increase the ductility of the joint. In structures where the inclusion of some steel can be tolerated this is potentially a cheap way to increase the load carrying capacity of a right angle joint. The lay-up of Joint 4 is the same as that of Joint 1b. No computer analyses were conducted for this joint.

TEST SET UP

All joints were loaded in pure bending using an in-house developed testing rig (see Figure 11). Counter balance weights were used to make sure that the joints were without load at the start of the test.

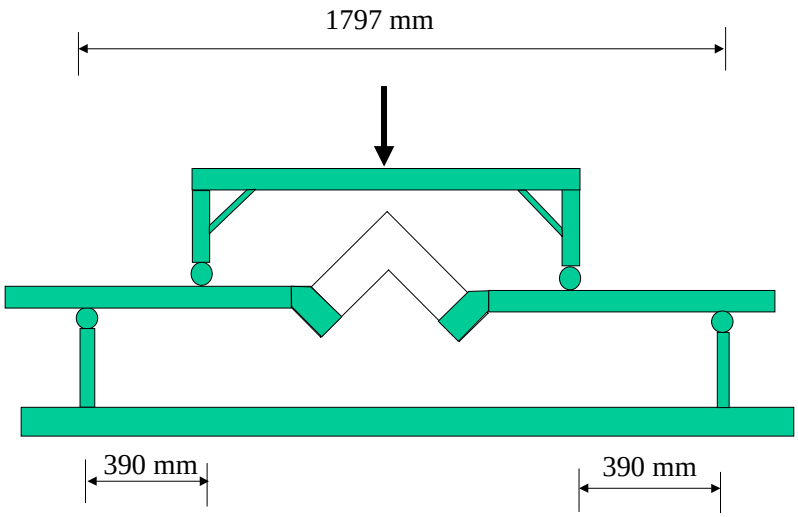


Figure 11: Testing rig

The displacement between two points on the centre line of each member was measured using an LDVT (see Figure 12). The points were located 225 mm from the intersection of the centre lines of the members.

Figure 12: Displacement measurement

TEST RESULTS

The test results are shown in Table 1:

Table 1: Test results

Type of joint	**Joint number**	Ultimate bending moment (kNm)	Finite Element prediction of first ply failure (kNm)	Displacement at failure (mm)
Joint 1a	1	2.013	Infinite stress	3.85
	2	2.062		4.02
	3	2.143		3.84
Joint 1b	1	2.101	Infinite stress	3.04
	2	2.257		3.40
	3	2.157		2.82
Joint 2a	1	3.067	0.789	3.05
	2	3.169		4.10
	3	2.913		3.65
Joint 2b	1	3.282	0.789	4.47
	2	2.954		3.81
	3	3.182		3.80
Joint 3a	1	2.294	0.564	6.40
	2	2.267		6.09
	3	2.044		5.86
Joint 3b	1	2.970	0.894	6.37
	2	3.160		6.74
	3	2.954		6.24
Joint 4	1	3.452	No FE analysis undertaken	3.73
	2	3.649		4.35
	3	3.102		3.31

As shown in Table 1, three joints were tested for each type of joint. The ultimate bending moment within each set of 3 joint specimens is reasonably consistent. The modes of failure are also very consistent. In the case of Joint 1a and 1b the crack starts in the corner and then slowly works its way through the cross section as indicated in Figure 13. Joint 2a and 2b also have very similar failure modes. The crack starts in the fillet, slightly off centre, at an initial angle of 45 degrees. After having penetrated about 5mm at 45 degrees it turns normal to the inside edge and works its way through the cross section. Joint 3a and 3b had different failure modes, very much in agreement with the finite element predictions (see Figure 10a and b). In Joint 3a the crack starts perpendicular to the cross section at the deepest point of the cut-out and quickly works its way through the total cross section. In Joint 3b the crack starts at an angle of 45 degrees at a position slightly away from the deepest point of the cut-out towards the end of the member. Figure 10b shows a clear stress concentration at that position. After having travelled at 45 degrees for 10-15mm the crack turns and follows the shortest distance through the cross section. Joint 4 did not fail in the joint but next to the hard point where the load is introduced. However, there was clear evidence of yielding of the steel in the corner and white spots in the laminate at the same location, indicating local failure of the laminate.

