# NUMERICAL AND EXPERIMENTAL STUDY ON THE FAILURE OF NON_CONVENTIONAL LAMINATES

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**Abstract**

The capacity of predicting the failure for non-conventional laminates using the stresses derived from laminate theory is studied in this paper. The following stacking sequences $[45_n, -15_n]_s$, $[90_n, 45_n, -15_n]_s$ and $[45_n, -15_n, 15_n, 45_n]_n$are studied. n is taken as n=1 and n=3 to consider the size/scale effect on the failure of these laminates. Additionally, conventional laminates have also been studied with stacking sequences $[0_n, 90_n]_s$ and $[0_n, 90_n, 45_n]_s$, which have 0 degrees dominant layers, to check the behavior of these laminates in comparison to the others.

In the case of non-conventional laminates, experimental results have provided failure stresses for n=1 higher than for n=3, this difference being less significant for conventional laminates.

As classical laminate theory provides the same predictions for laminates with n=1 and with n=3, a study on the singular stresses associated to the change of properties between plies has been carried out, as well as a refined finite element study of the non-singular stresses.

Finally, a micromechanical analysis of the incipient debonding failure, generally accepted as the onset of the damage of the laminas of the laminates has been conducted to check the scale effect at this stage.

## 1. Introduction

The difficulty to predict the failure of composite laminates is high due first to the accuracy of existing failure criteria and second to the level of representativity of the stresses state (or strains) involved in the criteria. With reference to the first question, a comparative study on failure criteria of composites, París [1], alerted on the erroneous predictions associated to the generalized use of non-physically based criteria. Several questions helping in the understanding of failure of composites have been explained by París et al in subsequent papers [see 2, 3, 4, 5, 6 among others]. With reference to the second question, classical experimental studies carried out by Parvizi et al [7] and Flaggs and Kural [8], among others, showed the presence of a phenomenon known generally speaking as *scale effect*, indicating that the stresses may not be representative of the failure of a laminate, what led to introduce the *in-situ strength* concept.

Although it could be thought that the important feature of the failure of a laminate, and of a lamina in particular, would be the failure of the fibre, it is clear that the first damage will appear associated to the weakest direction, normal to the fibres, not involving then the breakage of any fibre. It has also to be mentioned that a lamina of a laminate placed in a actual aircraft structure must suffer different types of loading, which lead to have all type of stress state, what has led to consider in this study laminates in which there are no laminas oriented in the direction of the load, what allow us to denote these laminates, generically speaking, as non-conventional laminates.

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The purpose of this contribution is first to confirm the scale effect on these non-conventional laminates through experimental tests. Once it is confirmed, then a detailed stress analysis is carried out, first on the nominal singular stresses associated to the jump in the properties of the laminas of the laminate, and second on the non-singular stresses, which may be also affected by the aforementioned jump. Finally a micromechanical study, using Boundary Elements, is carried out to check the presence of scale effect in the lamina of a laminate in the first evidence of appearance of damage, the debonding between a fibre and the surrounding matrix.

## 2. Laminates and Tests

4 types of laminates, fabricated and tested, including two configurations associated to a value of n=1 and n=3 are reflected in table 1. Fibres oriented with the loading direction have been put in one of them to visualize clearly, in comparison with the other 3 not having fibres aligned with the loading, the influence in the scale effect of this fact. The material used is AS4/8552 having performed the tests with glass fibres end tabs.

**Table 1.** Laminate tested and stiffeness and strength properties.

| Laminate | Stacking sequence | n | $E_x \pm\sigma$ (GPa) | $\sigma_S \pm\sigma$ (MPa) | $\varepsilon_S \pm\sigma$ (%) |
|---|---|---|---|---|---|
| 1 | [45°n,-15°n]$_s$ | 1 | 60,7±3,59 | 663,4±32,21 | 1,37±0,041 |
| | | 3 | 50,5±4,38 | 411,5±10,58 | 0,90±0,087 |
| 2 | [90°n,45°n,-45°n]$_s$ | 1 | 22,6±1,67 | 226,9±3,59 | 1,22±0,083 |
| | | 3 | 20,8±0,29 | 113,9±4,86 | 0,56±0,043 |
| 3 | [45°n,-15°n,15°n,-45°n]$_s$ | 1 | 63,6±2,40 | 766,8±21,02 | 1,25±0,024 |
| | | 3 | 64,6±0,86 | 523,6±14,54 | 0,82 |
| 4 | [0°n,90°n,45°n]$_s$ | 1 | 54,2±2,27 | 685,8±43,13 | 1,27±0,095 |
| | | 3 | 51,2±2,50 | 604,0±8,20 | 1,26±0,087 |

Table 1 includes the values of the nominal stiffness of the laminate ($E_X$) in the loading direction and the values of the nominal average stress and strain at the instant of failure, $\sigma_S$ and $\varepsilon_S$, respectively. The results show in general an acceptable consistency in terms of the standard deviation obtained from the five tests carried out for each of the configuration studied.

