INFLUENCE OF CONTACT PHENOMENA ON EMBEDDED DELAMINATIONS GROWTH IN COMPOSITES

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Keywords: *buckling, delamination growth, contact, composites*

Abstract

In this paper, numerical geometrically non-linear analyses have been performed to investigate the influence of contact phenomena on multiple embedded delaminations growth in composite panels under compressive load. An in-house FEM code based on the Modified Virtual Crack Closure Technique to analyse delaminations growth and with the Penalty Method Approach to take into account contact phenomena has been used for computations. Compressed composite panels with two embedded delaminations has been investigated for various geometrical configurations with different delaminations' sizes and positions. Comparisons with a single embedded delamination model adopted in previous works have been presented. Finally a comparison between contact and no-contact approaches has been shown for a significant geometrical configuration.

1 Introduction

The high specific strength and stiffness of laminated composites, make them suitable for use in aircraft structures. However, High sensitivity of Composites to the presence of delaminations, arising after impact with foreign objects or caused by manufacturing defects, has been observed in experimental tests.

The lack of robust models for predicting the damage tolerance of composite structures has led to over-conservative designs, not fully realising promised economic performances benefits.So it is necessary to produce much more information on these kind of structures taking into account the effects of delaminations and their evolution.This should be done introducing new numerical models representing phenomena governing structural behaviour of composites like contact between delaminated plies and delaminations growth.

The through-the width delaminations have been investigate using a great number of analytical and numerical models [1-3] and with the aid of experimental tests [4-6].

Embedded delaminations have also been studied. In literature analytical models [7-10], experimental tests [11,12], and numerical models [13-15] are presented. In [13], numerical analyses to study the influence of embedded delaminations' geometrical parameters on the buckling modes of composite panels, have been carried out; while in [14], the influence of contact phenomena on the Strain Energy Release Rate distribution along the embedded delaminations front has been investigated for composite panels with single delaminations. However, no one of the above mentioned papers have introduced models to simulate growth of delaminations.

On the contrary, in [15] a detailed investigation on delamination growth has been carried out, but only panels with single delaminations has been investigated giving no information on the single opening crack modes contributions to the Total Strain Energy Release Rate.

The present paper is the natural extension of previous works about the study of stable through-the-width delamination growth [16], unstable through-the-width [17], single embedded [18,19] delamination growth. The numerical approach described in [19] has been adopted here to analyse the compressive behaviour of composite panels with multiple embedded delaminations.

In section 2 the adopted finite element approach is presented. In section 3 a numerical investigation on the importance of contact phenomena and delamination growth in compression of composite panels with two embedded delaminations for various geometrical configurations with different delaminations' sizes and positions is introduced. Comparisons with the results obtained for the single embedded delamination model used in [19] are also shown. Finally a comparison between contact and no-contact approaches is presented for a particular geometrical configuration to point out the influence of contact phenomena on the embedded delamination propagation and on the general compressive behaviour of delaminated composite panels.

2 Finite Element Approach

Numerical analyses have been performed using the non linear finite element code B2000. The code is based on Total Lagrangian Formulation. The Incremental Continuation Method by Riks [20] is adopted to solve the non linear equilibrium equations.

In order to perform the numerical analyses to predict delamination growth, the B2000 features have been enhanced by means of:

a) modifications to continuation method

b) introduction of a contact element

c) introduction of an interface fracture element

The modifications to continuation method have been carried out to simulate unstable crack growth; further details on them can be found in reference [18].The next two subsections describe the main characteristics of new elements introduced in B2000.

2.1 Contact element

Depending on delaminations' geometrical parameters and laminate stacking sequences, contact may occur somewhere in delaminated regions.

In order to prevent inter-penetrations between the two contacting surfaces, contact forces should be taken into account during analyses; so a 3D node-to-node contact element (shown in fig 1) has been introduced in our FEM code. This element is based on the Penalty Method that can be considered one of the most effective methods for contact problems in engineering, because of its minimum requirements of computational cost.

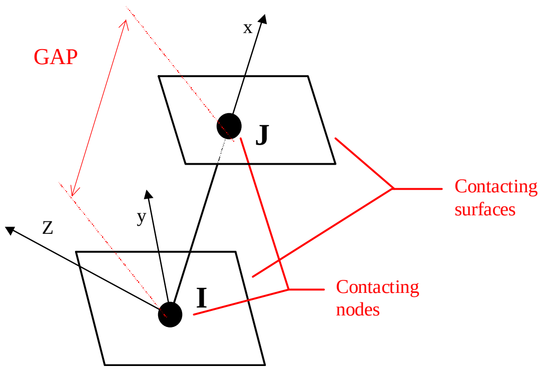

Figure 1 - 3D node-to node contact element

In the Penalty formulation, when contact occurs (see fig 2) a little overlapping (corresponding to a GAP < 0) between the two contacting nodes is permitted and the contact force F_C associated to these nodes is found as a linear function of their GAP, according with the following expression:

$$|F_c| = \alpha \cdot |GAP| \qquad (1)$$

where α is the penalty constant.

