# EXPERIMENTAL AND FINITE ELEMENT STUDIES OF ADHESIVELY BONDED LAP JOINTS FOR NATURAL FIBRE COMPOSITES

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## *Abstract*

*Little attention has been paid to joining unidirectionally reinforced high strength natural fibre composites. Therefore the main objective of the paper is to investigate the influence of joint geometry on the strength of joints. Epoxy bonded single lap shear joints (SLJs) between henequen and sisal fibre composite elements have been manufactured and tested to assess the strength of the structural bonds. The joints have been successfully modelled using finite element analysis and experimental measurements have been verified theoretically.*

*A second phase of the research concerned the performance of integrated joints, termed "intermingled fibre joints" (IFJs) and "laminated fibre joints" (LFJs). These joints are manufactured by intimately combining fibre bundles (IFJs) or laminating layers of fibre bundles (LFJs). These joint configurations possess much higher lap shear strengths than the single lap shear joints and the failure modes of the three joint configurations are compared.*

## 1 Introduction

The use of composite materials in the automotive and aerospace industries is constantly increasing due to their high strength and low weight. Natural fibre composite materials are being introduced into the manufacture of car components by companies such as Toyota, Ford, Mercedes Benz and BMW. There are two essential methods for joining composite materials. The first is mechanical joining and the second one is by adhesive bonding of the adherends.

Mechanical methods for assembling composite structures can cause stress concentrations around the holes of riveted or bolted joints and at the same time the introduction of rivets or bolts into the composite structure damages the continuous reinforcing fibres, affecting the overall load capacity of the structure. On the other hand, adhesive joints can be designed to meet specific load conditions. The main disadvantage of adhesive bonding of joints is their inability to be disassembled [1].

The quality of bonded joints is very important for the integrity of structures involving composites as unless all the parts are co-cured simultaneously, the inclusion of joints is unavoidable and stress concentrations are likely to occur. A structure comprising of many smaller bonded sections can offer more flexibility to the assembly process and reduce the overall cost of manufacture. The properties of the joints therefore become a critical factor as it is likely that the efficiency and integrity of the composite's structure is dependant on the joints rather than the composite itself, as it is likely that the joint will become the weakest part of the structure.

The literature reports many different joint configurations for composite materials. According to Zhou and Lesko [2], the most commonly used are single-lap, double-lap, lap strap, stepped and scarf joints. Other configurations have also been used, such as the joggle lap joint (widely used to bond aircraft fuselage halves, doublers and repair patches) and the L-section joints (used to join internal structures to outer skins of aircraft wings). In terms of joints for natural fibre composite materials, there is a lack of information in the literature.

Several studies have been conducted in order to analyse the mechanical properties and behaviour of adhesively bonded joints. Volkersen [3], presented a study on single lap joints considering shear stresses only. Goland and Reissner [4], extended this study by considering the eccentricity of applied load resulting in a bending moment. They obtained the normal peel stress in addition to the shear stress.

A model proposed by Hart-Smith [5], considered an adhesive line with elastoplastic behaviour and the author showed that the maximum load an adhesive bonded joint can transfer depends on the shear deformation energy of the adhesive line. This study gives a better prediction of the mechanical properties and behaviour of ductile adhesive layers. The geometric deflection effect in the overlap area was first introduced by Oplinger [6] to improve Hart-Smith's model. But four years later it was demonstrated that the solution was only valid for thin and flexible adhesives [7].

Standard un-jointed natural fibre composites (NFCs) were tested in tension by the authors of this paper in a previous study [8]. In the present paper, mechanical tests were carried out in order to analyse three different configurations of adhesively bonded joints. Single lap joints (SLJ) are widely known in the literature [9]. The other two joints are co-cured during the manufacturing process of the composite laminate itself. These joints are termed intermingled fibre joints (IFJs) and laminated fibre joints (LFJs). The latter two joints were chosen because it is believed that they would be an effective way of transferring the stress between two sections of NFC. At the moment, no studies have been published investigating these kinds of joints.

## 2 Experimental procedures

### 2.1 Materials and manufacturing methods

The adherends used in this investigation were manufactured using henequen or sisal fibres and an epoxy resin system. Henequen is a natural fibre extracted from a species of agave. It is closely related to sisal in terms of microstructure and mechanical properties and its more important uses are the manufacture of agricultural twines, cloths and sacks. The matrix component is based on Araldite LY 5052 and Hardener HY 5052. This epoxy system is well recognised for its good performance in aerospace and industrial composite applications and it was qualified by the German Aircraft Authority. For the SLJ, the same resin used for the matrix of the composite material was selected to bond the composite adherends together. The quality of the bonded joint depends mainly on surface preparation of the adherends. In order to get good bond strength and durability, it is required to roughen the contact surface, and to clean it of contaminants (mostly any wax, grease or chemicals resulting from the composite manufacturing process). A post cure cycle was followed in order to finalise the polymerization of the matrix. This process was carried out following the resin manufacturer's directions, [10].

The adherends were manufactured by hot compression moulding. The composites obtained have an aligned longitudinal fibre orientation in order to improve the tensile properties of the composite material.

Additional tabs of the same composite material were added to the SLJs in order to get symmetry. Then aluminium end tabs were also added in order to protect the integrity of the specimens from the grips before testing them in tension, Fig. 1.

