MODELLING DELAMINATION CAUSED BY DEFECTS IN LARGE DIAMETER COMPOSITE CYLINDERS

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ABSTRACT

In the framework of the VEGA European small launcher programme it was necessary to assess the damage tolerance of composite solid rocket motor casings. Advanced manufacturing techniques have allowed the development of large diameter cylinders leading to mass and cost savings, but as for any composite structure defects may occur due to the manufacturing process or due to impact damage. In particular delamination at defect locations was an important failure criterion for the structure.

The Virtual Crack Closure Technique (VCCT) based on the fracture mechanics approach was adopted to model and predict the onset of delamination. The VCCT method has been around for a quarter of a century, but the application to large diameter cylinders with relatively thick walls had to be studied in detail. The VCCT is a method that calculates three strain energy release rates for interlaminar tension, interlaminar sliding shear and interlaminar scissoring shear at the delamination front.

An important aspect of the VCCT method was deriving the correct element size at the delamination front to ensure convergence of the strain energy release rates. Once an appropriate element size was ascertained and convergence verified it was possible to carry out sensitivity studies. Apart from the length and depth of the defect, the initial thickness or void can alter the results in terms of energy release rates.

Specimen testing of the specific layup is required to derive allowable values for the interlaminar tension and sliding. In addition a mixed mode failure criterion known as the power law is derived to predict the onset of delamination. Besides determining the allowable values, the specimen tests will be used to correlate FE models and the associated post-processing techniques applied.

This paper will outline the analytical approach adopted for the analysis of the VEGA solid rocket motor cases with the emphasis on modelling defects and predicting delamination onset using finite element techniques. The results will allow design improvements with respect to the layup to be studied and provide valuable input for determining an allowable defect size.

1. INTRODUCTION

VEGA shown in Fig. 1 is a small European launcher designed to deliver 300 to 2000 kg payloads into Polar and low Earth orbits. VEGA is a single body launcher, which consists of three solid rocket stages and a fourth liquid propellant upper stage. A very interesting feature for a small launcher will be the capability to deliver multiple payloads.

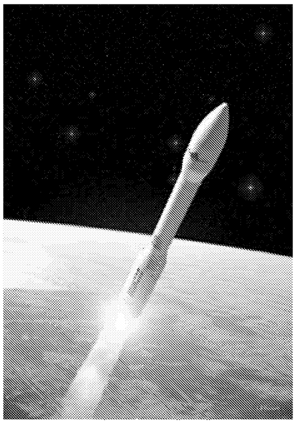

Fig. 1. Artist's impression of VEGA

The novel filament winding technology developed by Avio S.p.A has enabled casings to be manufactured up to three metres in diameter. The filament wound casing is thus also suitable for future evolutions of the Ariane 5 solid rocket boosters, leading to a significant reduction of mass and subsequent increase in payload capability. Further low-cost technologies being developed for the VEGA solid rocket motors include low density rubber for the internal insulation, low binder content and high

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aluminium percentage for the propellant, a simplified nozzle architecture, a consumable casing for the igniter and an electromechanical thrust vector control system using lithium ion batteries.

A number of failure modes were addressed as part of the structural analysis of the VEGA solid rocket motor cases, for example global and local buckling, ply failure and delamination. Delamination was already known to be a significant failure mode and the Virtual Crack Closure Technique (VCCT) described in section 2 was the most widely used method to assess delamination onset in composite structures [1-8].

2. VIRTUAL CRACK CLOSURE TECHNIQUE

To determine whether or not a defect will cause delamination the Energy Release Rate (ERR) at the crack tip must be determined. The energy release rate consists of three separate modes, namely tension, sliding shear and scissoring shear as shown in Fig. 2.