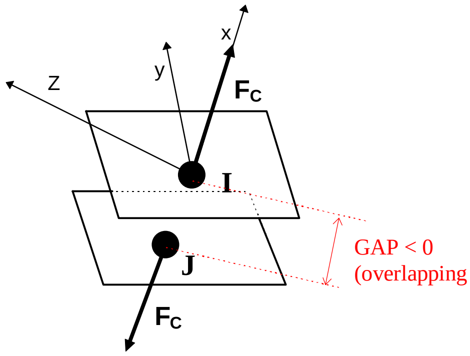

Figure 2 - 3D node-to-node contact element (contact condition)

With respect to equation (1), it is possible to underline that, contact force being constant, low values of GAP can be obtained from high values of penalty constant. The major weak-point of penalty method is just related to the choice of α : too low values of α allow big overlappings while too high values of α can cause convergence problems in the solution of non linear equilibrium equations.

From the above consideration follows that a high degree of experience in the choice of penalty constant is needed to perform effective analyses with the Penalty Method.

2.2 Fracture element

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From fracture mechanics of composites, it is well known that Strain Energy Release Rate rules propagation of cracks.

For each fracture mode (opening mode I, forward shear mode II and parallel shear mode III) a strain energy release rate can be defined: G_I for mode I , G_{II} for mode II and G_{III} for mode III.

Once Known, from ad hoc experiments, the starting crack propagation values for the basic fracture modes (G_{IC}, G_{IIC} and G_{IIIC}), it is possible to predict mixed modes crack propagations in laminates by mean of suitable criteria. In particular we have adopted the power law criterion. It states that if relation:

$$\left(\frac{G_I}{G_{I_C}}\right)^{\alpha} + \left(\frac{G_{II}}{G_{II_C}}\right)^{\beta} + \left(\frac{G_{III}}{G_{III_C}}\right)^{\gamma} = E_d \geq 1 \qquad (2)$$

is satisfied, then crack propagation occurs.

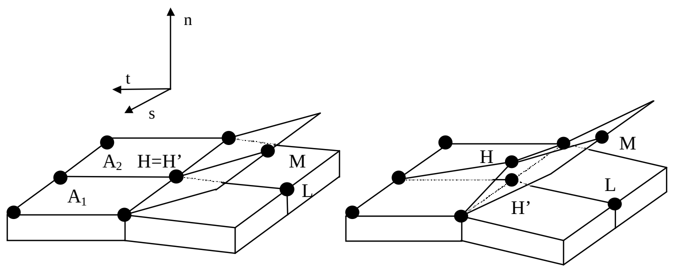
The delaminations' growth model was implemented in our finite element code by means of a new interface fracture element that uses the Modified Virtual Crack Closure Technique to calculate the Strain Energy Release Rate along the delamination front. This technique is based on the consideration that the Strain Energy released by a crack growing from length a to $a+\Delta a$ is equal to the amount of work required to close the same crack from $a+\Delta a$ to a.

The interface fracture elements are placed among brick elements lying along the delamination front. They are adopted to calculate the Unit Virtual Crack Closure Work (= Strain Energy Release Rate) for each fracture mode as the product of forces and displacements, at nodes near the delamination front, normalised by the average of the surrounding brick elements areas.

For example, the Energy release Rates associated to the interface fracture element shown in fig 3 are:

$$G_I^H = \frac{1}{2} \cdot \frac{1}{(A_1 + A_2)/2} \cdot F_n^H \cdot (u_n^M - u_n^L)$$
$$G_{II}^H = \frac{1}{2} \cdot \frac{1}{(A_1 + A_2)/2} \cdot F_t^H \cdot (u_t^M - u_t^L) \qquad (3)$$
$$G_{III}^H = \frac{1}{2} \cdot \frac{1}{(A_1 + A_2)/2} \cdot F_s^H \cdot (u_s^M - u_s^L)$$

The interface fracture element local co-ordinate system (t,s,n), the nodes and the geometrical quantities involved in computations of G_I^H, G_{II}^H and G_{III}^H are described in fig 3a.



a) Interface Fracture element activated

a) Interface Fracture element released

Figure 3 - Interface fracture element

Introducing the values of : G_I , G_{II} and G_{III} in relation (2) it is possible to check whether the propagation occurs. In particular for interface fracture element of fig 3. ; if relation (2) is satisfied the node H will be released (see fig 3b) leading to a modification of delamination front.