IFJs and LFJs were manufactured by a co-curing process. This process is an efficient joining technique where the curing and joining processes are achieved simultaneously. An advantage of using this process is that surface preparation is eliminated, increasing the performance and reliability of the joint.

These types of joints (IFJ and LFJ) were produced by overlapping, or "intermingling" the fibres from two composite parts in the course of the curing process Fig. 2a. The finished joint consisted of two sets of fibres embedded in a matrix encompassing a region where the fibres from each side overlap each other (Fig. 2b); the principal function of this interface is to facilitate an efficient transfer of stress from fibre to fibre, across the matrix. The size of this overlap would likely determine the strength of the joint.

### 2.2 Specimen configuration and test method

The single-lap joint (SLJ), intermingled fibre joint (IFJ) and laminated fibre joint (LFJ) configurations are shown in Fig. 3.

Specimens were made in the SLJ configuration by cutting a strip of composite in half and overlapping the two halves to form a bonded lap joint. The SLJ configuration was tested with three different overlap distances (50, 30 and 15 mm), and 10 specimens of each were tested. For the IFJ and the LFJ joints, 12 specimens were tested per configuration, divided into four specimens for the 10 mm joints, four specimens for the 20 mm joints and four specimens for the 40 mm joints.

The adherend average thickness was 2.55 mm for the SLJ joint configuration. Since all of the adherends were composite laminates, the specimens were tested in tension according to ASTM D 3165, in order to determine experimentally the ultimate strength of the chosen joints [11].

All the mechanical tests were performed at room temperature on an Instron machine, model 1195, equipped with a 100 kN capacity load cell. The crosshead loading rate was 1 mm/min. The specimens were loaded in quasi-static tension in the fibre direction. For each test specimen, dimensions, failure load and location were recorded. After the tests, the fracture surface of each sample was photographed.

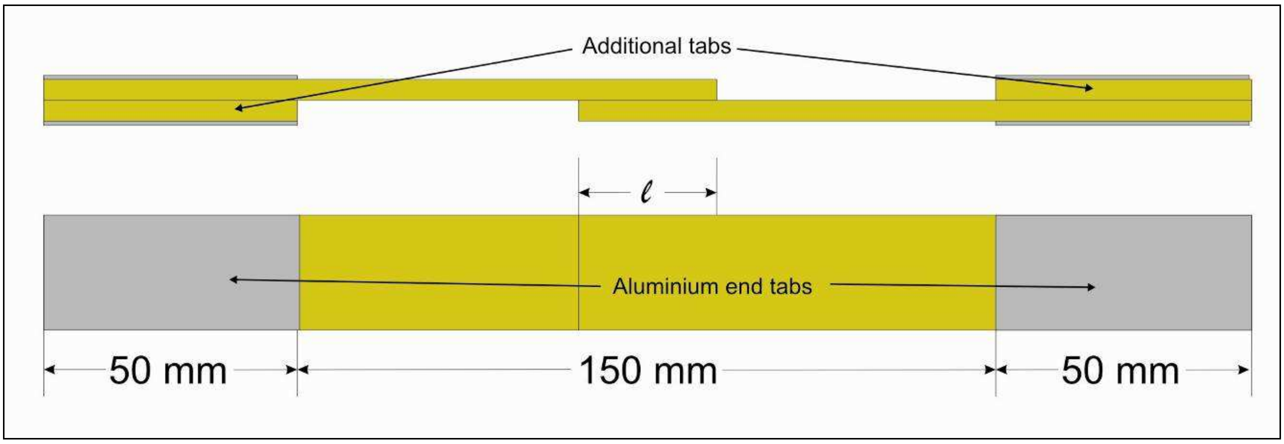

Fig. 1. Sketch of SLJ with additional and end tabs.

