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NUMERICAL SIMULATION OF THE MECHANICAL BEHAVIOR OF A REPAIRED SANDWICH BEAM USING A COHESIVE DAMAGE MODEL

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Abstract. Delamination caused by low velocity impact is one of the most frequent cases of damage in sandwich composite materials. In order to avoid premature replacement of components, repair techniques acquire more and more relevancy. Consequently, the development of suitable numerical tools to predict the behavior or repaired structure is fundamental. Using the ABAQUS® software the behaviour of a repaired sandwich beam subjected to four point bending is simulated considering a two dimensional nonlinear material and geometrical analysis. The two major repair configurations for sandwich structures namely overlap and scarf repair are studied. Interface elements were used to simulate the adhesive along all the bond lines. A trapezoidal mixed-mode cohesive damage model adequate for ductile adhesives is implemented in the formulation of finite elements. The interface elements allow to simulate crack onset and growth, as well as to obtain peel and shear stresses in the repair region. The main parameters concerning the good performance of the repair such as overlap length and patch thickness, in the case of overlap repair, and scarf angle, in the case for scarf repair, are studied in terms of stress analysis and strength predictions. Conclusions were drawn about design guidelines for the sandwich composite repair.

1. INTODUCTION

Sandwich materials are extensively used nowadays in transportation industries such as aerospace, aeronautical, railway automotive and marine industry. Their many advantageous characteristics such as high flexural resistance and stiffness, high impact strength, high corrosion resistance and low thermal and acoustics conductivity made them preferable over conventional materials for applications in satellites, large aircrafts, high speed trains, metro, bushes and navy's ship hulls [1]. The development of new materials, and the need for high performance, low-weight structures insure that sandwich construction will continue to be in demand. During the operational life of sandwich composite structures, damage caused by low velocity impact is very likely to occur. Low velocity impact can lead to delamination within the outer skin, or at the skin and core interface. Drastic reduction of the residual strength can occur, specifically under compression loads [2, 3]. Consequently it is necessary to develop repair methods so that costly components are not scrapped due to in-service damage. Moreover, considering current ecological requirements, repair becomes a major step for non-recyclable materials and enhanced product life. The repair of composite structures with composite patches may use several techniques, such as mechanical fastening or adhesive bonding. Bonded repairs are widely used in composite structures, taking over mechanical fastening methods because of the low weight penalty of the process and more uniform stress distributions. Basically, the repair procedure consists of two steps; removal of the damaged material and bonding of a patch. A primary issue in administering the repair is the attachment of the patch. Considering the repair techniques used in the case of composite laminates, in sandwiches, there are two major options available to bond the patch, namely overlap and scarf joining. In the overlap joining, a circular patch is applied external over the damaged zone. This kind of repair is temporary, being also used as a permanent for lightly loaded and low responsibility structures. On the other hand, scarf joining, in which a tapered circular patch is inserted in the damaged area and adhesively bonded, is more structurally efficient but also more expensive and time consuming. In all of the types of repair the main concerns are the prediction of the residual strength of the initially damaged composite and the durability of the repaired one. In fact, adhesive bonds require only minimal design to achieve substantial strengths, but require meticulous attention to produce durable and long lasting repaired joints [4]. The study of the durability of the joints involves the consideration of several parameters such as repair geometries, materials, loading conditions etc. A durability analysis requires reliable and efficient tools to obtain stresses, strains, and fracture parameters of bonded joints. Numerical methods provide a general tool to analyze arbitrary geometries and loading conditions. Among the numerical methods, finite element analysis has been extensively used with success; however, this kind of analysis requires the generation of a large set of data in order to obtain reasonably accurate results. This translates into a large investment in time and computer resources.

The work in this paper is dedicated to the study of overlap and scarf repairs of sandwich structures (Fig. 2) loaded under four point bending using the commercial software ABAQUS®. The objective of the simulations is to obtain stress distributions at critical regions and to evaluate the residual strength of the repaired beams using a trapezoidal cohesive mixed-mode damage model. This model, adequate for ductile adhesives, is incorporated in the ABAQUS® software via interface elements. The interface elements replace the adhesive along all the bond lines allowing to simulate damage initiation and propagation. The main parameters concerning the good performance of the repair such as overlap length and patch thickness, in the case of overlap repair, and scarf angle, in the case for scarf repair, are studied in order to asses their influence on the repair efficiency.