Looking at the most significant parameter of the study, the strength of the laminates, all of them are affected by the scale effect although clearly the laminate with a final failure dominated by 0 degrees laminas (laminate 4) is less affected than those with no 0 degrees laminas, laminates 1, 2 and 3. It can also be observed, in coherence with the previous observation, that the level of influence of the scale effect increases as the dominant laminas (those oriented closer to 0 degrees) of each laminates differ more from the loading direction. In this way, the laminate more affected by the scale effect is laminate 2, laminates 1 and 3 having a similar effect as they share 15 degrees oriented laminas as the most dominant plies.

## 3. Stress Analysis of the laminates

Once the presence of the scale effect has been found in all laminates tested, a deep stress analysis, further from that associated to laminate theory, is carried out.

The presence of adjacent laminas with different properties opens the possibility of having singular stresses at boundary points placed along the interface of the adjacent laminas.

Figure 1 shows an scheme of the laminate [-45, 15]$_S$ taken as reference for this study. The nominal stress state at a point located at the lateral free edge of the laminate and along the interface between the

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-45 degrees lamina and the 15 degrees lamina, is represented, in the *xy* plane, normal to the direction of the load, direction *z*, by:

$$\sigma_{ij}(r,\theta)=\sum_k K_k r^{\delta_k} f_{ij}^{(k)}(\theta)$$

where *r* and $\boldsymbol{\theta}$ are the coordinates of a point located in the *xy* plane, as represented in Figure 1, $\delta_k$ are the order of the singularities and $K_k$ represent the values of the generalized stress intensity factors associated to each singular stress state. The analysis to determine the singularities is carried out following the approach developed by Barroso et al [9, 10].

The analysis for the case considered has led to detect the presence of a single singularity affecting the values of the stresses associated to the *xy* plane, stresses represented in figure 1. The order of the singularity is $\delta$=0.036, which is a very weak singularity. To give a comparative example, a similar study for a $[0,90]_S$ configuration would lead to a singularity of 0.103 which is in turns also very weak, if is compared with the reference value of 0.5 associated to the presence of a crack in an isotropic material. The effect of this nominally singular stress state can then be considered negligible.

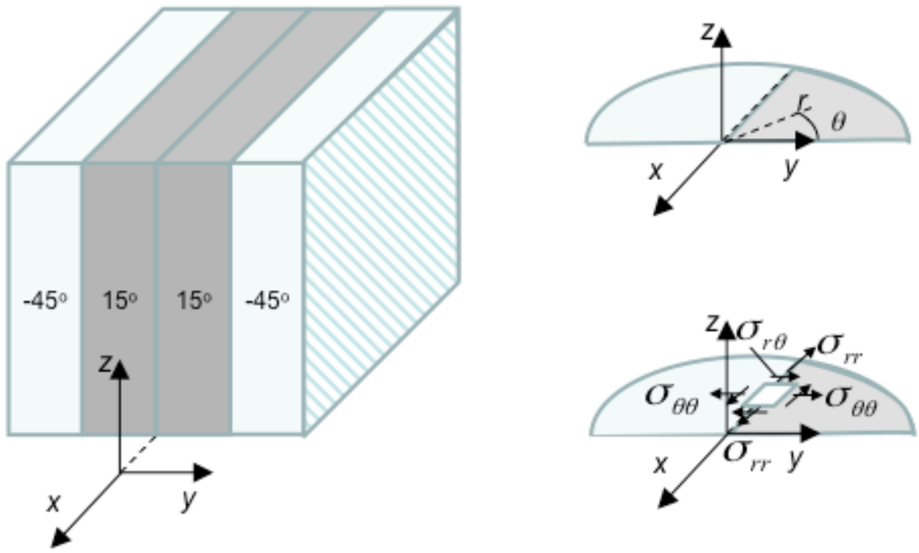


**Figure 1.** Stress state at a boundary point located at the interface of the laminas of a $[-45, 15]_S$ laminate.

Although having proved that the unique stresses having nominal singular values (with a very weak singularity associated) are those associated to the plane transversal to the application of the loading, the longitudinal stress, not being singular, can also be affected by the presence both of the adjacent laminas with different properties as of the free boundary.