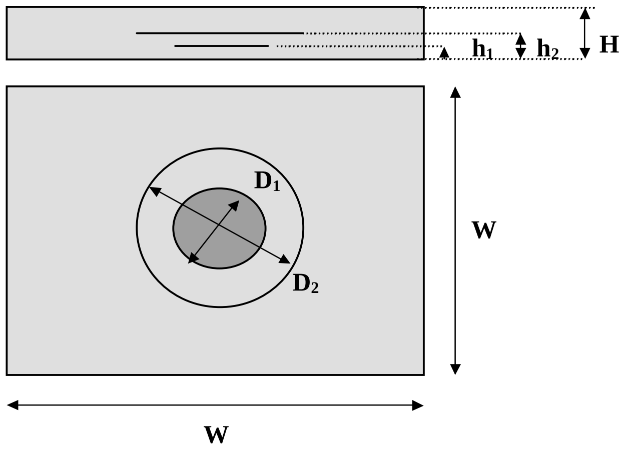
3. NUMERICAL RESULTS (composite panels with two embedded delaminations)

3.1 Parametric study

A cross-ply laminate $[90^o/0^o/90^o]_{16}$ containing two embedded circular delamininations has been selected to perform a parametric study. Material and geometrical characteristics are shown respectively in table 2 and in figure 4. Delaminations' size and delaminations' position through the thickness have been considered as parameters.

Material properties (HTA/6376C)	
Longitudinal Young's modulus, E_L (GPa)	146
Transverse Young's modulus, E_T (GPa)	10.5
Out-of-plane Young's modulus, E_z (GPa)	10.5
Poisson's ratio, ν_{LT}	0. 3
Poisson's ratio, ν_{LZ}	0. 3
Poisson's ratio, ν_{TZ}	0.51
In-plane shear modulus, G_{LT} (GPa)	5.25
Out-of-plane shear modulus, G_{LZ} (GPa)	5.25
Out-of-plane shear modulus, G_{TZ} (GPa)	3.48
Critical ERR- Mode I (J/m^2)	200
Critical ERR- Mode II (J/m^2)	570
Ply thickness (mm)	0.125

Table 2 - Material Property of the cross-ply laminate



Geometrical Characteristics	
h_1 (mm)	.375
h_2 (mm)	1.125, 4.875
H (mm)	6
D_1(mm)	40,60, 70
D_2(mm)	80,
W(mm)	150

Figure 4. - Geometrical Characteristics of the cross-ply laminate with embedded delamination

Four cases with different combinations of delamination diameters (D_1, D_2) and delaminations' abscissa along the thickness (h_1,h_2) have been analyzed. Due to the symmetry only a quart of the structure was modeled.

Twenty nodes brick elements, fracture interface elements and 3D node to node contact elements were used to discretize the problem.

Composite panels are compressed by means of the applied displacement field $U_x=U_0$.

In figure 5 the finite element mesh (in X,Y plane) used in the analysis is shown. Contact elements are positioned between the delaminated plies and fracture element are positioned between the delaminated plies in the region with D/2 < Radius < (D/2 + damax) and 0° < Θ < 90° .

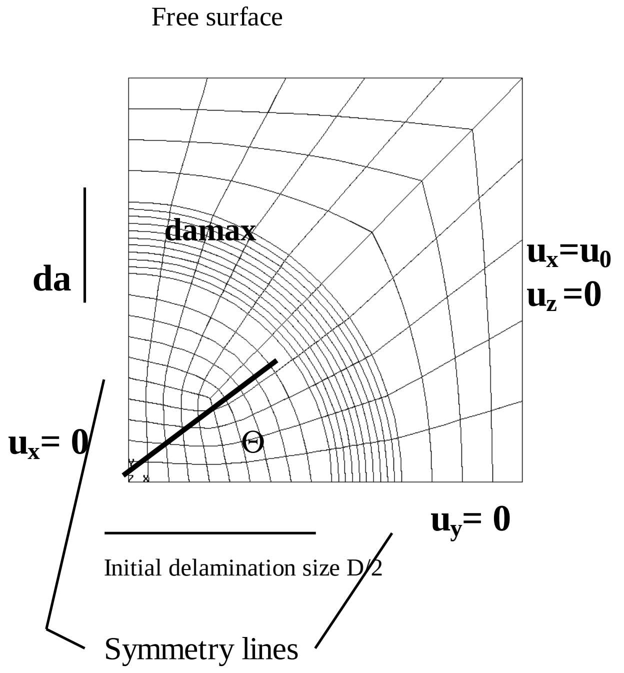


Figure 5 - Finite element mesh with applied boundary condition -In plane view

In figure 6 the position of the control points used to monitor the compressive behavior of delaminated plies is schematically shown.