1. TRAPEZOIDAL COHESIVE DAMAGE MODEL

A cohesive mixed-mode (I+II) damage model based on interface finite elements was developed to simulate damage onset and growth. The adhesive is simulated by these elements, which have zero thickness. To simulate the behaviour of ductile adhesives, a trapezoidal softening law between stresses (σ) and relative displacements (δ_r) between homologous points of the interface elements was employed (Fig.1).

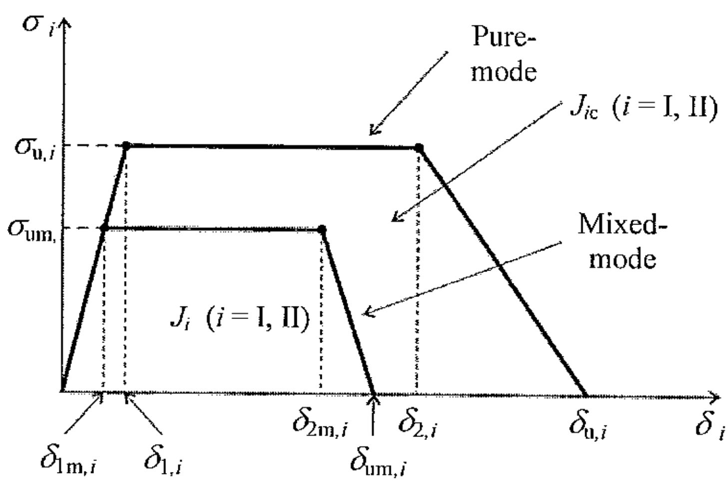


Fig. 1 - The trapezoidal softening law for pure-mode and mixed-mode.

The constitutive relationship before damage onset is

$$\boldsymbol{\sigma}=\mathbf{E}\boldsymbol{\delta}_{\mathrm{r}} \tag{1}$$

where **E** is a stiffness diagonal matrix containing the stiffness parameters e_i (i=I, II) defined as the ratio between the elastic modulus of the material in tension or shear (E or G, respectively) and the adhesive thickness t. Considering the pure-mode model, after $\delta_{1,i}$ (the first inflexion point, which leads to the plateau region of the trapezoidal law) the material softens progressively. The softening relationship can be written as

$$\boldsymbol{\sigma}=(\mathbf{I}-\mathbf{D})\mathbf{E}\boldsymbol{\delta}_{\mathrm{r}} \tag{2}$$

where **I** is the identity matrix and **D** is a diagonal matrix containing, on the position corresponding to mode i (i=I, II) the damage parameter. In general, bonded joints or repairs are subjected to mixed-mode loading. Therefore, a formulation for interface finite elements should include a mixed-mode damage model (Fig. 1). Damage onset is predicted using a quadratic stress criterion

$$\begin{cases} \left(\dfrac{\sigma_{\mathrm{I}}}{\sigma_{\mathrm{u,I}}}\right)^2+\left(\dfrac{\sigma_{\mathrm{II}}}{\sigma_{\mathrm{u,II}}}\right)^2=1 & \text{if} \quad \sigma_{\mathrm{I}}>0 \\ \sigma_{\mathrm{II}}=\sigma_{\mathrm{u,II}} & \text{if} \quad \sigma_{\mathrm{I}}\le 0 \end{cases} \tag{3}$$

where σ_i, (i=I, II) represent the stresses in each mode. It is assumed that normal compressive stresses do not induce damage. Considering equation (1), the first equation (3) can be rewritten as a function of the relative displacements

$$\left(\frac{\delta_{1\mathrm{m,I}}}{\delta_{1,\mathrm{I}}}\right)^2+\left(\frac{\delta_{1\mathrm{m,II}}}{\delta_{1,\mathrm{II}}}\right)^2=1 \tag{4}$$

where $\delta_{1\mathrm{m},i}$ (i=I, II) are the relative displacements in each mode corresponding to damage initiation. Stress softening onset ($\delta_{2,i}$) was predicted using a quadratic relative displacements criterion similar to (4), leading to

$$\left(\frac{\delta_{2m,I}}{\delta_{2,I}}\right)^2+\left(\frac{\delta_{2m,II}}{\delta_{2,II}}\right)^2=1 \quad (5)$$