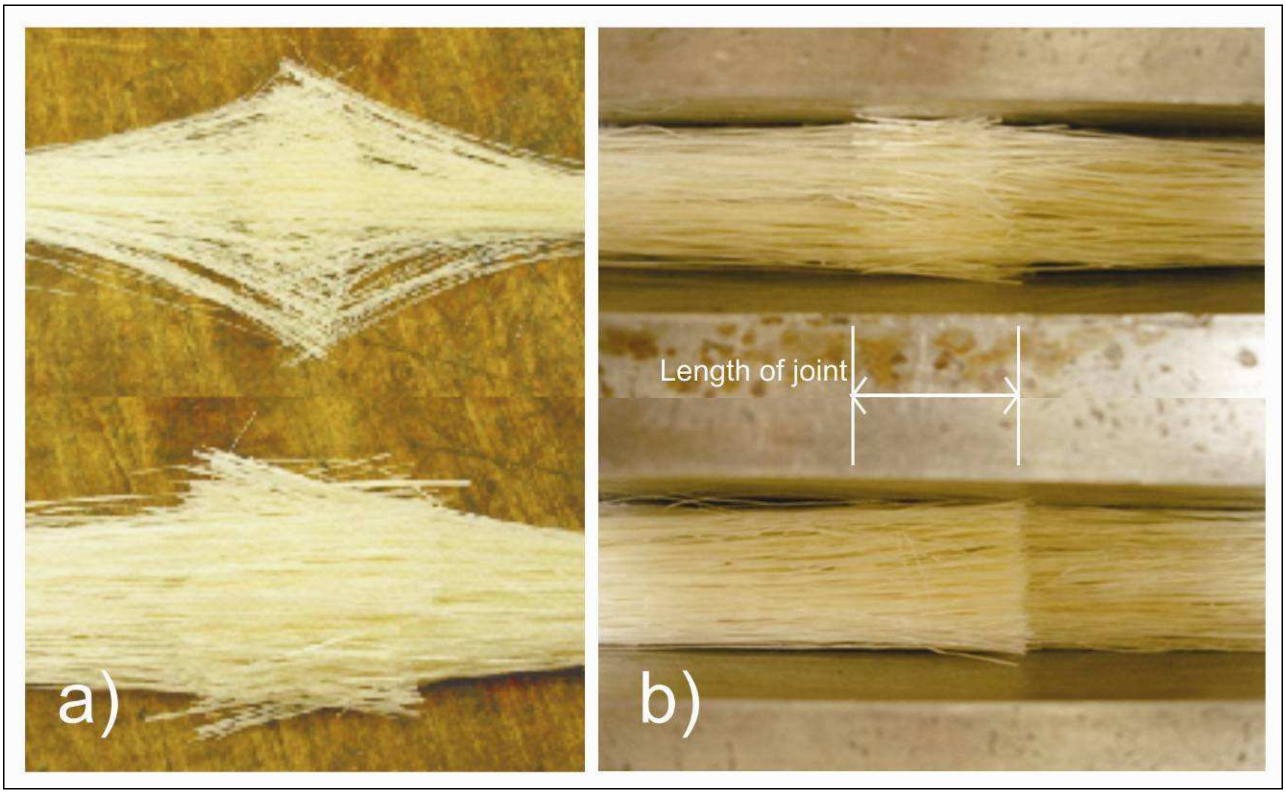

Fig. 2. a) IFJ joint preparation, b) IFJ and LFJ joint manufacturing process within mould.