To check this question a detailed Finite Element Analysis has been carried out on the laminate. Figure 2 shows a view of the model studied (half of the laminate, using its symmetry), the values of the longitudinal stress $\sigma_z$ being represented along lines ABC (middle of the laminate) and DEF (edge of the laminate). The predictions in accordance with Laminate Theory are included for comparison. The Finite Element results shown correspond to the case *n*=1, as corresponding to Figure 1.

It can be clearly seen that there are no significant alterations in the Finite Element predictions versus Laminate Theory results, in what refer to the distribution of the stresses along the line ABC located at the middle of the central section of the laminate. As expected, there are, due to the presence of a free boundary, some alterations in what refer to the same distribution along line DEF located at the edge of

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the laminate. In any case, the alterations are so tiny, that they do not seem to produce any influence in the breakage of the laminate.

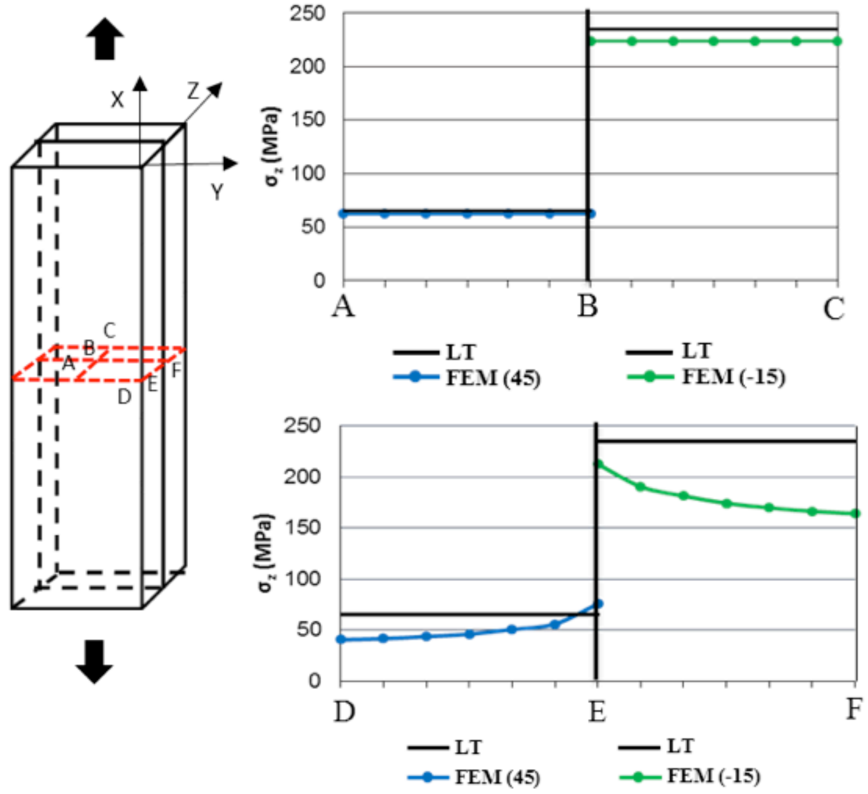


**Figure 2.** Evolution of longitudinal stress through the thickness of a [-45, 15]$_S$ laminate.

## 4. The Scale Effect and a micromechanical view of the starting of the failure

The lack of evidence that the stress state might be directly, and in an isolate way, involved in the scale effect has historically opened the mind to other considerations. A complete view of the scale effect to the light of the double stress and energy criterion has been recently studied by García et al [11], the predictions based in this approach being very close to the experimental results obtained by Parvizzi et al.

The approach, however, predicts that, at the mesoscale level at which the analysis has been carried out (each lamina is considered as homogeneous), there is a minimum size for a crack to develop, i.e. from the absence of cracks, the first crack appearing will have a minimum size, not having arguments, to the light of the double criterion mentioned, to find defects smaller than that corresponding to this size. However, there are many evidences of damage at micromechanical level consistent on isolated debondings between fibre and matrix that appear before a mesocrack is apparent in the lamina.

The purpose of this section is to investigate how the scale effect affects this micromechanical damage. To this end a Boundary Element model, París and Cañas [12], using a program developed by Graciani [13], has being developed. The [0n,90n]$_S$ laminate is taken as reference for this study, as is the laminate more classically studied and consequently that having more experimental results published.