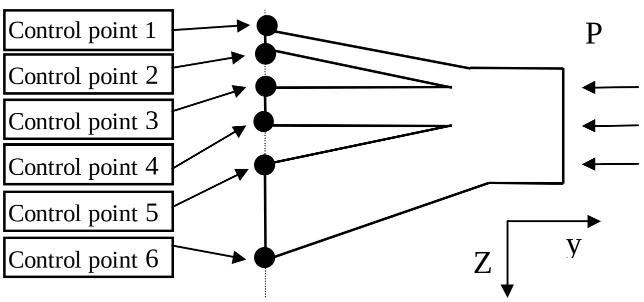


Figure 6 - Control points locations

In figures 7-10 the deformed shape and both the delaminations sizes at maximum computable growth for the four analyzed geometrical configurations are shown. The maximum computable growth depends on the number of interface fracture elements used to build the model; with reference to figure 5, maximum computable growth is reached when at least one delamination radius reaches the damax value at any Θ location.

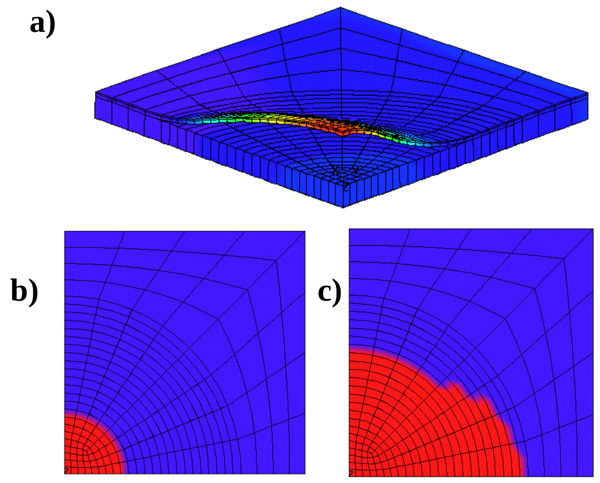


Figure 7 - a) Deformed shape, b) first delamination size and c) second delamination size at maximum computable growth for specimen with D1=40 (mm), D2=80 (mm), h1=0.375 (mm) and h2=1.125 (mm).

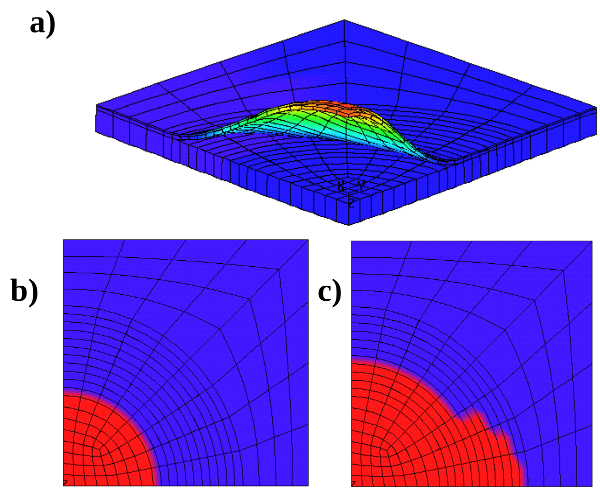


Figure 8 - a) Deformed shape, b) first delamination size and c) second delamination size at maximum computable growth for specimen with D1=60 (mm), D2=80 (mm), h1=0.375 (mm) and h2=1.125 (mm).