where $\delta_{2m,i}$ (i=I, II) are the relative displacements in each mode corresponding to stress softening onset. Crack growth was simulated by the linear fracture energetic criterion

$$\frac{J_I}{J_{Ic}}+\frac{J_{II}}{J_{IIc}}=1 \quad (6)$$

When equation (6) is satisfied damage growth occurs and stresses are completely released, with the exception of normal compressive ones. Using the proposed criteria (equations (4), (5) and (6)), it is possible to define δ_{1m}, δ_{2m} and δ_{um} and establishing the damage parameters in the plateau region

$$d_m=1-\frac{\delta_{1,m}}{\delta_m} \quad (7)$$

and in the stress softening part of the cohesive law

$$d_m=1-\frac{\delta_{1,m}\left(\delta_{u,m}-\delta_m\right)}{\delta_m\left(\delta_{u,m}-\delta_{2,m}\right)} \quad (8)$$

A detailed description of the model is presented in Ref [5].

The adhesive used in this study was Araldite® 420, whose properties are listed in Table 1

Table 1 – Cohesive properties used to simulate the adhesive.

Adhesive (Araldite® 420)								
J_{Ic} [N/mm]	J_{IIc} [N/mm]	$\sigma_{u,I}$ [MPa]	$\sigma_{u,II}$ [MPa]	$\delta_{2,I}$ [mm]	$\delta_{2,II}$ [mm]	E [MPa]	ν	h [mm]
0.6	1.2	40	23.1	0.013	0.052	1850	0.3	0.2

3. ANALYSIS

The presented work consists of a two-dimensional non-linear material and geometrical analysis of a repaired sandwich beam subjected to four point bending considering plane stress conditions and rectangular 8-node and triangular 6-node solid finite elements available in the ABAQUS® library. Interface finite elements were used to replace the adhesive along all the bond lines. Two different repair configurations were simulated: overlap and scarf repair (Fig. 2). The faces and the patches of the repaired sandwich beams are considered unidirectional carbon-epoxy laminates with 0^0 orientation, the core in the form of foam and the adhesive a high resistant resin that undergoes large plastic strain prior to failure. Their mechanical properties are given it Table 2.

Table 2 – Mechanical properties of the materials used.

Skins and patches (carbon-epoxy)			Core (Divinicell H100, PVC foam)	Adhesive (Araldite® 420)
E_1=1.09E+05 MPa	ν_{12}=0.342	G_{12}=4315 MPa	E=111 MPa	σ_e=8.325MPa
E_2=8819 MPa	ν_{13}=0.342	G_{13}=4315 MPa	ν=0.1	E=1850 MPa
E_3=8819 MPa	ν_{23}=0.380	G_{23}=3200 MPa		ν=0.3

Geometrical details for both repair configurations are given in Fig. 2. Due to the symmetry of the problem, and in order to save on computer resources, only half of the beam was represented (symmetry line A-A in Fig. 2). Details of the mesh at the overlap and scarf region are shown in Fig. 3. The main objective is to obtain the geometrical parameters such as overlap length, patch thickness and scarf angle which allow minimizing the stress concentrations after repair for both the configurations considered.