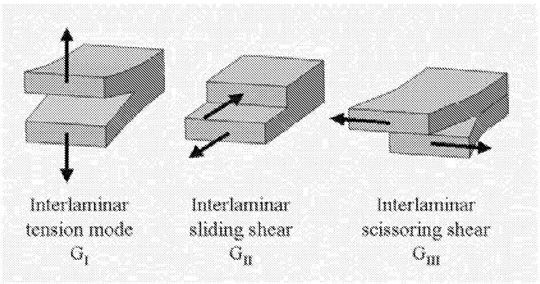

Fig. 2. Modes

The VCCT is based on the hypothesis that the energy released when a crack is extended by an increment Δa is equal to the work required to close it by the same increment Δa, as described by Eq. 1.

$$W = \frac{1}{2}\int_0^{\Delta a} \sigma(x)\delta(x)dx \qquad (1)$$

In additional it is assumed that the geometry at the crack tip remains constant after the crack has been extended by Δa. The latter is justified for a small Δa. The benefit of the additional assumption is that it reduces the computation of the ERR from two separate analyses to a single analysis. Eq. 1 can be modified to obtain Eq.2.

$$W = \frac{1}{2}\int_0^{\Delta a} \sigma(x)\delta(x+\Delta a)dx \qquad (2)$$

The equations to compute the ERR modes can be obtained by integrating Eq. 2 and the separate ERR components may be described in terms of stresses or forces. Eq. 3 shows the resulting components in terms of forces.

$$\begin{aligned} G_I &= \frac{1}{2\Delta A}\cdot F_Z(w_2 - w_1) \\ G_{II} &= \frac{1}{2\Delta A}\cdot F_X(u_2 - u_1) \\ G_{III} &= \frac{1}{2\Delta A}\cdot F_Y(v_2 - v_1) \end{aligned} \qquad (3)$$

The analysis requires extraction of the forces (F_X, F_Y, F_Z) or stresses at the crack tip and the displacements (u, v, w) of the two adjacent nodes. Fig. 3 shows an exploded view to illustrate the geometry and results obtained from the FE analysis. The shaded area ΔA is the area given by Δa multiplied by the element width at the crack tip.

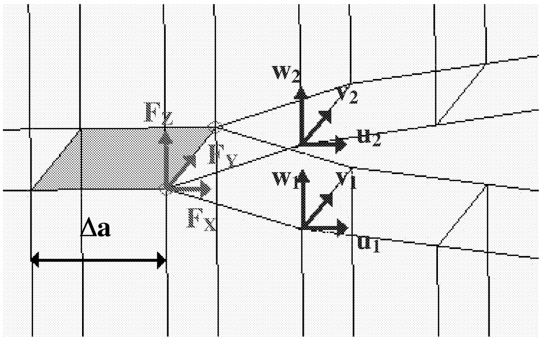

Fig. 3. Details at the crack tip

The robustness of the method relies on a number of complications that have to be addressed, for example convergence, contact between cut layers, local coordinate frames at the crack tip and corrections for elements of varying length or width at the crack tip.

Once the components have been obtained, the delamination growth criterion has to be evaluated. A few of the different criteria proposed in literature were the linear criterion, bilinear criterion and the power law criterion. The power law criteria defined by Eq. 4 appeared to be the most appropriate. Growth occurs if the relationship shown in Eq. 4 is satisfied. Full failure was assumed if delamination growth occurred and hence propagation was not considered.

$$\left(\frac{G_I}{G_{IC}}\right)^{\alpha} + \left(\frac{G_{II}}{G_{IIC}}\right)^{\beta} + \left(\frac{G_{III}}{G_{IIIC}}\right)^{\gamma} \geq 1 \qquad (4)$$

3. SOLID ROCKET MOTOR SKIRT LAYUP

The discussion will be limited to the 2nd and 3rd stage Zefiro solid rocket motor skirts under a compression load, which was one of the main areas of interest. The skirts were a combination of filament wound hoop layers and hand lay-ups. The Zefiro skirt laminates were approximately 8 to 10 mm thick, but as the design process is ongoing and partly as a result of current analyses the layup is continuously evolving.

4. MODELLING

Two independent methods were used for the Finite Element (FE) modelling and analysis of delamination onset, because the complexity and the relatively recent introduction of the VCCT method in industry warranted an independent verification of the modelling. A 3D model was created with MSC NASTRAN and an axisymmetric model was created in MARC.

The axisymmetric model had many benefits in terms of nonlinear analyses and computation time compared to the NASTRAN model, which required a very large number of degrees of freedom mainly due to the size of the elements at the crack tip region. The NASTRAN model was used to verify the results and the convergence, whilst the MARC model was also used to select the maximum allowable delamination size on the Zefiro's skirt. In section 7 an overview of the adopted procedure to define the acceptance defect range is given.