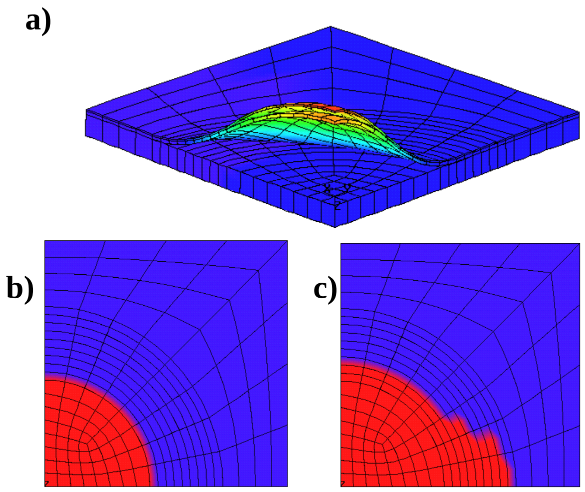


Figure 9 - a) Deformed shape, b) first delamination size and c) second delamination size at maximum computable growth for specimen with D1=70 (mm), D2=80 (mm), h1=0.375 (mm) and h2=1.125 (mm).

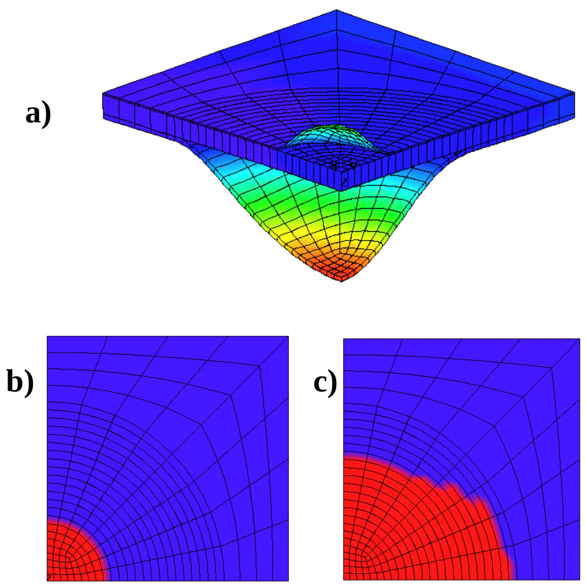


Figure 10 - a) Deformed shape, b) first delamination size and c) second delamination size at maximum computable growth for specimen with D1=40 (mm), D2=80 (mm), h1=0.375 (mm) and h2=4.875 (mm).

From all of the preceding figures the importance of contact phenomena can be pointed out. In particular in the first analysed configuration (figure 7) the contact between sublaminates appears to be extended to the entire delamination size while in the others the contact zone is located near the delamination front.

For all the analysed geometrical configurations, growth has been found only for the delaminations between thicker plies. This is due to the high amount of load needed for these delaminations to reach the local buckling (see table 3) that leads to an increase of tip stresses (and consequently of ERR) needed to get the momentum equilibrium.

Also contacts between sublaminates influence the ERR distributions along the delaminations fronts bringing down the G1 (Mode I of fracture) values as it can be seen from figures 11-14.

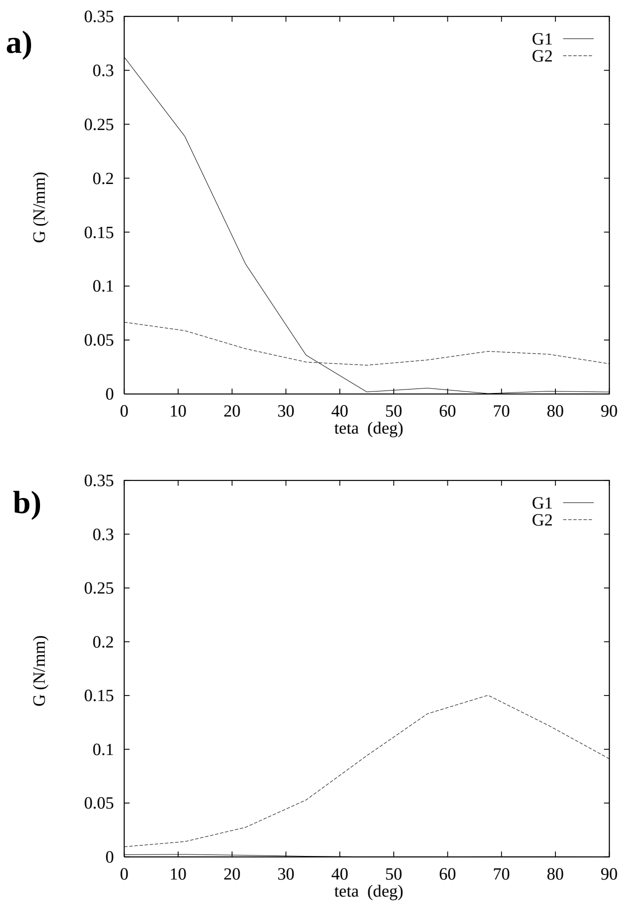
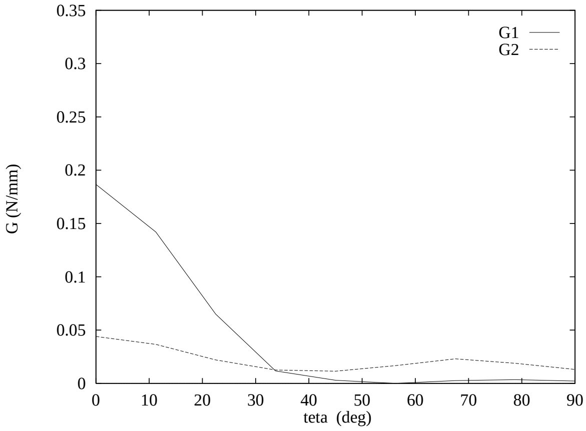