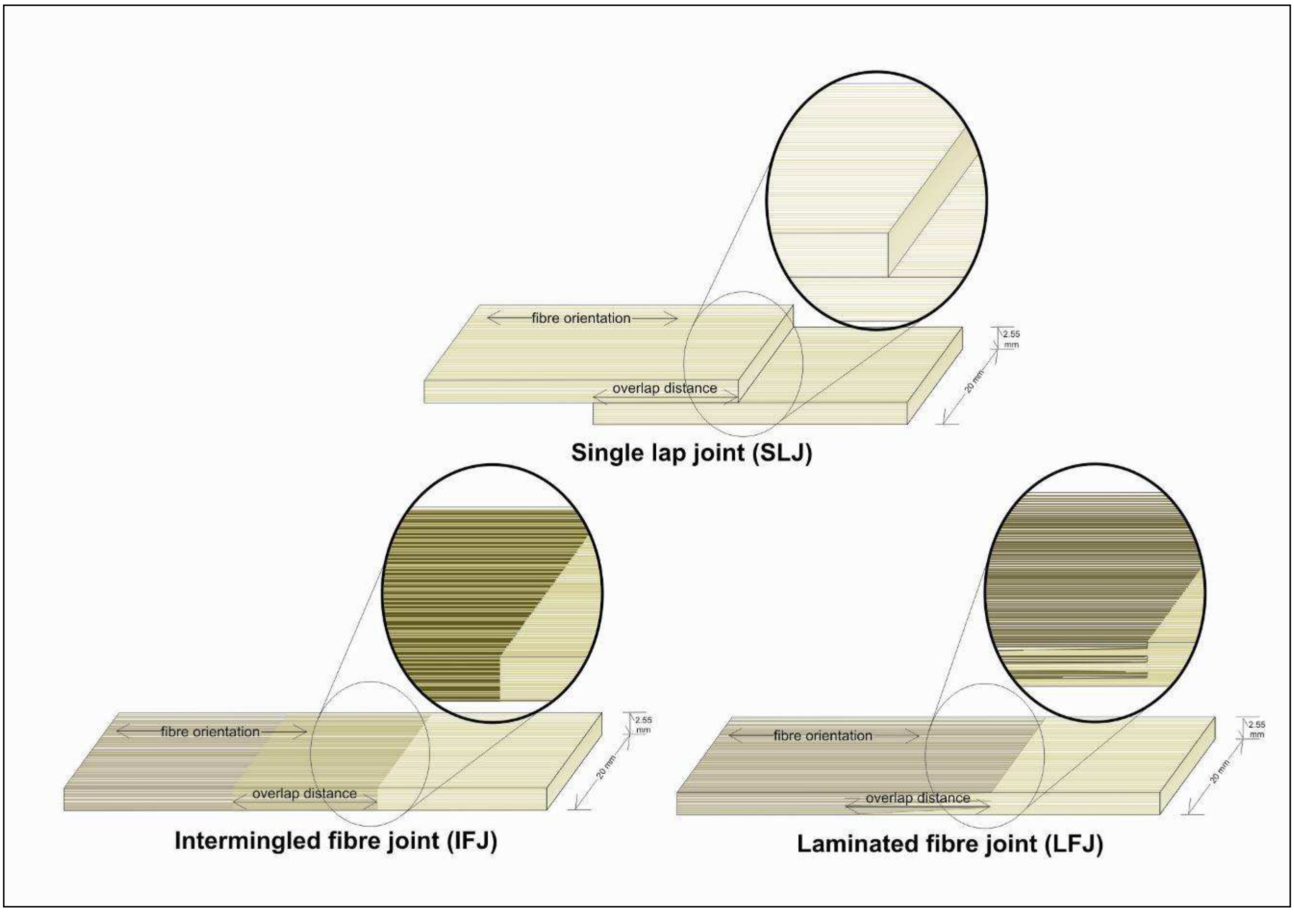

Fig. 3. Joint configurations.

## 2.3 Description of failure modes for SLJ

ASTM D5573 [12], classifies seven failure types in fibre reinforce plastic (FRP) joints. These failure types are listed below. The sixth class below is not relevant to the current study.

1. Adhesive failure, rupture of the adhesively bonded joint, such that the separation appears to be at the adhesive–adherend interface (sometimes referred to as interfacial failure).
2. Cohesive failure, rupture of an adhesively bonded joint, such that the separation is within the adhesive.
3. Thin-layer cohesive failure (TLCF), failure similar to cohesive failure, except that the failure is very close to the adhesive–adherend interface, characterized by a ‘light dusting’ of adhesive on one adherend surface and a thick layer of adhesive left of the other (sometimes referred to as interphase failure).
4. Fibre-tear failure (FTF), failure occurring exclusively within the fibre reinforced plastic (FRP) matrix, characterized by the appearance of reinforcing fibres on both ruptured surfaces.
5. Light-fibre-tear failure (LFTF), failure occurring within the FRP adherend, near the surface, characterized by a thin layer of the FRP resin matrix visible on the adhesive, with few or no glass fibres transferred from the adherend to the adhesive.
6. Stock-break failure. This occurs when the FRP substrate breaks outside the adhesively bonded-joint region.
7. The last class is called mixed failure where the failure is a mixture of different classes.

## 2.4 ANSYS model of SLJ

The SLJs have been modelled using finite element analysis (FEA) and the finite element (FE) simulations were compared with experimental results. ANSYS V.10 was used to simulate two and three dimensional models of the SLJs.

Variations in mesh density (Fig. 4), element order, boundary conditions, analysis type and material modelling were applied to optimize the accuracy of the FE model. For example a very fine mesh was used to model the adhesive bond line (Fig. 4).

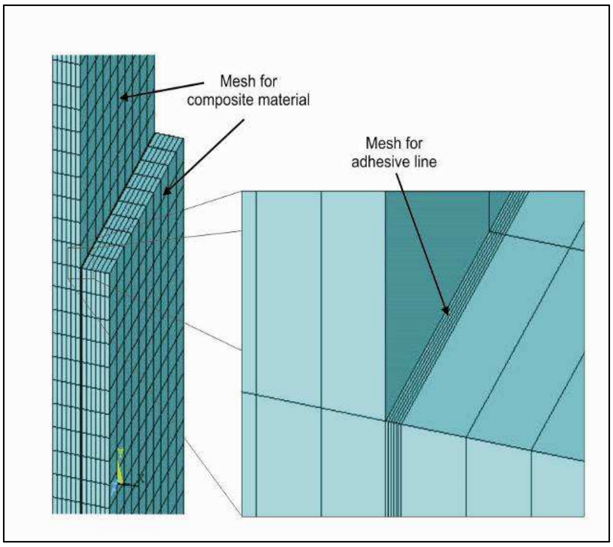

Fig. 4. Mesh for a 50 mm SLJ.

FE numerical simulations provided good predictions of stress distributions in the joints. The ability of FE software to capture three-dimensional effects such as secondary bending (Fig. 5 and Fig. 6) and the effect of overlap distances on stress distributions were evaluated. Fig. 5 depicts three LSJs with overlapped distances of 15mm, 30mm and 50mm. A virtual force of 5kN is applied in tension along the y-axis (specimen axis) and y-axis tensile stresses are plotted. Zones of concentrated tensile stress appear at the end of the overlapped region and because of the secondary bending effect the specimen on either side of the overlapped region experiences tension on one side and compression on the other. The zones of concentrated tensile stress increase in size as the overlapped region of the SLJ increases in area.

The x-y shear stresses (acting on the x face in the y direction) are plotted in Fig. 6 for the same geometries of overlap as for Fig. 5. High shear stresses at the two ends of each overlapped part of the specimen are visible as expected but as the length of the overlap increases the central portion of the overlap experiences less shear stress. Hence the failure mode is likely to be due the debonding of one end of the joint and the level of shear stress will become less dependent on the length of overlap as the overlap distance increases.

## 3 Results and discussion

### 3.1 Effect of joint configuration on tensile strength and shear strength

For comparison purposes, all test results, are summarized in Table 1. The conventional SLJs contain an offset shear zone whereas the IFJs and LFJs have an intermingled or interleaved jointed region. Hence the force to fail the specimens per unit area of unjointed cross-section is one way to compare joint performance.