4.1 NASTRAN FE Model

The model consisted of multiple layers of solid elements. To avoid time consuming modelling a parametric file was created using the Patran Command Language (PCL). The PCL function allowed the depth, length and initial opening of the defect to be varied. The ERR results were derived from the NASTRAN output by means of an awk script.

The NASTRAN models were mainly local sections with dimensions of approximately 50 mm by 17 mm, which was equivalent to an angle of approximately one degree.

The loads were applied by means of rigid body elements. The boundary conditions were applied such that the bottom was fixed in the translational degrees of freedom whilst the sides were constrained in an axisymmetric fashion.

The detailed modelling at the crack tip and having solid elements for each individual layer caused the total number of degrees of freedom to become very large. Therefore the model was almost entirely restricted to use for linear analyses.

The full skirt models that were used to assess nonlinear behaviour, buckling of layers and ply stresses for the full skirt configuration and boundary conditions were created with an axisymmetric model using MARC.

4.2 MARC FE Model

A global-local approach has been used to model the composite case delamination growth phenomena [1]. The local model represents the portion of the skirt around the delamination and is within the region from the dome tangent line up to and including the metallic flange as shown in Fig. 4.

Four-nodes axisymmetric elements (10 of the MARC library) were employed to model both the metallic and composite parts of the skirt.

Sine shaped delaminations were modelled and contact surfaces between the two sub-laminates were introduced in order to avoid any possible interpenetrating phenomena. The basic assumption of the axisymmetric modelling was that delamination occurred along the whole circumferential direction.

A nonlinear incremental analysis was performed up to the collapse load in order to estimate the Safety Factor (SF) with respect the onset growth.

Due to the nature of the element formulation the composite properties could not be assigned directly layer-by-layer, so the equivalent orthotropic properties were applied and assigned for homogeneous lamina orientation.

Boundary conditions coming from the global model (see Fig. 4) are imposed at the dome tangent line end of the local model whilst at the other end (metallic flange side) all degrees of freedom were constrained. A Fortran 77 subroutine has been linked to the main MARC source code in order to extract and manipulate crack tip forces and displacements to find the basic energy release rate contribution.

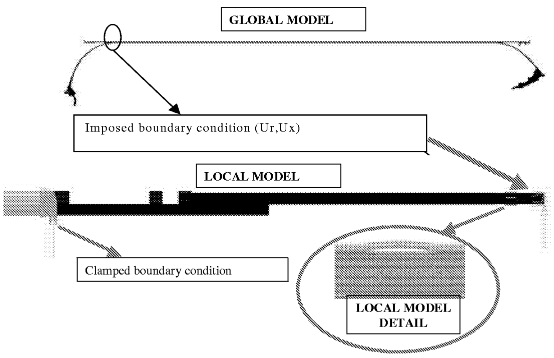

Fig. 4 Global–Local MARC modelling

4.3 Defect Definitions

Analysis showed that an initial thickness or void increased the ERR noticeably. Therefore standard defect definitions such as the length, depth and shape were used to define the defect, but in addition an initial opening or thickness was introduced.

A sine-like shape was selected as a representative shape for the delamination edge as detected by NDI and micrography inspection on the typical composite skirt.

The clay parameter is an alternative way to express the depth. The depth is in millimetres from the outer ply, whilst clay is the number of the layer just below the defect at which the laminate was cut.

Either side of the crack tip there was a 1mm region, d, with a dense mesh. In that region the element size was 0.1 mm in order to satisfy convergence requirements. All of the described parameters are shown in the cross-section in Fig. 5