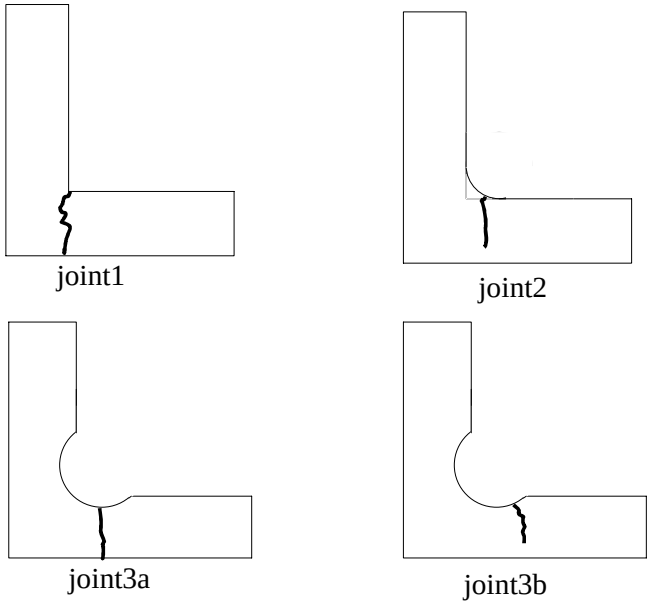


Figure 13: Typical failure modes for the joints

DISCUSSION AND CONCLUSIONS

It is important to realise that the finite element results shown in Table 1 indicate so-called first ply failure in the joints. Depending on the type of lay-up, first ply failure is normally not the same as the ultimate failure load of a structure under static loading. This difference has to be taken into account when comparing computer results with actual test results. In the case of the joints, local failure happens in the double bias and 90 reinforcements long before ultimate failure of the 0 plies. This early (local) failure results in the large discrepancy between the finite element results and the ultimate failure loads of the joints.

For reasons of comparison, the ultimate failure load of the members away from the corner was also determined. A hand calculation for lay-up 1a gives a failure moment of approximately 3.8 kNm, the failure moment for lay-up 1b is approximately 6kNm.

Based on these results, the average load carrying capacity of Joint 1a (2.07 kNm) is very reasonable, despite the theoretical infinite stress concentration. The load carrying capacity of Joint 1b (2.17) is slightly higher (5%) than that of Joint 1a, which is in agreement with the Tsai-Wu failure index for these joints.

The average failure load of Joint 2a (3.05 kNm) is very close to that of Joint 2b (3.14 kNm) as indicated by the finite element results. The book *'Formulas for Stress and Strain by R.J. Roark and W.C. Young'* [3] lists stress concentration factors for filleted right angle joints made of isotropic material. The loading on the joint is a combination of bending and shear which is slightly different from the pure bending moment loading considered in this paper. The stress concentration factor for a 50mm fillet in a joint with 150mm deep members is given as 1.65. This value seems to be reasonable for Joint 2b but does not correlate well with the results for Joint 2a. This indicates that without careful consideration, stress concentration factors determined for isotropic structures should not be used for fibre composite structures.

The difference in load carrying capacity of Joint 3a (2.2 kNm) and Joint 3b (3.03 kNm) is significant. Joint 3b can carry 38% more load for the same amount of reinforcement. The load carrying capacity of Joint 3b is also very close to that of Joint 2 which shows the effectiveness of the cut-out in reducing the stress concentration. The deflections of Joint 3b are significantly larger than those of Joint 2 which, depending on the application, could be an advantage or disadvantage.

Joint 4 is the strongest and stiffest of all joints. In cases where the use of small amounts of steel is not a problem Joint 4 has a lot of potential. Additional testing is required to increase the understanding of this solution.

The results of this research work indicate that the influence of the large stress concentration on the static load carrying capacity of the right angle joint is less severe than initially expected. Furthermore, it has been demonstrated that a significant increase in load carrying capacity can be obtained through small changes to the inside corner of the joint. The results also demonstrate that there is a reasonable correlation between the failure mode of the joints and the location and severity of the stress concentrations predicted by the FE method. However, there is a significant difference between the FE prediction of failure and the experimental failure loads. This is mainly due to the fact that the FE analysis predicts first ply failure rather than ultimate failure.

ACKNOWLEDGEMENT

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