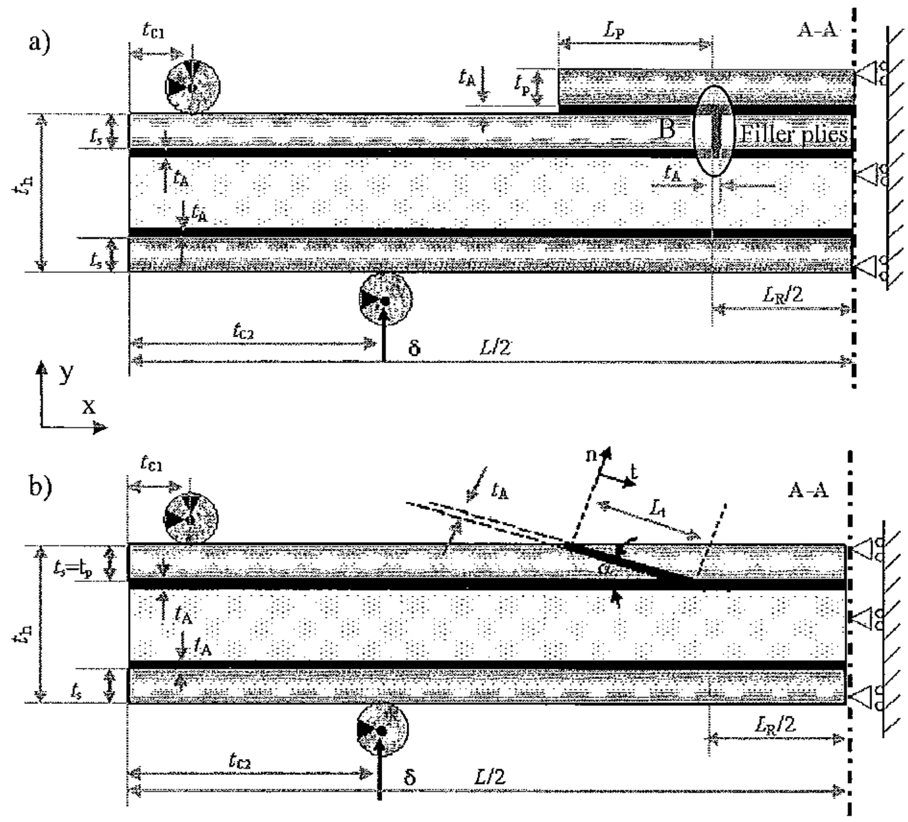
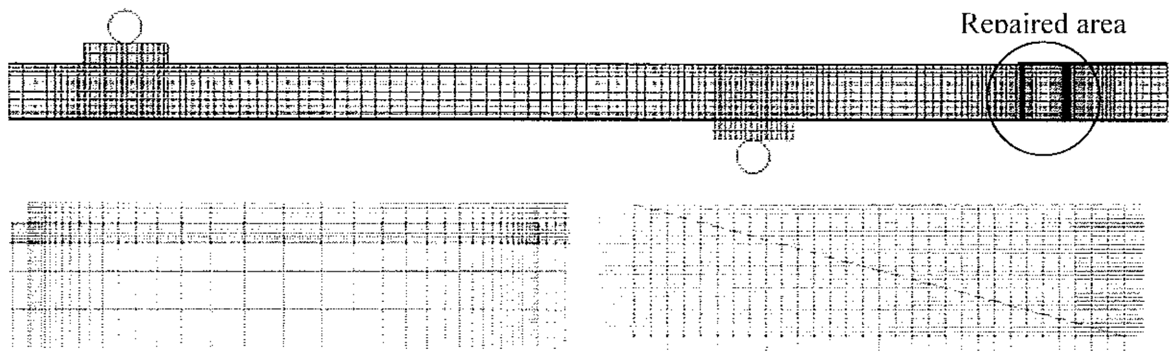


Fig. 2 – a) Overlap and b) scarf repair geometry.
t_h(thickness of the beam)=17.2mm; ts(thickness of the skins)=0.6mm; t_A(thickness of the adhesive)=0.2mm; t_p(thickness of the patch)=0.3-1.2mm, L(length of the sandwich beam =700mm; L_R(length of damage)=60mm; L_p(overlap length)=5-30mm, L_t(bond length along the scarf tangential direction); α(scarf angle)=3^0-45^0; t_{c1}= 35mm; t_{c2}= 225mm; A–A(symmetry line); δ(applied displacement); B(vertical adhesive bondline connecting the upper skin and the filler plies); t–n(local coordinate system).
* L_e(ply thickness)=0.15mm, w(width)=25mm.



a) b)

Fig. 3 – Finite element model of the repaired sandwich beam and details of the mesh for a) an overlap and b) a scarf repair.

3.1. Overlap repair

Stress analysis was performed initially for a 15 mm overlap repair using a 0.6 mm thick patch, equal to the thickness of the skins of the sandwich beam. The observed shear and peel stress distribution profiles along the overlap bond line normalized by τ_{avg}, the average shear stress along the overlap (Fig. 4), correspond to the typical ones obtained for these kinds of joints [6, 7]. Shear stresses present two peaks at the overlap ends while peel stresses present a compressive behaviour at the inner region near the overlap ends and two tensile peaks at the edges. Shear and peel stress peaks are higher at the beginning of the overlap signifying a point where damage is prone to occur.

