OPTIMISATION OF HIGHLY LOADED JOINTS

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Abstract

A simple evolutionary structural optimisation (ESO) procedure was employed for the shape optimisation of adherends in single (SLJ) and double lap joints (DLJ) and then modified to allow for the shape optimisation of metallic inserts into composite materials. The main goal of shaping the adherend profiles is to reduce peak stresses at the end of the overlap. The ESO method consists basically of removing the low stressed part of material progressively from the structure. A reduction of 36% (SLJ) and 17% (DLJ) in maximum peel stresses was obtained. Shear stresses were slightly increased in the SLJ by 2% but decreased in the DLJ by 8%. The aim of the shape optimisation of inserts is to reduce the high stress concentration factor present in mechanically fastened composite joints to increase their bearing strength. The modified ESO process consists in substituting the property of highly stressed elements; such as composite material in the bearing area; by aluminium in an iterative manner until an optimum has been reached. The optimised shape aluminium insert achieved a reduction in maximum compressive stress concentration at the laminate interface of approximately 54% when compared to a 4.2 mm circular insert of equal weight.

Introduction

Joints are sources of stress concentrations which diminish the overall efficiency of a structure. In strength critical components it becomes imperative to reduce these stress concentration factors so as to increase structural efficiency.

Stress concentrations in bonded joints arise from abrupt changes in adherend/adhesive thicknesses and from differences in elastic moduli(1). The evolutionary structural optimisation method (ESO) aims at reshaping the bonded joint to obtain fully stressed adherends, thus minimising the peak stresses at the end of the overlaps.

Fibre-reinforced composite materials can be considerably weakened by the introduction of holes. This can be attributed partly to the large stress concentrations that occur in the region of geometric discontinuities and partly to a lack of plasticity. The plastic behaviour found in isotropic materials, helps in reducing the effect of stress concentrations. Unfortunately, this forgiving phenomenon is not present in composite materials, at least at a macroscopic level. At a microlevel, microcracks and delaminations around bolt holes cause internal load redistribution, thus producing some softening of the material (2) . The proposed method, aims to achieve this stress and strain redistribution by providing a localised plastic zone in the vicinity of the hole.

Typically, the selection of an adequate joint requires a number of design and analysis cycles which rely heavily on the trial and error method. The ESO method relies for the cases presented in this paper on an iterative f.e.a analysis and progressive removal of elements (bonded joints) or property changes in elements (bolted joints) which takes the guess work out of the design loop. The objectives in both cases are to minimise the maximum stresses in the joints.

Adhesively bonded joints optimisation

A simple Evolutionary Structural Optimisation procedure (3,4) developed by G.P. Steven and Y.M. Xie has been employed for the optimisation of adhesively bonded joints by shaping the adherend profiles to reduce peak stresses at the end of the overlaps. The authors could find only one reference in the literature to the application of f.e.a shape optimisation to bonded joints (5). The ESO method consists basically of removing the low stressed part of the material progressively from the structure.

Firstly, a finite element analysis of the desired structure is performed and the stress distribution found. A plate stress file is then set-up and using some criterion for rejection, here called a Rejection Criterion (RC), such as the Von Mises stress, the low stressed material is removed. For example, elements which have a Von Mises stress lower than a Rejection Ratio (RR) times the maximum Von Mises stress in the structure are deleted. The finite element analysis and rejection cycle are then repeated until a steady state is reached. An Evolution Rate (ER) is then introduced and added to the current RR until another steady state is reached. This process is repeated until the desired optimum is reached, for example, till all stress levels are 20 % of the maximum in the whole structure. This procedure was applied to both single (SLJ) and double lap joints (DLJ). In these cases the overlap length and adhesive thickness were set as constants and only the adherends along the overlap were allowed to evolve. The shape of the adherends (SLJ) correlates very well to that obtained with a different optimisation program (5).

Analysis

The dimensions of the joint together with the loading and kinematic constraints are shown in Figure 1. A plane strain analysis with QUAD4 elements was employed. The load corresponded to a nominal shear stress in the adhesive of 1 Mpa and the materials had the following properties: aluminium adherends (E=70000 Mpa,υ=0.3); epoxy adhesive (E=2000 MPa, υ=0.3). The geometrical non-linearity present in single lap joints is not accounted for in the analysis. The starting models had square ended adherends. The optimum adherend shape (SLJ) is shown in Figure 2. The optimum rejection ratio was found to be RR=13.1 %, yielding a reduction in peel stress at the end of the overlap of approximately 36 %. The maximum shear stress increased by only 2 % and its peak was shifted inwards to the joint by one element (0.2mm).