It is clear that the IFJs are the most effective in transferring stress, especially at small overlap distances. For example the 10mm overlap IFJ is more than five times stronger than the 15mm SLJ. The LFJs become almost as strong as the IFJs as the jointed zone length increases.

A comparison may also be made between the average shear stress which develop in the overlapped zone. Here the peak force has simply been divided by the cross-sectional area of the overlapped joint, irrespective of joint design. In general short overlaps result in the highest average shear stresses. As the overlap distance increases the stress concentrations at the end of the overlapped zones have a strong influence on the shear strength and fracture initiates form stress concentrations visualized in Figure 3 in the SLJ FE model. For the LFJs the overlapped zones are at the level of the thickness of the laminations but for the IFJs the overlapped zones are of fibre bundle size (~120 microns). Irrespective of the dimension of overlaps, stress concentrations still exist. However the intermingling of fibres or laminating of fibre layers produces a much more effective joint.

### 3.2. Failure modes

#### *3.2.1 Single lap-joints*

During the tests, the applied load created a bending moment within the joints. Consequently, the induced normal stresses caused the initial damage in the joint system. Even though this effect was observed in all the specimens and also in the FEA model see Fig. 7, the joints remained together, accumulating damage until the maximum load was reached.

It can be seen that the failure mode is not adhesive (Fig. 8). In all the cases for the SLJs, the failure observed was the fibre-tear mode (type 4). This can be explained by the excellent quality of the surface preparation at the adhesive interface. It is believed that the epoxy interface is stronger than the henequen fibre-epoxy interface and as a result, the thin glue line covering the henequen fibres was not fractured.

### *3.2.2 Intermingled fibre joints*

IFJ joints seem to be very sensitive to the overlap length distance. This type of joints displayed the highest ultimate load. In terms of its configurations, the highest and the lowest ultimate loads were displayed by the 10 mm and 40 mm joints respectively. It was observed a very high fibre density in the overlap regions of the IFJ joints. This was probably caused by poor resin penetration into the fibre during sample manufacturing and could be the cause of the result discrepancies.

Scanning electron microscopy (SEM) was used in order to investigate the fibre packing within the IFJs. The transition between the fibre bundles in the joint, Fig 9 is clearly visible. This transition is more gradual than the transition presented in the LFJ. One possible cause could be attributed to the manufacturing process; it is inherently more difficult to position the fibres in the mould when using the merged method and so it is possible that there would be more variation in the end point of the fibres than when using the layered method where the fibres are laid on top of each other.