Overlap length

One of the most important parameters that influence the joint residual strength is the overlap length. Six different overlap lengths were considered in the analysis: 5, 10, 15, 20, 25 and 30mm. In Fig. 4 the shear - and peel -stress distributions normalized to the average shear stress τ_{avg} of an overlap repair of 15mm, are presented for the different values of overlap length considered. It can be observed that the shear stresses along the bong line as well as the peaks at the extremities of the overlap increase at a non negligible amount for overlap lengths smaller than 15mm. Fig. 5 presents the failure load (P_f) and the efficiency of the repair (η) as function of the overlap length. η is considered to be the ratio between P_f of the repaired specimen and the failure load of an equivalent undamaged one. It is observed that the increase of the failure load and subsequently of the efficiency of the repair is higher for smallest overlap lengths, decreasing for overlaps higher than 15mm. The strength of the undamaged beam seems to be reached with an overlap repair of 18mm. After 20mm of overlap repair no further increase of the repair efficiency is obtained. This behavior is explained by the shear stress distribution at the adhesive (Fig. 4) since, as the overlap length increases, the inner region of the adhesive becomes unloaded.

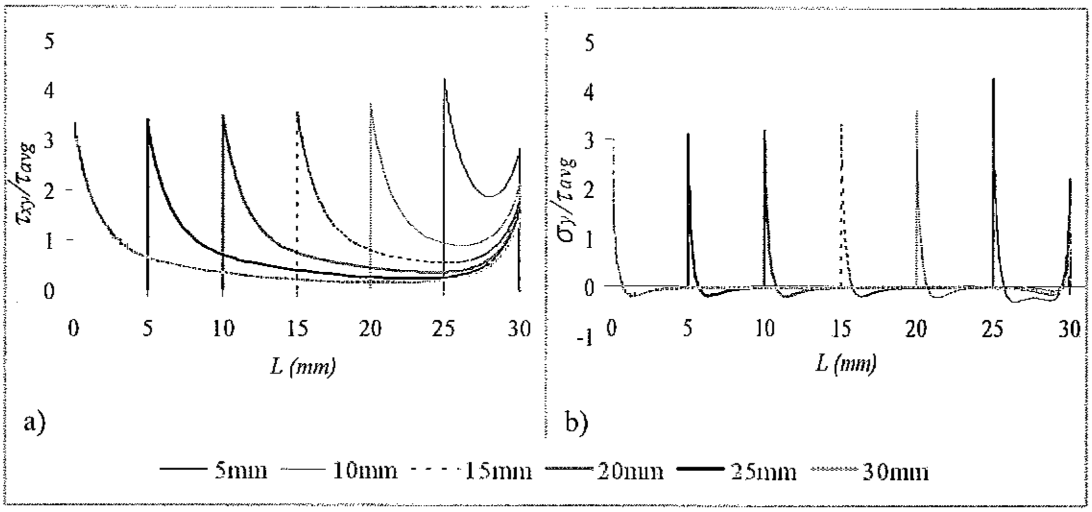


Fig. 4 - Normalized a) shear and b) peel stress distributions at the adhesive for different values of overlap length.

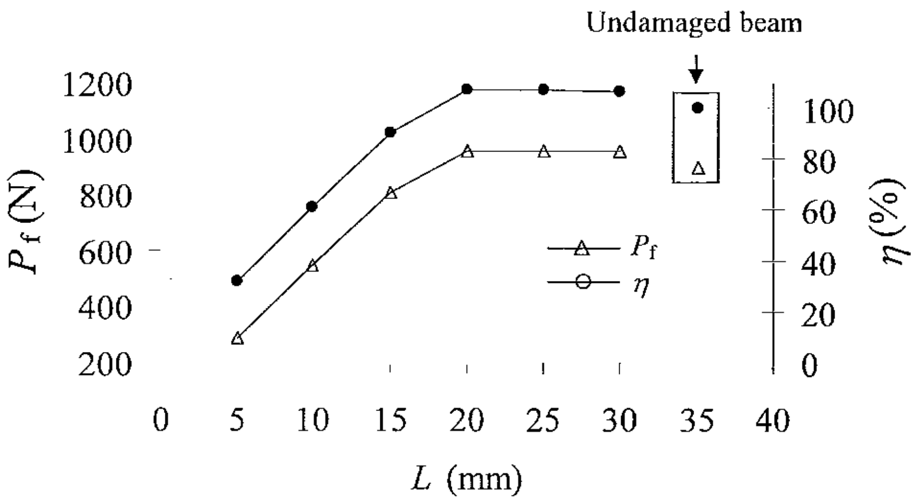


Fig. 5 -Failure load, P_f, and repair efficiency, η, for different values of overlap length.