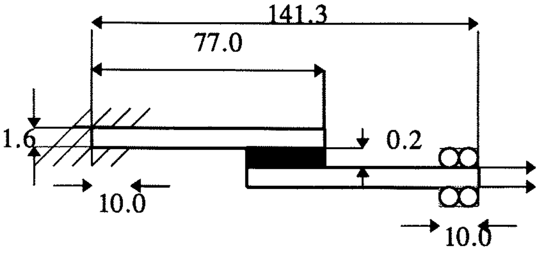


Figure 1: Geometry and boundary conditions of SLJ

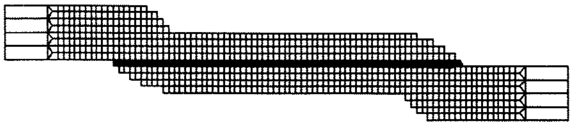


Figure 2: Optimum adherend profiling along overlap
(Single Lap Joint)

To obtain the optimum rejection ratio, the different design cycles had to be run independently and the stresses along the overlap compared for each cycle. In future analysis, the stresses along the overlap length will be obtained for each steady state thus reducing the post-processing of results considerably.

The shear and peel stress distributions vs overlap length for both original and optimised model are shown in Figures 3 & 4 respectively.

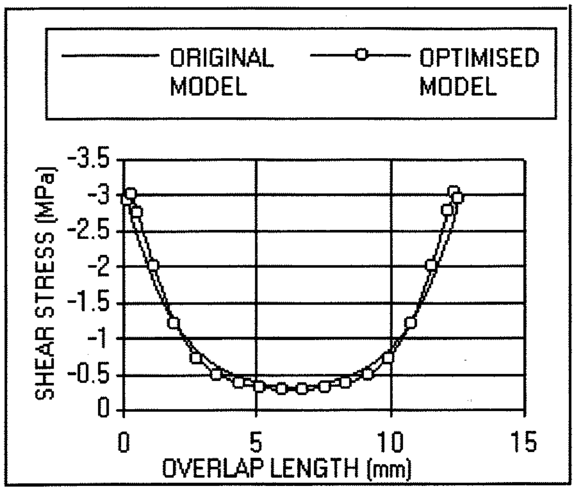


Figure 3: Shear stress distribution (SLJ)

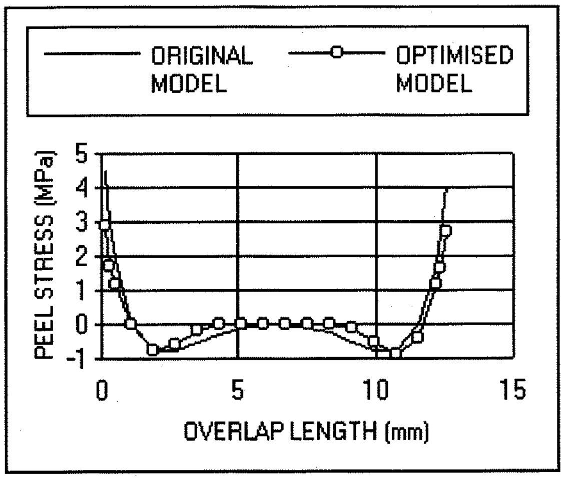


Figure 4: Peel stress distribution (SLJ)

The DLJ model was similar to the SLJ model, but with different boundary conditions as shown in Figure 5.

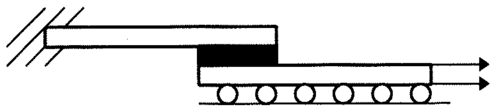


Figure 5: Boundary conditions for DLJ

For the DLJ a reduction in peel and shear stress of 17 % and 8 % respectively was achieved with a RR=16.4 %. In the DLJ case, only the upper adherend was allowed to evolve so as to keep boundary conditions due to symmetry. The optimum adherend shape (DLJ) is shown in Figure 6.