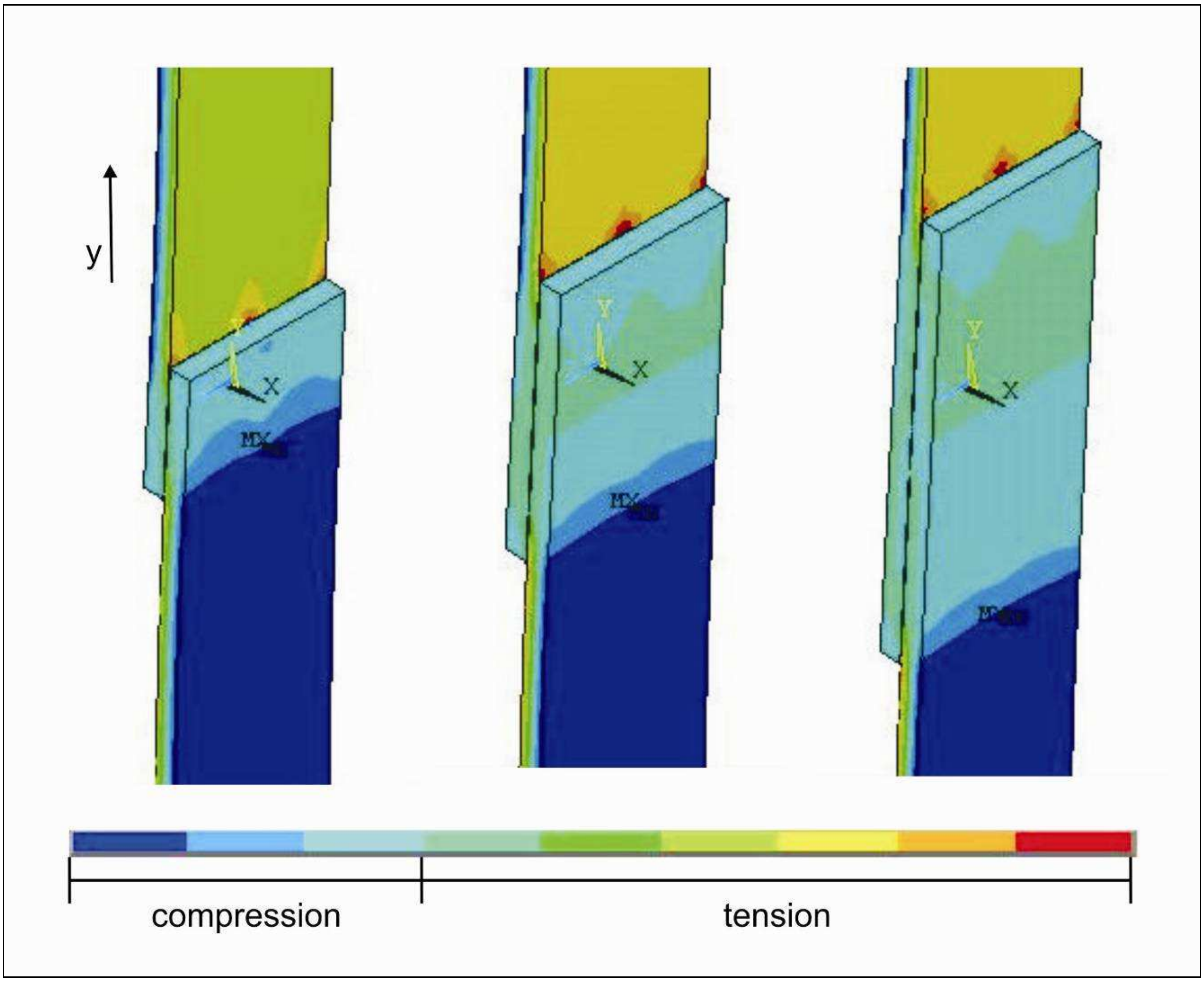

Fig. 5. Stress distributions along the y-axis for 15, 30 and 50mm SLJs loaded in tension.

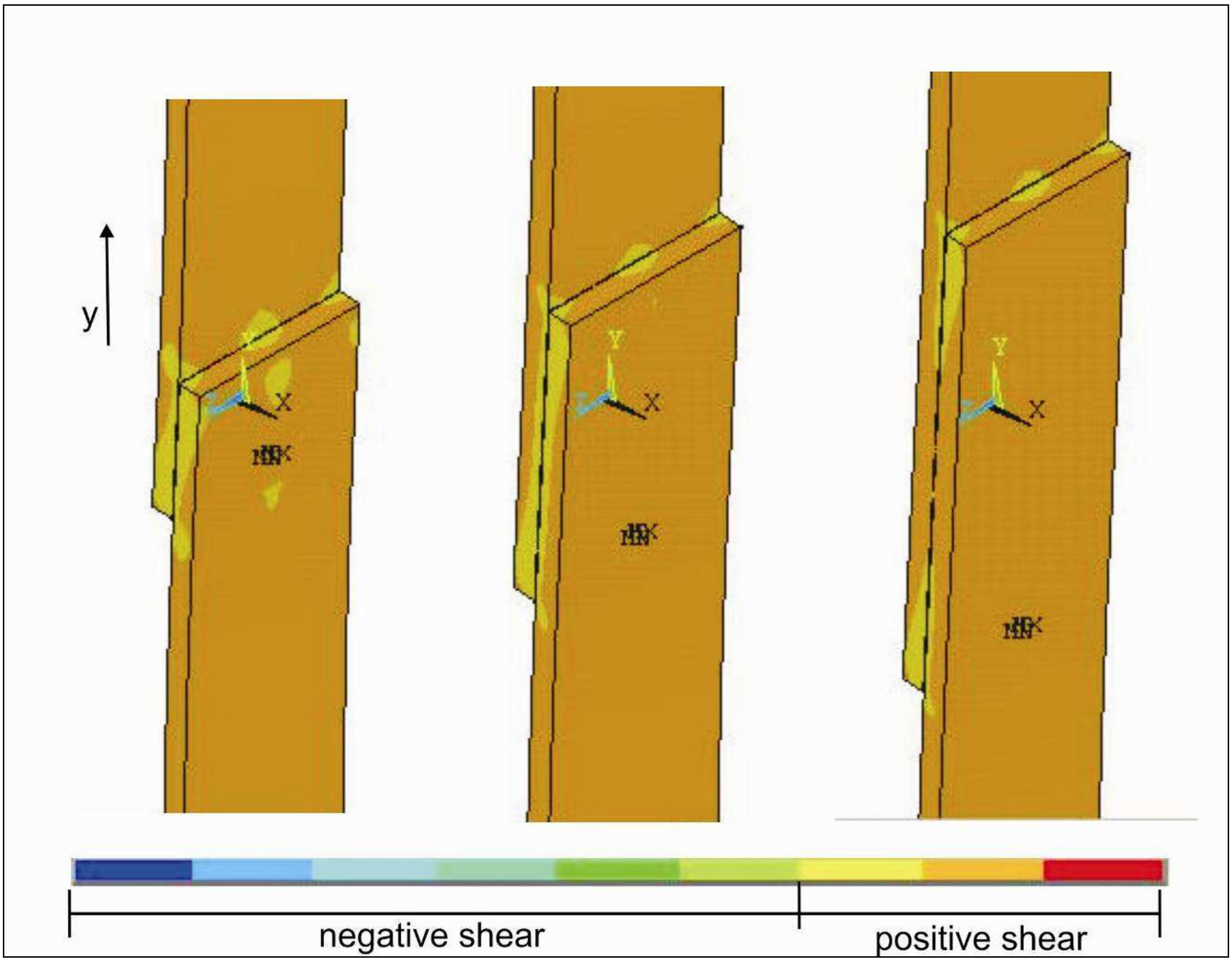

Fig. 6. Shear stress distributions (XY) for 15, 20 and 50 mm SLJs loaded in tension.