Patch thickness

Analyzing the effect of the patch thickness, it is noticed that this parameter does not have a great influence on the repair efficiency (Fig 6). A slight increase on P_f when the patch thickness increases from 0.3 (2 plies) to 0.6 (4 plies) mm is observed. This increase on failure load is explained by the decrease of shear stress peaks at the end of the overlap. It is obvious that as the patch thickness decreases, the deformability of the joint increases leading to higher shear strains in the B region (Fig. 2). It is expected that for thin patches, the failure mechanism in the joint will no longer happen at the adhesive, but will occur by tensile stress failure of the patch. For patch thicknesses over than 0.6mm a decrease on P_f is observed. It was observed in the analysis and also verified by previous studies [6] that as the patch thickness increases, the peel peak stresses at the beginning of the overlap increase as well. In this specific case of sandwich structure, although failure always initiates at the vertical adhesive region (B, Fig. 2), high values of peel stresses lead to prior disbond of the patch. Very high values of peel stresses in the beginning of the overlap could also induce delamination between adjacent layers of the patch before shear failure in the adhesive takes place, which could limit even more the repaired joint strength [6].

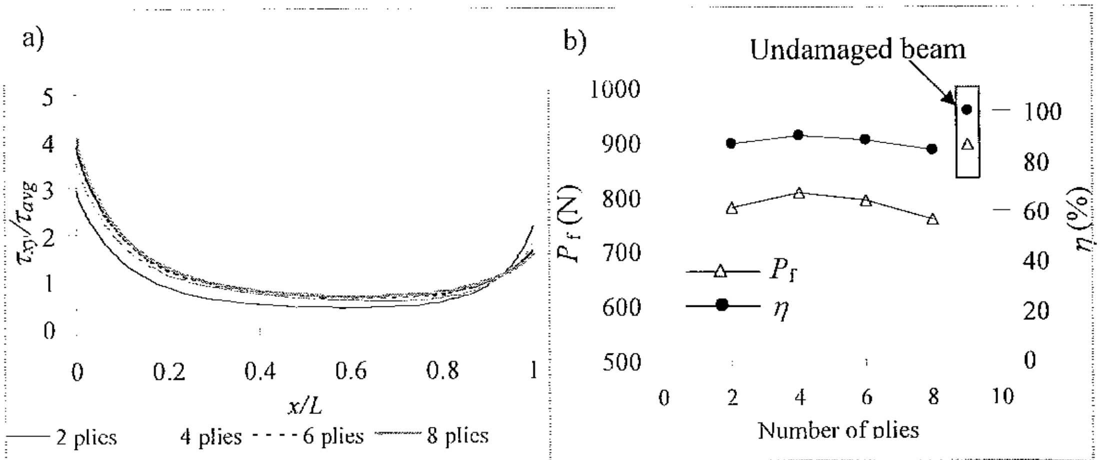


Fig. 6 - Influence of the patch thickness a) on shear stress distributions along the overlap length and b) on the repair efficiency, η, and failure load, P_f.

3.2. Scarf repair

The shear and peel stress distribution profiles along the scarf length can be observed in Fig. 7. In general, both stresses are positive and nearly constant between the bond edges. No stress concentrations are observed at the ends of the bond line.

Scarf angle

Peel- and shear-stress distributions are plotted for scarf angles of 3, 6, 9, 15, 25, 30 and 45°. Smaller scarf angles lead to a larger bond lengths and respective higher strengths of the repairs but they also lead to a larger repair area, which may not be possible in all cases. For lower scarf angles, failure of the adhesive is dominated by shear, with peel stresses increasing with the scarf angle [8]. Peel- and shear-stress distributions are presented in Figs 8 and 9, respectively, for the seven values of scarf angles considered. It is observed that peel stresses are much lower than shear stresses for smaller scarf angles, and increase up to a scarf angle of 45°, at which both stress components present approximately the same magnitude. These results are in agreement with the analytical results presented by Objois et al. [9]. It should be emphasized that shear- and peel-stress profiles are not influenced by the scarf angle.