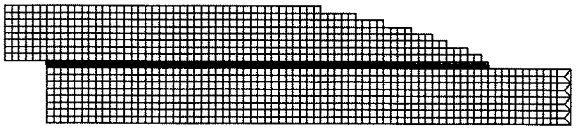


Figure 6: Optimum adherend profiling along overlap (Double Lap Joint)

The plotting of the shear and peel stresses of original and optimised model vs overlap length are shown in Figures 7 & 8 respectively.

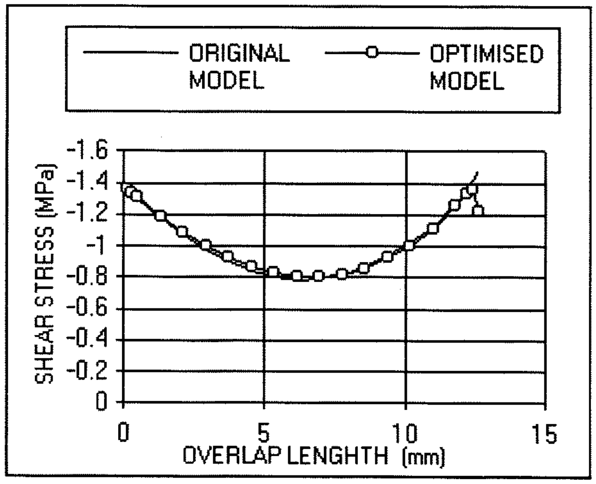


Figure 7: Shear stress distribution (DLJ)

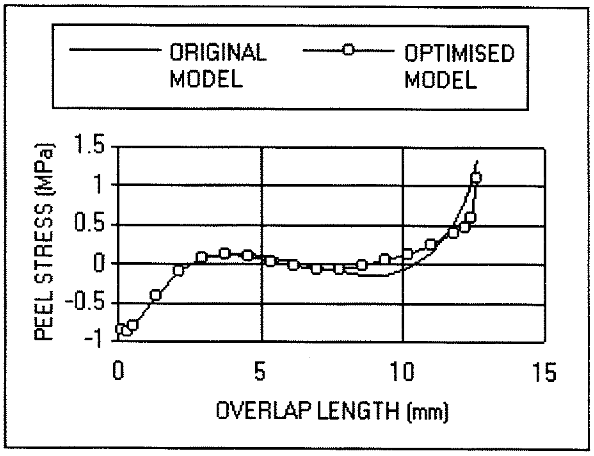


Figure 8: Peel stress distribution (DLJ)

Optimisation of pin-loaded joints

A theoretical and experimental investigation by Nilsson (6) on increasing the bearing strength of composite bolted joints, showed that by bonding a 2 mm circular metallic insert in the hole, the compressive stresses at the hole boundary were reduced by 50% and the failure load was increased by up to 55%. The use of isotropic inserts to obtain stress concentration relief in GFRP was also studied by Herrera-Franco et. al. (7) and proved to be successful in reducing the bearing stress by 75% in the bearing region.

To achieve a more efficient structure, it is proposed to optimise the shape of the insert by modifying the existing evolutionary structural optimisation method (E.S.O). The proposed method aims at reducing the compressive stresses at the hole interface and at creating a redistribution of stresses and strains in the vicinity of the hole thus maximising the strength of the joint. The modified ESO process consists of substituting the highly stressed elements iteratively until an optimum has been reached. The process differs from the original ESO in that material is not removed but modified, ie the material property is changed from composite to insert material. Elements will then have their properties substituted from composite material to insert material, where the Von Mises stress in the element is greater than a Substitution Ratio (SR) times the maximum Von Mises stress in the whole structure. The procedure is then identical to that described before with the exception that the ER is now subtracted to the current SR. The process is repeated until the SR becomes equal or smaller than the Termination Criterion, which could be for example when the stress levels at the interface between composite and insert material are 30% of the maximum in the whole structure.

From the above description of the method, it is seen that two parameters need to be defined. The first is the initial substitution ratio SR_0 and the second is the evolutionary rate ER. Typical values of SR_0=99% and ER=0.25% have been used for the present analysis, ie. after the first steady state has been reached, the new SR will be of 98.75%.