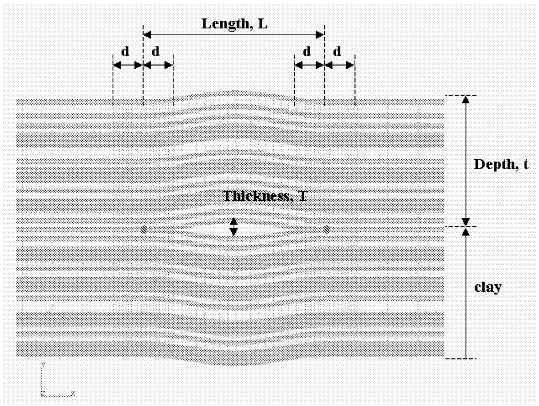

Fig. 5. Definitions used to define the defect

5. CONVERGENCE

Convergence may cause problems when applying the VCCT. As the element size varies, both the forces or stresses at the crack tip and the displacements at the crack tip are affected. If Δa is too small the stresses start to oscillate as the length Δa goes to zero. A practical range of element sizes was suggested by literature. A lower limit of 0.1 and an upper limit of 1.0 times the ply thickness were suggested. The upper limit avoided grouping plies of different material and orientation. The lower limit should avoid the stress oscillations [2].

Two cases were studied in detail to confirm that convergence was satisfactory for both G_I and G_{II} and both for the MARC and NASTRAN models. To verify the convergence of each basic mode it was very important to analyse specific conditions for which the considered ERR value was non-negligible. For the case of compressive axial load and for the selected axial delamination, a defect position at the centre of the layup location was appropriate to study G_I but not G_{II} (as G_{II} was negligible for such a defect). Fig. 6 showed that the results converged for G_I as the element size reached 0.1 mm.

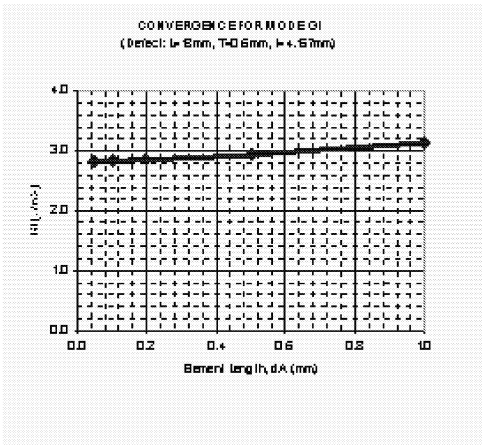

Fig. 6. Convergence for G_I (NASTRAN model)

The convergence for G_{II} required a defect near the edge of the laminate. The results for the defect near the edge are shown in Fig. 7.

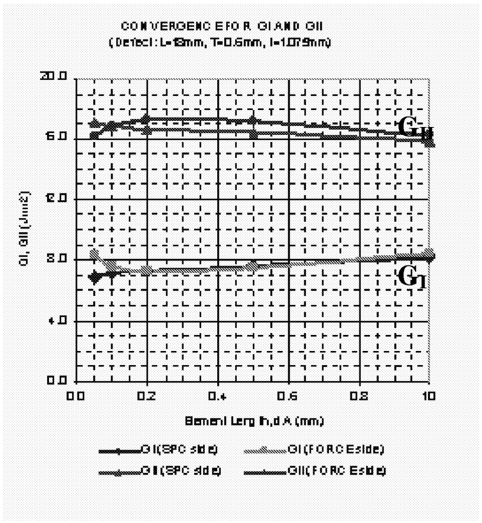

Fig. 7. Convergence for G_I and G_{II} (NASTRAN model)

G_I and G_{II} were evaluated for the side on which the force was applied (FORCE side) and the side at which the model was constrained (SPC side). There was a small difference between the two sides, but more importantly convergence of G_I and G_{II} was satisfactory. An element size of 0.1 was chosen for all subsequent analyses, which was approximately equal to two thirds of the ply thickness.

The same investigation has been performed to verify convergence of the MARC model. The estimated G_I and G_{II} values as a function of the virtual crack element length are shown in Fig. 8 and Fig. 9 respectively.