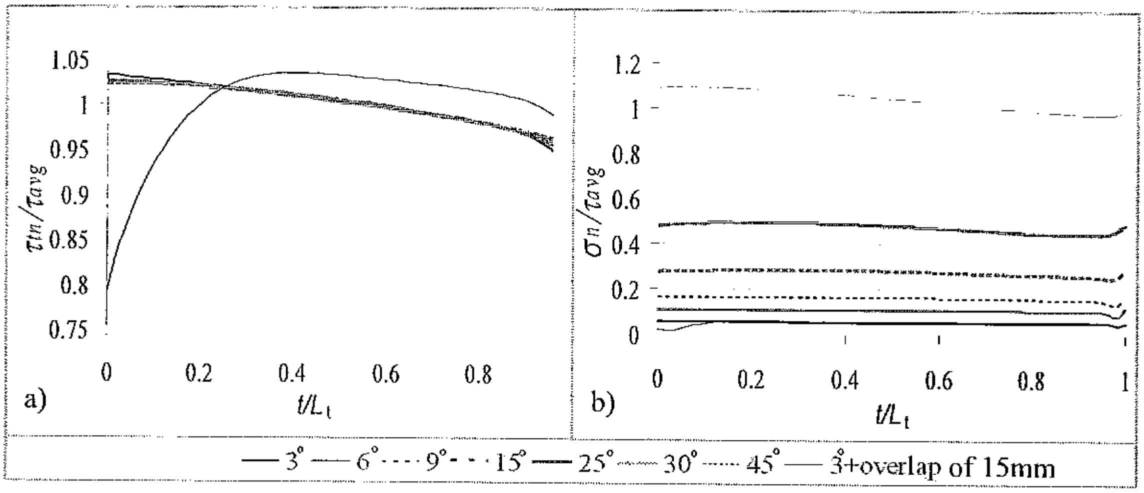


Fig. 7 - Normalized a) shear and b) peel stress distributions for different scarf angles along the normalized scarf length.

Fig. 8 presents the failure load (P_f) and the efficiency of the repair (η) as function of the scarf angle. For scarf angles ranging from 15 to 45°, only a small difference is observed in terms of P_f and η. For angles below 15°, these two parameters increase exponentially with scarf angle reduction. This fact is closely related to the increase of the bond length and reduction of peel stresses (Fig. 7b), as the scarf angle is reduced. A 69% efficiency is recorded for a 3° scarf angle, corresponding to a failure strength of 615 MPa. The exponential trend observed in Fig. 8 is consistent with that found in Refs [10, 11, 5] where experimental, numerical or both results are presented for scarf repaired laminates, although for different properties of the laminates and adhesive used.

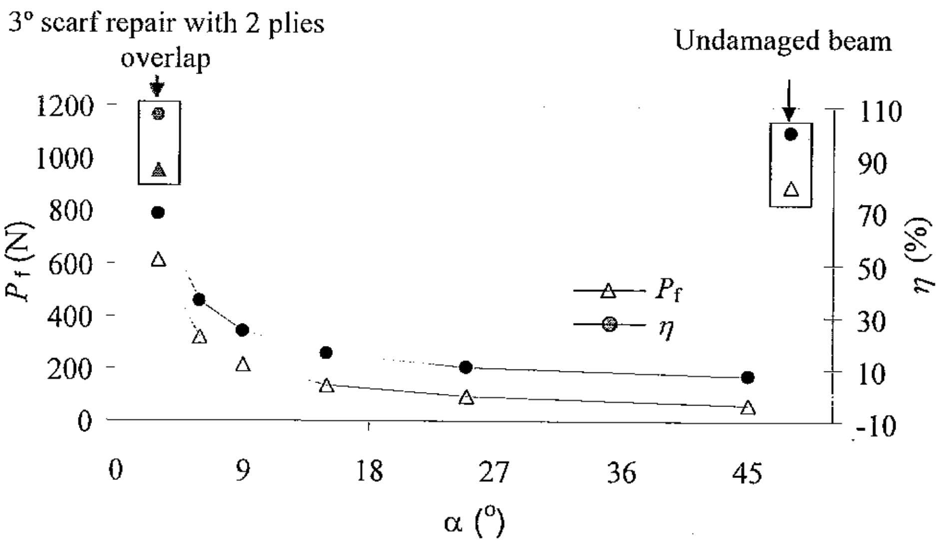


Fig. 8 -Failure stress and efficiency for the different scarf angles considered.