Analysis

The mesh employed and kinematic constraints are shown in Figure 9. The loading due to the bolt was simulated by introducing rigid beam elements in the points where the contact area was known and gap elements were employed closer to the ligament region. This was found to be necessary after running the same analysis with an assumption of a cosinusoidal loading which proved that the contact area varied as the insert grew. For the finite element analysis, a two dimensional model using 4 noded Linear Quad elements was employed and symmetry constraints were applied so as to analyse only half of the model. The width to diameter ratio was chosen to be approximately 11.5 and the edge to diameter ratio 7.85 to ensure a bearing type failure.

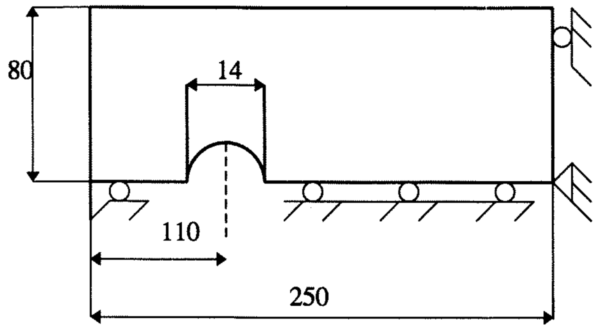


Figure 9: Dimensions and kinematic constraints

This was found to be necessary as earlier tests on smaller specimens failed in a net tension type failure. The properties for the composite material chosen for this study correspond to a quasi-isotropic laminate. Material properties used in the f.e.a are presented in Table 1.

	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	υ_{12}
Laminae properties	138.0	10.0	3.6	0.35
Laminate properties used in f.e.a	52.2	52.2	19.6	0.33
Aluminium	71.0	71.0	27.3	0.3

Table 1

The reasons for using a quasi-isotropic panel are mainly due to the low structural efficiency of bolted joints in highly orthotropic laminates.

The substitution criterion used to achieve the optimised shape insert was the Von Mises stress. The Termination Criterion was the size of the insert. This ensured that the optimised insert weighed the same as the circular insert for which a bearing failure was calculated.

Results

The results obtained from f.e.a for a loaded composite hole without insert, showed that the maximum compressive stress concentration factor at the hole boundary was -13.55 and occurs at $\alpha=0^{\circ}$ while the maximum tensile stress concentration factor was 10.7 and occurs at $\alpha=90^{\circ}$. As shown by Nilsson(6), these high stress concentration factors can be significantly reduced by enlarging the existing hole and placing a circular ring. The circular insert chosen had a wall thickness of 4.2 mm. This ensured a w/d and e/d ratio which should cause bearing failure. The analysis of the failure mode for different w/d and e/d ratios was carried out using the "BOLT" code(8).

The stress concentration factors present in the loaded composite hole without insert are then reduced to -6.2 at $\alpha=0^{\circ}$ and 2.7 at $\alpha=66.5^{\circ}$ respectively by the introduction of the circular insert. The proposed method of optimising the shape of the inserts achieved a further reduction in compressive stress concentration of 54% using the Von Mises stress as driving criterion. The corresponding compressive stress concentration factor at $\alpha=0^{\circ}$ is -4. The tensile stress concentration factor at $\alpha=90^{\circ}$ increased when compared to the circular insert by 60% but was still 140% lower than for the no insert condition. This higher stress concentration at the ligament region is acceptable as the objective is to decrease the compressive stresses at the composite interface where bearing failure occurs. When compared to a composite laminate without insert, the reduction in compressive stress concentration is larger than 230%. The Von Mises stress concentration was also reduced at the interface of composite/insert material by 89% when compared to the circular insert of equal weight.

A Graph of the Von Mises stress at the composite/insert interface is show on Figure 10.