Table 1. Summary of mec.hanical properties of joints

| | No of spec tested | Mean max force (kN) | Mean tensile stress at failure $\sigma$ (MPa) | Std dev | Mean shear stress at failure $\tau$ (MPa) | Std dev |
|---|---|---|---|---|---|---|
| Std composite | 20 | 15.16 | 311.7 | 2.54 | - | - |
| SLJ 15 mm | 10 | 2.49 | 47.72 | 1.74 | 8.31 | 0.34 |
| SLJ 30 mm | 10 | 3.43 | 62.80 | 3.47 | 5.71 | 0.30 |
| SLJ 50 mm | 10 | 4.66 | 89.26 | 5.10 | 4.66 | 0.24 |
| IFJ 10 mm | 4 | 12.67 | 251.00 | - | 63.35 | - |
| IFJ 20 mm | 4 | 12.40 | 240.02 | - | 31.00 | - |
| IFJ 40 mm | 4 | 11.47 | 203.03 | - | 14.34 | - |
| LFJ 10 mm | 4 | 8.91 | 174.83 | - | 44.55 | - |
| LFJ 20 mm | 4 | 10.48 | 203.06 | - | 26.20 | - |
| LFJ 40 mm | 4 | 11.65 | 202.41 | - | 14.56 | - |

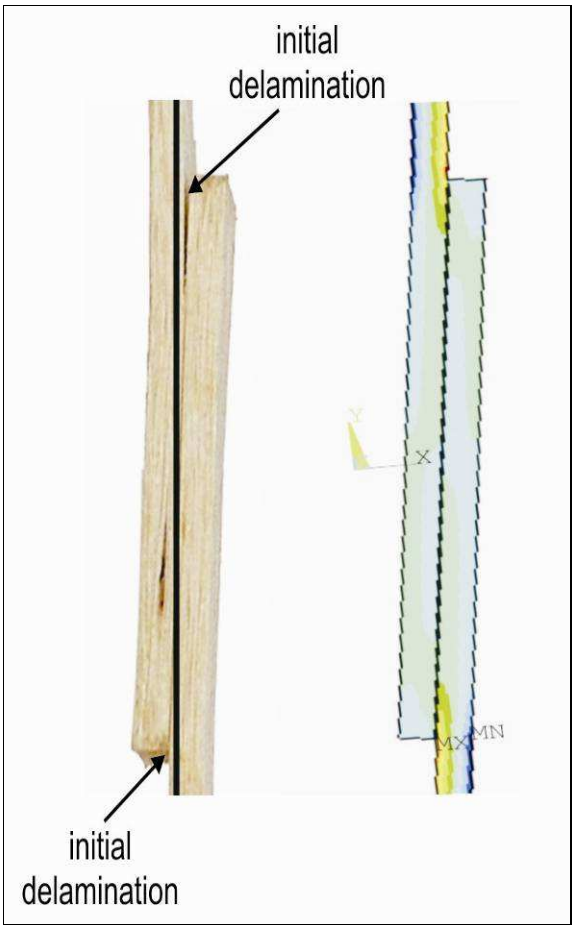

Fig. 7. Bending distortion in the overlapped zone of a SLJ loaded in tension (ANSYS).

Fig. 8. Fibre-tear failure mode.

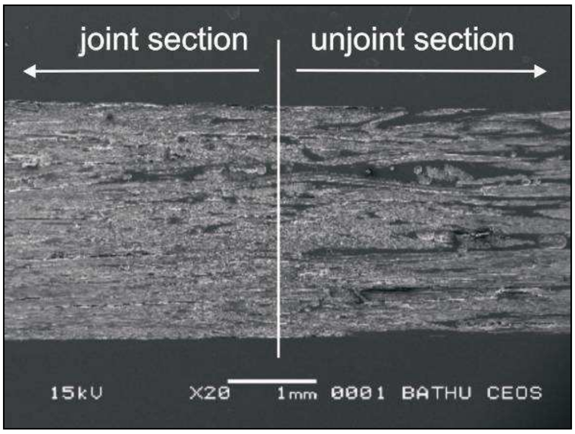

Fig. 9. SEM image of longitudinal section of the IFJ.

The failure mode of the 10 and 20 mm IFJ were similar to the failure mode of the un-jointed composites with a difference in the location of the crack initiation point, which for the IFJ initiated at the edge of the intermingled sections. Fibre delamination was also common where the crack initiated at the end of the intermingled section Fig. 10. A relationship between the scale of fibre delamination and the strength of the joint was evident. That is the less delamination, the stronger the joint. Again, this is probably related to fibre alignment.

Fig. 10. Typical failure mode of an IFJ.

The 40 mm IFJ displayed some differences to the other overlap lengths. In general these specimens had fewer, larger cracks instead of having more numerous smaller longitudinal cracks. The other main difference between this type of configuration and the others was that the crack did not initiate at the edge of the intermingled region but within a short distance away from the edge of the intermingled region (about 5 mm) Fig. 11.