Figure 11 - ERR mode I (G1) and mode II (G2) values along the delamination front at growth initiation load for first delaminatio (a) and second delamination (b) in specimen with D1=40 (mm), D2=80 (mm), h1=0.375 (mm) and h2=1.125 (mm).

a)



b)

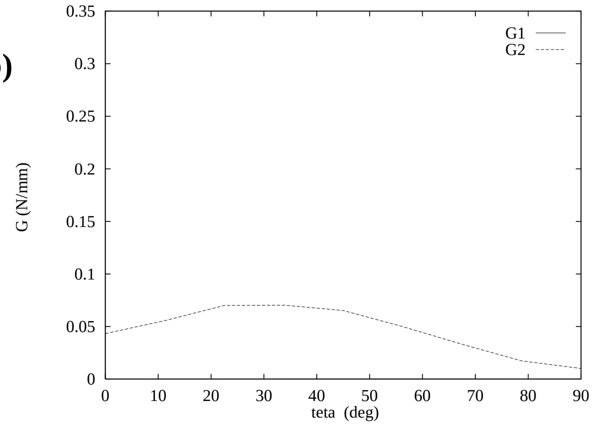
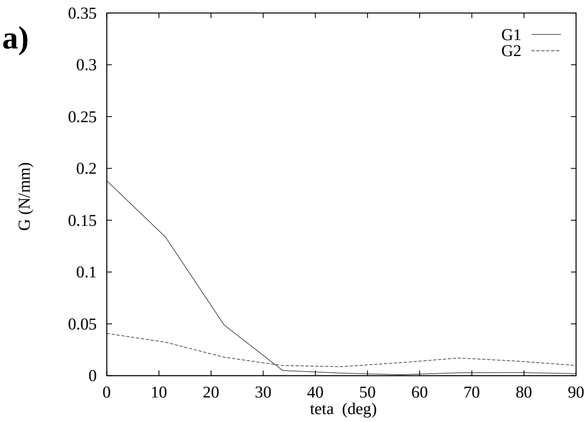


Figure 12 - ERR mode I (G1) and mode II (G2) values along the delamination front at growth initiation load for first delaminatio (a) and second delamination (b) in specimen with D1=60 (mm), D2=80 (mm), h1=0.375 (mm) and h2=1.125 (mm).

a)



b)

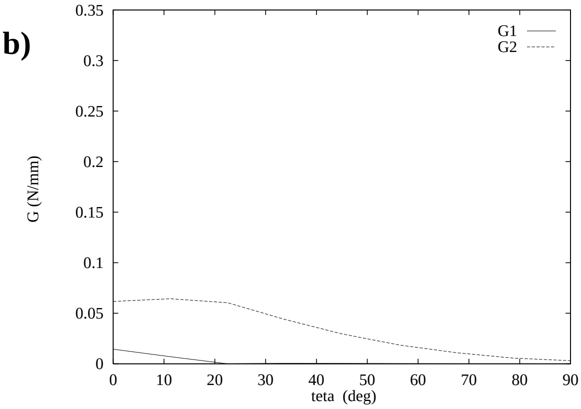
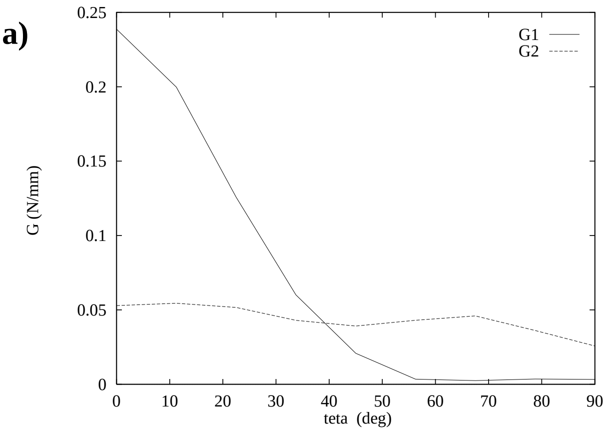