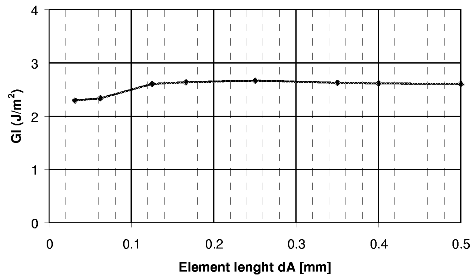

Fig. 8. Convergence for G_I (MARC model) (L=12mm, T=0.6mm, t=4.16 mm)

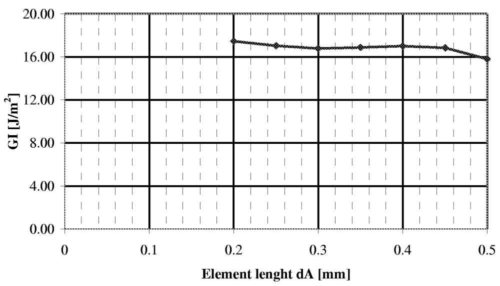

Fig. 9. Convergence for G_{II} (MARC model) (L=12mm,T=0.6mm, t=1.075 mm)

Convergence was successfully achieved in the range from 0.25 mm to 0.4 mm. For the selected mesh refinement that meant that the useful ratio of element size divided by ply thickness was from 0.75 to 1.2. As the final selection an element size ratio of 1.0 (equal to the ply thickness) was defined and used for the MARC evaluation performed on the Zefiro skirts.

6. VCCT VALIDATION

6.1 Double Cantilever Beam Test Verification

In order to perform a validation of the proposed FE methodology, available literature numerical results on DCB tests [3] have been used as reference for pure mode I. In Table 1 the main geometric and material properties, which were considered in the simulation, are reported. In order to take into account the free edge effect the crack front region should be properly modelled with 3D brick elements in the same way as reported in [3,8].

Table 1. Data for DCB test case

Geometrical Properties		Material Properties	
Width B(mm)	25	E_{11} (Gpa)	139.4
thickness H(mm)	3	$E_{22}=E_{33}$ (GPa)	10.16
Total length L(mm)	150	$\nu_{12}=\nu_{13}$	0.30
Delamination length a(mm)	111.5	ν_{23}	0.436
Total Load P(N)	12.66	$G_{12}=G_{13}$ (GPa)	4.6
Lay up	$[0]_{24}$	G_{23} (GPa)	3.54

Since the main objective of this numerical test was to validate the models to use for the VEGA SRM, a MARC plane strain model and a NASTRAN 3D brick model have been investigated. The MARC model was not able to catch the edge effect, but only to predict the G_I value in the central part of the specimens. Fig. 10 shows that in the central part of the specimens the predicted G_I value from the MARC model is in agreement with the full 3D literature model [3]

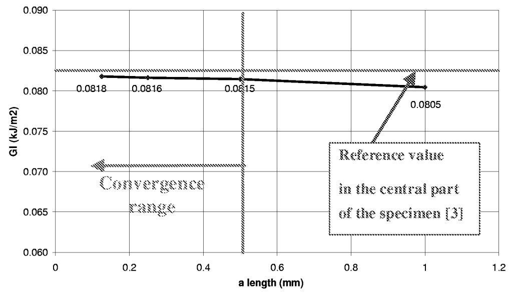

Fig. 10. Literature DCB test specimen (MARC model)

The full 3D NASTRAN model also demonstrated the compliance with the reference results. The deformed model is shown in Fig. 11.

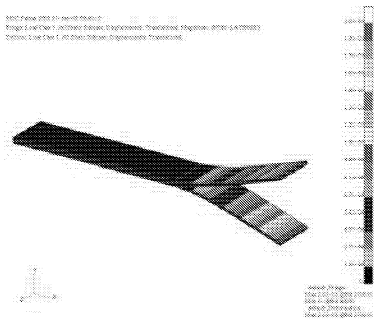

Fig. 11. Literature DCB test (NASTRAN model)

7. APPLICATION OF VCCT TO VEGA SRM COMPOSITE CASE-MARC MODEL

The dimensioning compressive load was applied to the composite case FE model in order to estimate the acceptable level of defect in the skirt. The following steps have been foreseen for the numerical procedure:

1) As described in section 4, the global-local approach has been applied to impose the correct boundary condition to the detailed model.