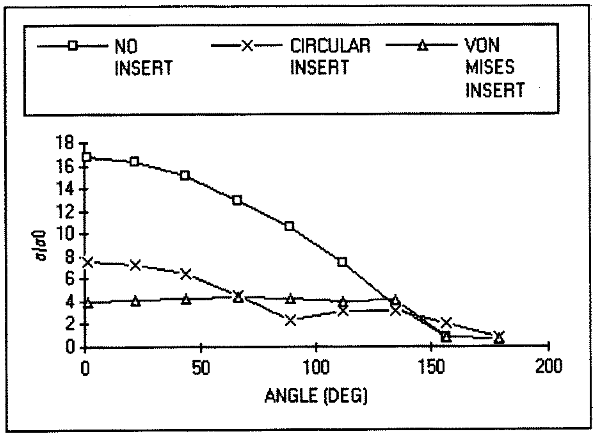
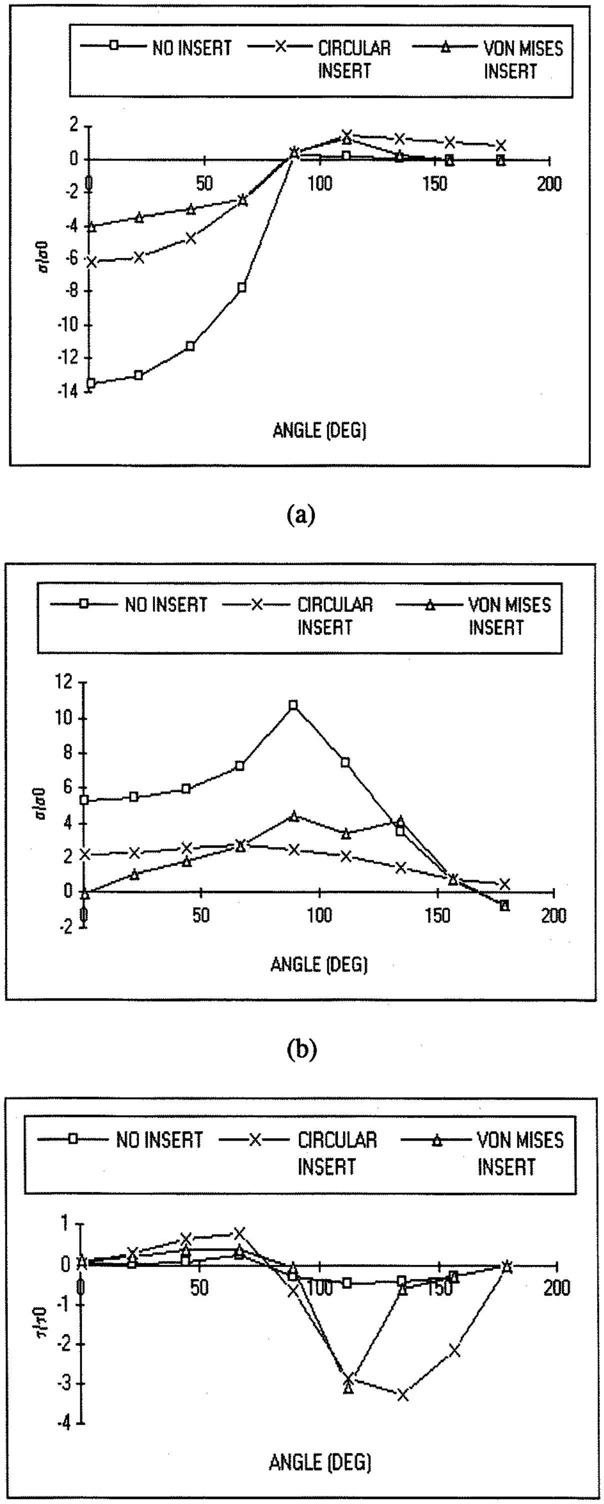


Figure 10: .Von Mises stress distributions at interface composite/insert

The radial, hoop and shear stress distributions are depicted in Figure 11. It is interesting to note from these graphs, that the substitution criterion used for the optimised insert produces an even distribution of the corresponding stress around the periphery of the loaded hole.



(a)

(b)

(c)

Figure 11: Radial (a), Hoop (b) and (c) Shear stress distribution at interface composite/insert

Manufacturing of pin loaded test specimens

Various alternatives were available to manufacture the metallic inserts. CNC machining was considered but found to be very time consuming and difficult to perform due to the required tolerances and the size of the inserts. Casting could become a good alternative if a very large quantity were to be manufactured. Extrusion of the desired shapes could also prove to be a cheap and efficient alternative of producing a large quantity of inserts. The chosen alternative was to have the metallic inserts wire cut. Although a relatively expensive alternative, a very good part was obtained with the desired tolerance in a small time frame and without the need to invest a large amount of capital. Furthermore, the cost was reduced by stacking the desired number of aluminium plates so as to obtain the same number of inserts. This resulted in one wire cut operation yielding six inserts of the particular shape. Both shapes of inserts analysed can be seen in Figure 12. The shape of the optimised insert was obtained by producing a dxf file from the final f.e.a solution. The coordinates of the points conforming the contours were then joined as splines and divided in arcs and lines using a CAD package.