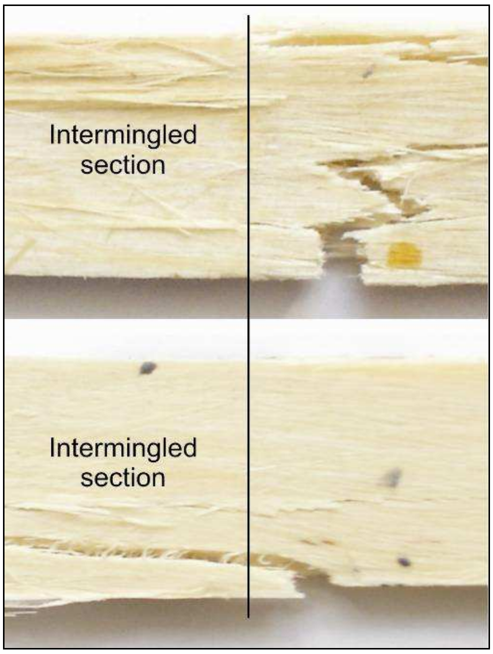

Fig. 11. Typical failure mode of a 40 mm IMJ.

### *3.2.3 Laminated fibre joints*

LFJ joints displayed lower ultimate loads than its IFJ counterparts, being the highest and the lowest the 20 mm and 10 mm joints respectively. Again as in the IFJ, the LFJ joints presented high fibre density in the overlap regions of the joint region.

SEM was used in order to investigate the composite structure. It was noted that the fibres were very densely packed at the joint section when compared to region outside of the joint. The transition between these two regions is clearly illustrated in Fig. 12.

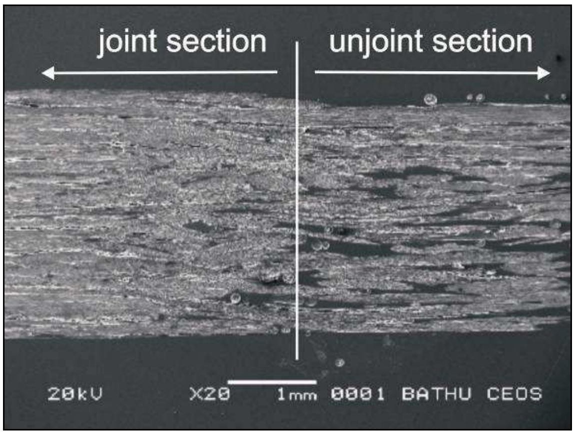

Fig. 12. SEM image of the longitudinal section of the LFJ.

The failure modes of the 10, 20 and 40 mm samples for this configuration were by delamination of the top layer of fibres, which broke away from the composite along the boundary of the intermingled region, Fig. 13.

Fig. 13. Typical failure mode of an LFJ

The failure modes of the IFJ and the LFJ were in a way similar because the failure initiation was in the overlap region. Because of this similarity, a comparison between the failure loads and the associated modes of the two configurations is possible.

The numerical analysis show that the IFJ configuration tends to eliminate eccentricity and lead to improvement of the mechanical behaviour of the joints. Tensile test results show that the failure load of the IFJ is much better that of the SLJ (see Table 1) and slightly better than the LFJ. It was expected failure load of the IFJ and LFJ to be significantly higher when increasing the overlap length as it happens with the SLJ configuration.

## 4 Conclusions

- The tensile behaviour of jointed henequen and sisal fibre composite laminates bonded by an epoxy adhesive has been investigated. This study has been conducted for three joint configurations: single lap joints (SLJs), intermingled fibre joints (IFJs) and laminated fibre joints (LFJs).
- For the SLJs, three different overlap distances were chosen, namely 15, 30 and 50 mm. For the IFJs and LFJs, the joint distances were 10, 20 and 40 mm for each configuration.
- In terms of ultimate tensile load, the IFJs and LFJs are comparable. On the other hand, the SLJ configurations fail at very low ultimate load.
- An important feature to report is that for all joint configurations, fracture is always the

result of crack propagation from the free edges. Any situation that favours crack initiation from the free edges will precipitate the crack propagation and hence, the joint rupture.

- For the IFJs and the LFJs, it was found that the ultimate load and displacement decrease when the overlap length is increased. On the other hand the opposite effect was observed in the SLJ configuration. For SLJs there is a large discontinuity at the ends of the overlapped region which results in high stress concentrations. However for the IFJand LFJs the shear contact is between fibre bundles is at the level of intervals of only a hundred microns up to a few hundred microns. Hence the concentrated stresses are diluted across many interfaces.
- The presence of dry resin areas on the surfaces of the composite joints was identified in some IFJ and LFJ specimens. This poor resin penetration into the fibres could be a cause of early fibre delamination and crack propagation during the tensile test. In the hot press the jointed zone contains twice as many fibres as in the rest of the specimen so adhesive content is accordingly reduced.
- The SEM images revealed that there was more evidence of the lay up process seen in the layered fibre composites than the merged. This favours the merged composite as a more gradual transition is likely to result in fewer stress concentrations. The layered composite is certainly not to be discounted though as there will exist many scenarios where it will not be possible to use the merged method, as in a right angled L or T joint, and so they will both be considered for further development.

## 5 Further work

Further work within this research programme will consist of developing a model based in ANSYS for the IFJs and LFJs. This model will permit us to establish closer predictions of natural fibre composite joint behaviours and fracture mechanics.

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