2) A sensitivity analysis with respect to the delamination geometrical parameters has been performed on the local model to detect the most critical region of the skirt concerning crack onset growth phenomena

3) Once the most critical region has been selected every interface along the thickness has been verified

4) In the most critical interface the delamination length is parametrically changed up to a predetermined threshold value above which the minimum required SF is no longer satisfied

5) As a final step the minimum interference distance between two defects has to be determined

7.1 Global-local approach

An incremental nonlinear analysis has been performed on the SRM composite case global model up to the final collapse load. Compressive axial displacements were imposed to the aft flange free edge whilst the other end was clamped. Due to the different components (composite, metal and rubber) and interface (polar boss stationary shell, polar boss igniter flange) involved in the case, several geometrical, material and contact non linear affects were included in the global model. The boundary conditions coming from the global model were imposed on the local one. Fig. 12 shows the global and local deformed shape under the dimensioning compressive flux. The two regions located close to the metallic flange and case connection exhibit bending phenomena.

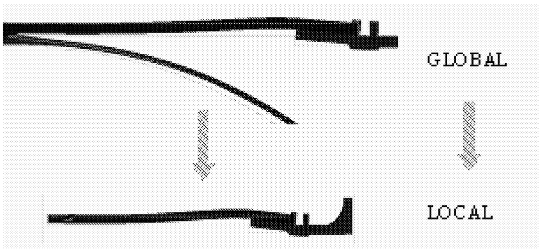

Fig. 12. Global and local deformations (MARC model)

8. SENSITIVITY ANALYSES

A number of significant defect parameters were studied to assess the sensitivity of the strain ERR. The depth and length were obvious parameters, but it was also found that the initial opening contributed significantly to the ERR. The worst case location in the skirt was assessed and that location was used for the axisymmetric models of the full skirt length to assess the sensitivity of the ERR results with respect to defect parameters.

8.1 Locations and depth positions for the sensitivity analysis

The axial and radial location of the defect, defined as in section 4.3 (L=12 mm, T=0.6 mm, sine-like shape), has been parametrically investigated. Five locations (see Fig. 13) have been selected on the basis of a preliminary analysis of the interlaminar stress field distribution and for each of those delamination regions a defect has been placed at three selected depths along the thickness (close to the top, in the middle, and bottom) as shown in Fig. 14.

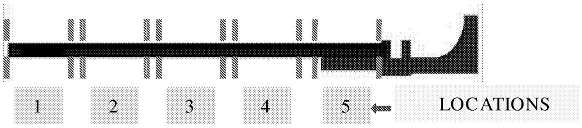

Fig. 13. Motor case skirt showing axial locations

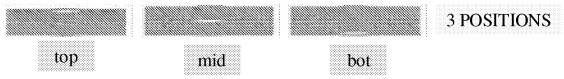

Fig. 14. Defects at various depths through the layup

8.2 Variation as a function of the depth

For every axial location a nonlinear curve resulted from plotting the linear law criterion ($G_I/G_{IC}+G_{II}/G_{IIC}$) versus the applied load. The worst case location was location 2 for which the results are shown in Fig. 15.

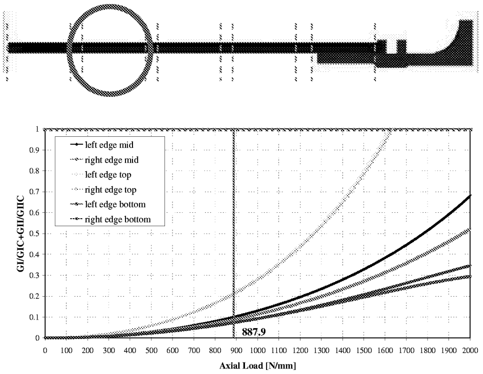

Fig. 15. Linear law criterion for defects at varying depth (MARC model)

Since the VCCT methodology allowed the separate modes to be derived, the G_I/G_{II} ratio was also an interesting parameter to investigate. Fig. 16 shows the G_I and G_{II} contribution for locations 2 and 4. It was clear from comparing the different contributions found at location 2 and 4 that the mixed mode ratio varies significantly as a function of the boundary conditions and also the depth (top, middle or bottom).