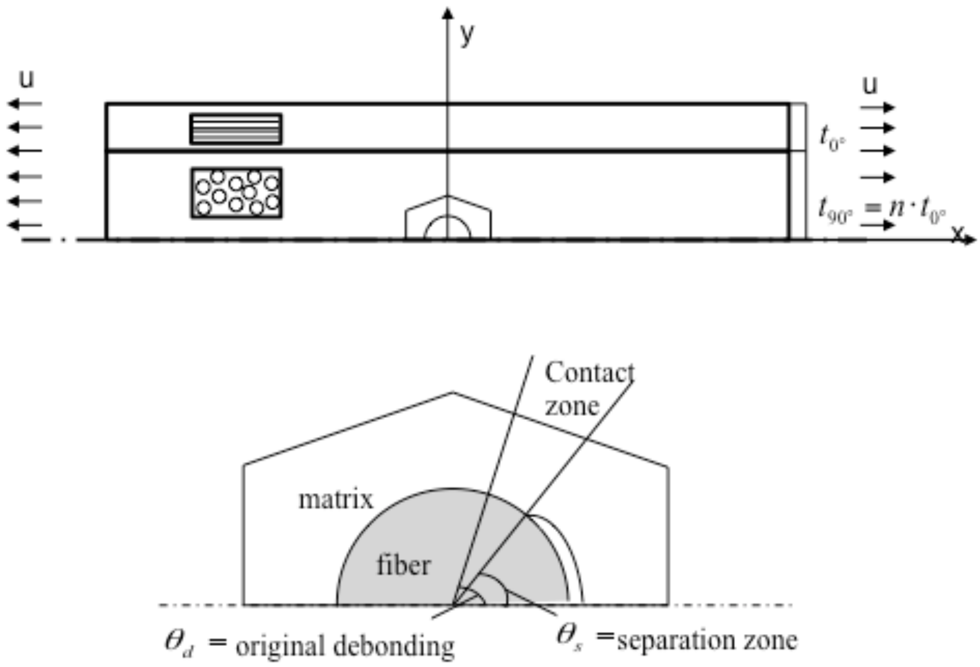


**Figure 3.** Multiscale BEM model of a $[0n, 90n]_S$ laminate with a detail of the micromechanical cell allowing debonding between fibre and matrix.

Figure 3 represents the multiscale BEM model developed for the purpose of question set up. The 0 and 90 degrees plies are modelled as homogeneous ortho and isotropic, respectively, media. A cell at micromechanical level describes the fiber and surrounding matrix, admitting the presence of a crack that can open or close depending on the load applied and on the morphology of the crack in relationship to the load. This model then allows the onset of a damage in a 90 degrees lamina, the debonding of a fibre from the matrix, to be characterized.

The properties of the materials involved in the model are detailed in table 2.

**Table 2.** Elastic properties of the bi-material system.

| Material | Properties |
|---|---|
| 0° ply (orthotropic) | $E_{11}$=135GPa, $E_{22}$=8.75GPa, $E_{33}$=8.75GPa, $\nu_{12}$=0.3, $\nu_{13}$=0.3, $\nu_{23}$=0.4, $G_{12}$=4.75GPa |
| 90° ply (isotropic) | $E(E_{22}=E_{33})$=8.75GPa, $\nu$=0.4 |
| Matrix (epoxy, isotropic) | E=4.2GPa, $\nu$=0.32 |
| Fibre (carbon, isotropic) | E ($E_{22}$)=15GPa, $\nu$=0.2 |

Figure 4 represents the evolution of the energy release rate as a function of the debonding angle $\theta_d$ in the model (semidebonding angle in the actual material).

The evolution obtained agrees with that found for a single fibre embedded in a matrix, París et al [2]. For small values of $\theta_d$ the debonding is small and it is oriented perpendicularly to the load and the dominant mode is the opening mode, mode I. When the debonding grows, it enters into a mixed mode, which transforms in a pure mode II when $\theta_d$ reaches a value in the neighbourhood of 50 degrees.

As mentioned, the values of the total energy release rate, $G_T$ in Figure 4, and its counterparts $G_I$ and $G_{II}$, present similar evolutions as those found in the analysis of a fibre embedded in a matrix in [2]. The most significant alteration is the location, in terms of the debonding angle $\theta_d$, of the maximum

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values of $G_T$, location associated to the end of unstable growth, which could be checked in experimental studies. This alteration might be motivated both by the presence of the *0* degrees lamina and by the presence of an isotropic material surrounding the cell, with properties (those of the *90* degrees lamina) stiffer than those of the matrix existing in the model studied in [2].