3.4. Scarf-overlap repair

A scarf-overlap repair is a combination of the repair methods described previously. A 3° scarf repair with a 2-ply patch of 15mm overlap was developed. The overlap patch protects the upper edge of the scarf repair where damage initiates. Its thicl α (°) very small (0.3mm) and for this reason does not influence significantly the aeroaynamic contour of the joint. A stress analysis (Fig. 7) showed that the shear stresses at the begging of the scarf are reduced drastically while the stress distribution along the bondline becomes more uniform. A slight decrease in the peel stresses at the beginning of the scarf is also attained with the use of the overlap plies. In Fig. 8 it can be observed that with the specific repair configuration more than 100% repair efficiency was achieved.

3.3. Damage growth

The damage onset was identified by simply observing the occurrence of softening onset at the nodes of the interface elements located at the singularity regions of the joint. In the overlap repair, it was observed that failure initiates in the vertical adhesive area which connects the skin with the filler plies (region B, Fig. 2) due to high pronounced normal stresses developed along the thickness of the adhesive. Once the vertical adhesive area fails, crack propagates at the interface between the plates and the core and a new crack starts at the left bond edge of the overlap and grows along the overlap bond line. This kind of failure was observed for all the overlap repairs studied, independently of the geometrical alterations considered. On the other hand, in scarf repairs the type of failure showed dependence on the scarf angle. For low scarf angles damage initiates at the upper edge of the scarf and grows along the adhesive due to higher shear stresses along the bond line. When the crack reaches the lower scarf edge it starts propagating along the interface between the skin and the core and between the patch and the core. For scarf angles higher than 15^0 the joint in the scarf area fails abruptly due to pronounced peel stresses along the scarf repair as indicated previously (Fig. 7). In the following, a crack propagates from the lower edge of the scarf to the interfaces between the composite and the foam. In the case of overlap-scarf repair geometry, damage initiates at the beginning of the overlap (singularity point) and grows along the overlap length. No detachment of the patch was observed for all the repair configurations.

4. CONCLUSIONS

The objective of this work was to analyze overlap and scarf repairs in composite sandwich materials, in terms of stress distributions and strength prediction using a trapezoidal cohesive mixed-mode damage model. The major geometric parameters for overlap and scarf repair were studied. One of the main findings of this work was related to the influence of the overlap length on the failure load of the joint. It was verified that after a certain value of overlap length, there is no strength advantage, since from a certain overlap length the central region of the joint becomes unloaded. It was also verified that extremely thin patches reduce the joint's strength as failure occurs prematurely in the vertical adhesive B region (Fig.2) connecting the skin to the filler plies. High values of shear strains are induced in this area due to higher deformability of the joint. It was also considered that in the case of thin patches, failure of the joint may occur due to tensile failure of the patch. For high values of patch stiffness, a slight decrease on the repair efficiency was observed due to the increase of the peel stresses at the beginning of the overlap leading to prior detachment of the patch. The strength of the undamaged beam seemed to be reached with an overlap repair of 18mm overlap having 0.6mm thickness, equal to the thickness of the skins of the sandwich beam. It was observed that the geometric parameters do not influence the failure mechanism of the joint. In the case of scarf repairs the strength increases with lower scarf angles because of the respective increase of the bond length, leading to an enhancement of the joint strength. For lower scarf angles, failure of the adhesive is dominated by shear. Peel stresses increase with the scarf angle. This fact influences the failure mechanism of the joint. The strength of the undamaged beam was not obtained for any scarf angle. Finally a combination of the aforementioned repair geometries was developed. It was verified that covering the upper edge of the scarf where failure initiates even with a thin patch, the repair efficiency increases exponentially. A combination of a 3^0scarf repair with a 15mm overlap patch of 0.3 mm thickness, leads to efficiency of 106%.

5. REFERENCES

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