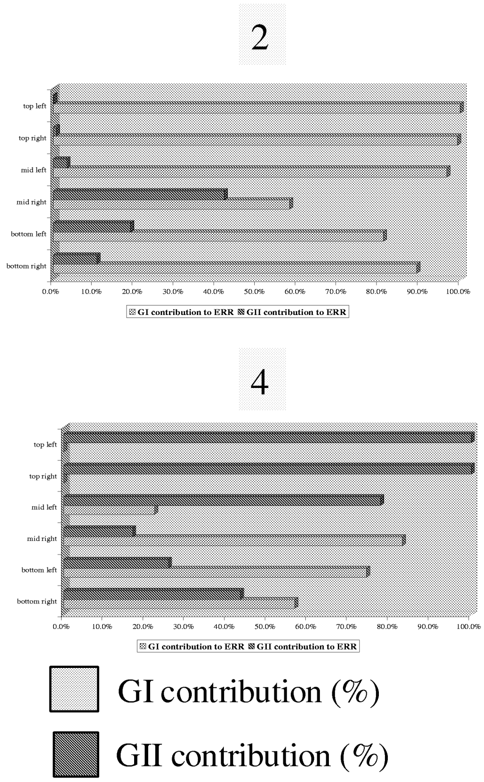

Fig. 16. GI and GII contributions for defects at varying depths for locations 2 and 4 (MARC model)

As stated previously the most critical region was selected (at location 2 close to the case connection for the considered dimensioning load). At that location, additional defect depths between various ply orientations were analysed through the thickness close to the most critical of the preliminary three depths (near the outer edge of the layup). The additional results are shown in Fig. 17.

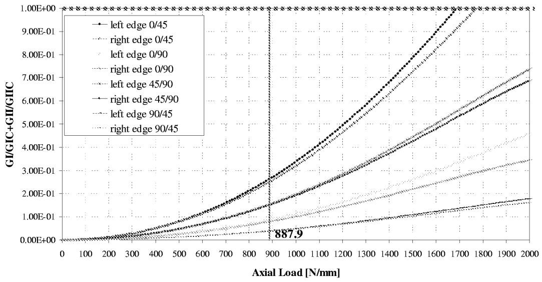

Fig. 17. Linear law criterion for defects between various ply orientations (MARC model)

Sensitivity analysis was also carried out on local specimens using the NASTRAN model. In particular the boundary conditions were not exactly the same as the global-local approach used for the MARC model and the analyses were linear rather than nonlinear. Nonetheless the results shown in Fig. 18 confirmed that defects near the edge were potentially worse for delamination growth. The model also confirmed that the G_I/G_{II} ratio varied significantly as a function of the depth and the interface between different ply orientations.

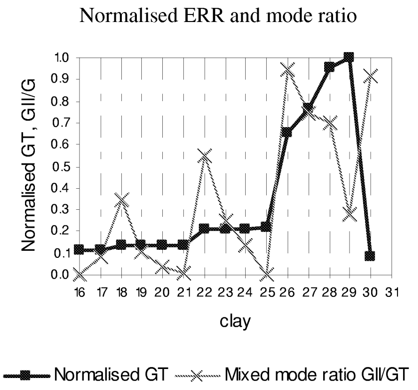

Fig. 18. Sensitivity analysis of defect depth in a local section (NASTRAN specimen model)

8.3 Variation as a function of length, L

Once the area that exhibited the lowest SF with respect to delamination onset growth was determined (both the interface depth and the axial location) a parametric analysis devoted to determining the maximum allowable defect dimensions was developed. Fig. 19 shows that as the initial delamination length increased the result was a remarkable decrease of the SF.

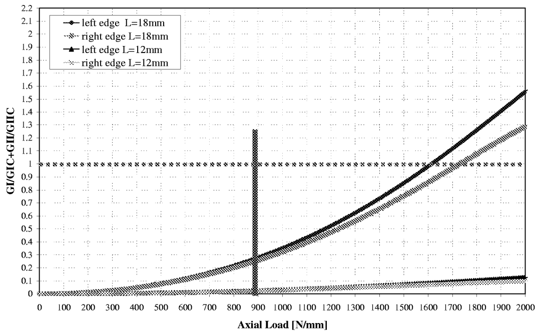

Fig. 19. Effect of defect length (MARC model)

8.4 Variation as a function of thickness or opening, T

It was found from analysis that an initial thickness of the defect could significantly affect the results from the VCCT analyses. Therefore the parameter was included in the sensitivity analyses. For a given axial load and with fixed length and depth the ERR increases as shown in Fig. 20.