Figure 13 - ERR mode I (G1) and mode II (G2) values along the delamination front at growth initiation load for first delaminatio (a) and second delamination (b) in specimen with D1=70 (mm), D2=80 (mm), h1=0.375 (mm) and h2=1.125 (mm).

a)



b)

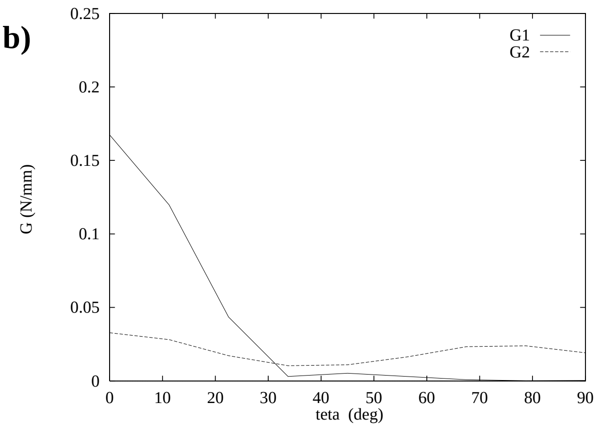


Figure 14 - ERR mode I (G1) and mode II (G2) values along the delamination front at growth initiation load for first delaminatio (a) and second delamination (b) in specimen with D1=40 (mm), D2=80 (mm), h1=0.375 (mm) and h2=4.875 (mm).

In all the specimens (figure 11,12,13 and 14) contact phenomena (due to the orthotropy of material) influence the delamination growth of second delamination bringing down the values of G1 for 45° ≤ Θ ≤ 90°. This behaviour is the same as the one observed for the panel with one delamination investigated in [19] (see fig 15) .

In the first three specimen (figure 11,12 and 13) contacts keep the G1 value low along the whole front of first delamination. On the contrary a higher value of G2 was observed along the first delamination front for the above mentioned specimens, due to the extended contact area between the buckled delaminated plies.

The last specimen - D1=40 (mm), D2=80 (mm), h1=0.375 (mm) and h2=4.875 (mm) - because of its particular delaminations' positions along the thickness exhibits an independent local buckling of the two delaminations that makes them both behave in a similar way (see fig. 14) with respect to the one delamination panel mentioned above.

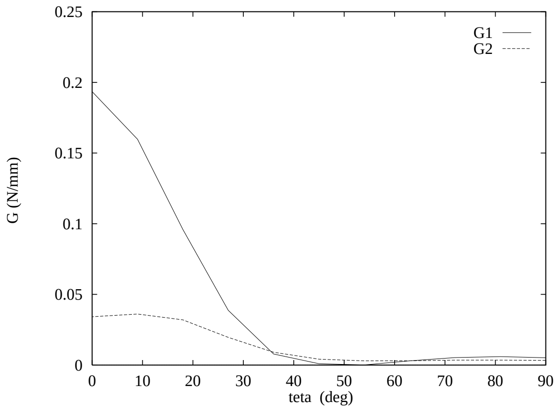


Figure 15 - ERR mode I (G1) and mode II (G2) values along the delamination front at growth initiation load in specimen with D=80 (mm) and h2=1.125 (mm).

As summary of the parametric investigation in table 3 the characteristics loads for all analysed geometrical configurations are shown.

Specimen	local buckling load (N) del. 1.	local buckling load (N) del. 2.	Growth initiation load (N) del 2.	Max growth load (N) del 2.
D1=40 mm D2=80 mm h1=0.375 mm h2=1.125 mm	11521.	35194.	84178.	83430.
D1=60 mm D2=80 mm h1=0.375 mm h2=1.125 mm	6776.	25523.	68192.	67598.
D1=70 mm D2=80 mm h1=0.375 mm h2=1.125 mm	4986.	21281.	62834.	62386.
D1=40 mm D2=80 mm h1=0.375 mm h2=4.875 mm	15973.	41767.	86154.	86154.

Table 3 - Summary of the parametric investigation

In table 3, clearly appears also the influence of the delamination size and position on the whole compressive behaviour of the investigated delaminated panels.