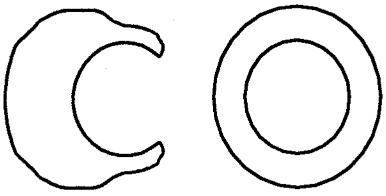


Figure 12: Von Mises insert (left), 4.2mm Circular insert (right)

The outer diameter of the circular insert was calculated using an average weight of the wire cut optimised inserts to ensure both the optimum and circular inserts would have the exact same weight. Laminates were fabricated from Fiberite HYE 3034K and the quasi-isotropic stacking sequence $(90/0/90/0/-45_2/+45_2/90/0/-45/45)_s$ was used, resulting in a laminate of 24 plies with an average thickness of 4.5mm. The composite panels were cut to the final dimensions (160 x 250 mm) using water jet technology. The cutouts with the corresponding shape including the circular holes were also cut using water jet technology. The metallic inserts were adhesively bonded to the composite panels with HYSOL EA9330.3 which possesses high peel and shear strength.

Testing program

Tests were performed on smaller type specimens with w/d and e/d ratios of 4 and 2.5 respectively. Details of the analysis performed for the above ratios and the different inserts shapes obtained can be found in a previous paper presented by the authors (9). Unfortunately, the failure mode obtained in most specimens with inserts was a net tension type failure, thus negating the use of any inserts to improve bearing strength. This is the reason of performing this new analysis on larger w/d and e/d ratios which will ensure a bearing type failure. Furthermore, future tests on the new configurations presented in this paper will not be conducted to failure. Strain gauges will be located in bearing critical areas and strain values will be compared for the no insert, circular insert and optimised insert condition.

Static tests will be performed on specimens with no inserts, circular inserts and Von Mises inserts. The tests will be performed at room temperature with load displacement and strain being recorded. The testing rig consists of a pair of steel plates which will load the high tensile strength steel bolt in double shear with the bolt mounted loose so as to simulate a pin-loaded condition.

Future Work

Multiple load case problems will be run for both bonded and bolted joints using the procedures described. For the shape optimisation of inserts, an "or" operator between load cases should be used as any element which has a high stress concentration on any of the load cases should be swapped to insert material. A test problem with 2 load cases has been run successfully using this technique. A failure analysis will be included within the optimiser to detect tension type failures. This could be used as the termination criterion ensuring that the insert only "grows" when there is an increase in overall efficiency of the joint. For the bonded joint optimisation it is clearly desirable that an element is removed if such element is lowly stressed for both load cases. This means that an "and" operator should be used for such analysis.

Conclusions and recommendation

Most work on optimisation of bonded joints has tried to achieve a uniform shear stress distribution along the overlap (10,11). In practice, a uniform shear stress distribution is not desirable due to creep considerations (12). In single lap joints, the most critical stresses are the peel stresses which are induced by the eccentricity of the load path. Similarly, the double lap joint also suffers from peel stress concentrations but in this case, the peak shear stresses are also important. The reason for this is that the double lap joint does not suffer from large bending moments in the adherend which are the main cause of peel stresses at the end of the overlap. The method presented in this paper, aims at reducing the maximum peak stresses at the end of the overlap. From the results presented, it becomes clear that the critical peak stresses are reduced for both the single and double lap joint, ie peel stresses in the SLJ and shear and peel stresses in the DLJ. This reduction in peak stresses will lead to an increase in joint strength and efficiency.

Several procedures can presently be employed to improve the strength of composite joints under loaded hole conditions. Most of these procedures are based on the incorporation of extra layers into the laminate in the holed region and although they are successful in improving the strength of the laminate, manufacturing costs are usually greatly increased. This confines such procedures to critical applications such as highly loaded lugs. Other procedures such as the incorporation of 45 deg fibres in the vicinity of the hole or local reinforcement with a stiffer fibre such as boron are also costly. The suggested method of incorporating an optimum shaped insert into a laminate could prove cost effective if such insert could be co-cured within the laminate. The 54% improvement in the capability of the optimised inserts in reducing the maximum compressive stress at the interface clearly shows that this procedure has potential in increasing joint strength.

Acknowledgments

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