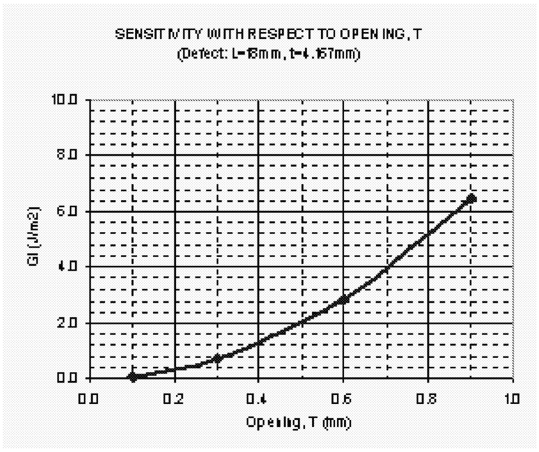

Fig. 20. Effect of defect opening (NASTRAN model)

8.5 Assessing Potential Multiple Delaminations

A novel acceptance criterion was added to the list of acceptance criteria to account for potential multiple defects. The region of influence was defined as the extent to which the stresses were significantly affected either side of a defect and no other defects would be allowed within that region.

Following a preliminary investigation based on the interlaminar shear stress, a verification of the region of influence distance was performed. The verification involved introducing another delamination of equal dimensions at the prescribed axial distance from the first most critical delamination (derived from the sensitivity analyses). The analysis with multiple defects has to demonstrate that irrespective of the depth of the second delamination, it does not affect the onset growth load of the first defect, see Fig. 21.

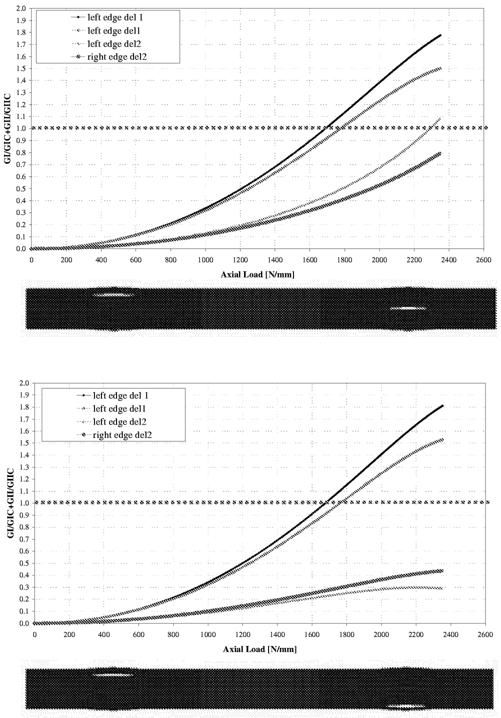

Fig. 21. Multiple defects at varying depth (MARC model)

9. CONCLUSIONS

The analytical approach followed to predict the affects of delamination on the Zefiro's composite skirt involved global and local MARC models. Independent analyses were performed with a simplified linear NASTRAN model to confirm the results of the complex nonlinear axisymmetric model.

The models were validated numerically to ensure convergence. Verification of the VCCT method was also performed by successfully reproducing specimen tests from literature. The results from analyses performed with the MARC model were very good, providing satisfactory verification for the ongoing work to define the allowable values for the VEGA specific materials.

A region of influence was defined to address the potential issue of multiple defects. A minimum allowable distance between two neighbouring defects ensures that the delamination onset caused by a single defect would not be significantly influenced by a second detectable defect.

Sensitivity analyses provided detailed insight into the behaviour of the delamination growth onset for the Zefiro skirt layup. Boundary conditions and the axial location of the defect affect the ERR. The ERR results increased as the initial opening increased and as the length of the defect was increased.

The depth of the defect within the layup also played an important part. Generally the ERR increased as a defect was moved from the centre of the layup towards the outer plies, but the location of the defect between plies of various orientations also affected the relative contribution of G_I and G_{II} modes to the total ERR.

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