3.2 Comparison between contact and no-contact approaches

To point out the importance of contact phenomena on the compressive behaviour of delaminated panels and in particular on the embedded delamination growth, a comparison between a contact and no-contact approach has been carried out for specimen with D1=40 (mm), D2=80 (mm), h1=0.375 (mm) and h2=1.125 (mm). In figure 16 the deformed shape and both the delaminations sizes at maximum computed growth for specimen with no-contact approach are shown.

In this figure the wide penetration zones between sublaminates are clearly visible. Comparing figure 16 with figure 7 we can have a measure of the influence of contact phenomena in our investigations.

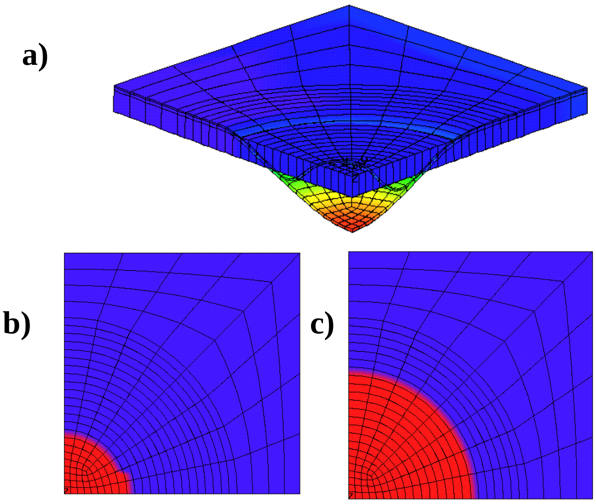


Figure 16 - a) Deformed shape, b) first delamination size and c) second delamination size at maximum computable growth for specimen with D1=40 (mm), D2=80 (mm), h1=0.375 (mm) and h2=1.125 (mm).- NO-CONTACT APPROACH

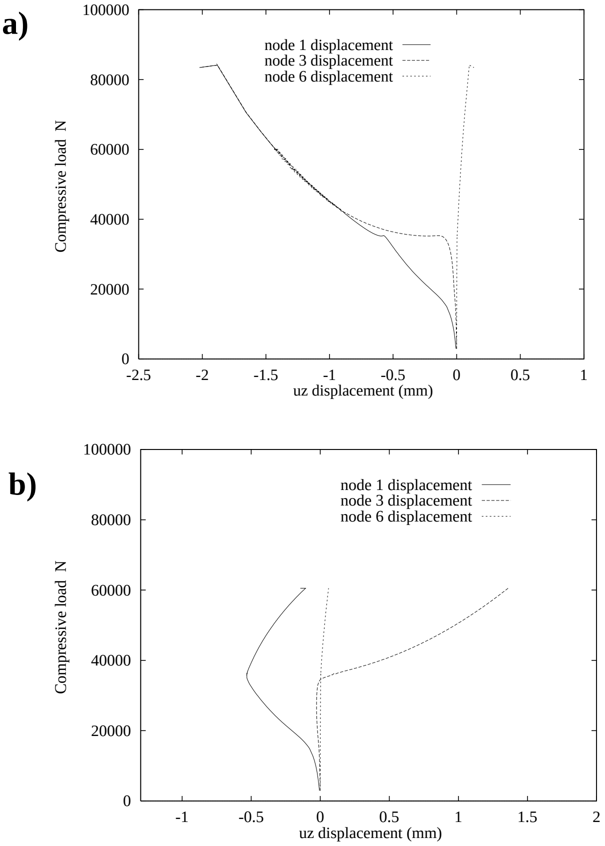


Figure 17 -out of plane displacement as a function of compressive load for contact (a) and no-contact approach (b) in specimen with D1=40 (mm), D2=80 (mm), h1=0.375 (mm) and h2=1.125 (mm).

A measure of the penetration between plies can be obtained from figure 17, where out of plane displacements of the control points (see figure 6) as function of the compressive load for contact and no-contact approaches are shown.

4 Conclusions

A numerical investigation on composite panels with two embedded delaminations has been presented. All the numerical results have been found by using a non linear FEM code enhanced with Penalty method for contact Phenomena and Modified Virtual Crack Closure Technique for Strain Energy Release Rate calculation. A parametric analysis based on different geometrical configurations showing high influence of contact phenomena on physics of compression of composite delaminated panels, has been performed for panels with circular embedded delaminations. The remarkable importance of contact phenomena has been pointed out also by means of comparisons between contact and no-contact approaches for one geometric configuration.

Acknowledgements

This Work is part of a co-operative agreement between CIRA, Dipartimento Aerospaziale of University of Rome and Dipartimento di Ingegneria Aerospaziale of II University of Naples.

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