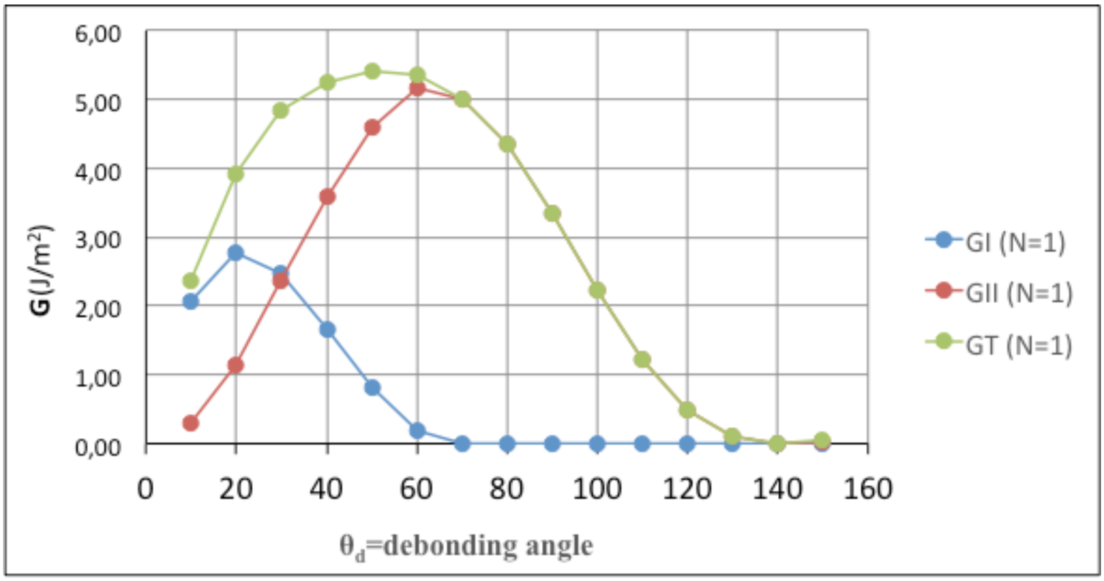


**Figure 4.** Evolution of *G* as a function of the debonding angle.

To check the influence of the scale effect in the damage mechanism investigated the value of *G*, as a function of $\theta_d$, for different values of *n* is represented in figure 5.

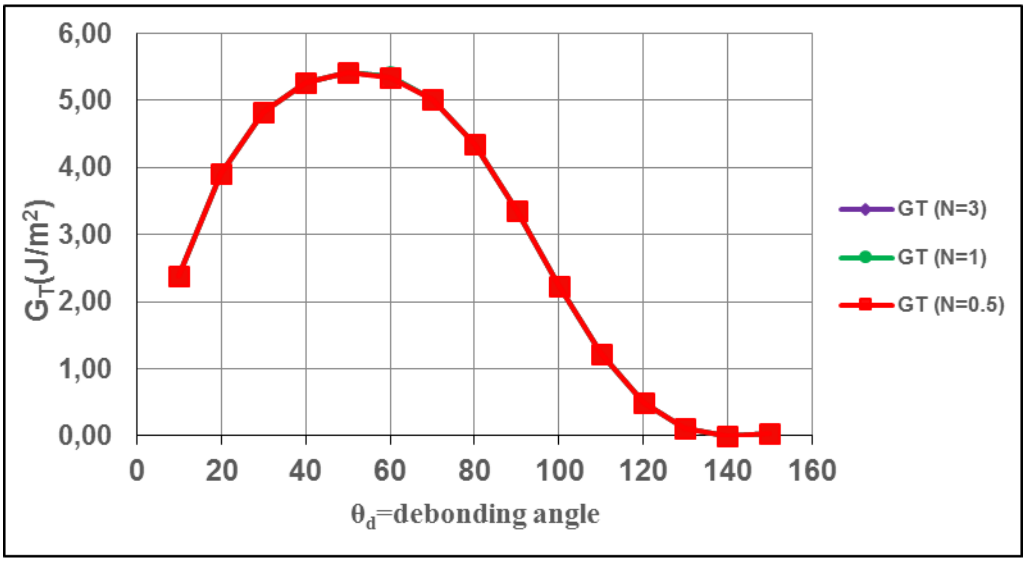


**Figure 5.** Scale effect on the values of the energy release rate *G* corresponding to a debonding crack between fibre and matrix.

As observed from the figure there are no differences between the evolutions of the energy release rate for the three cases analysed (*n*=0.5, 1, 3) what in fact means that the energy released for a potential debonding between fibre and matrix, in presence of a similar stress state, as proved equivalent and

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independent of the scale effect, is in turns independent of the proximity of the potential fibre to fail to the interface with the zero degrees lamina, it being then independent of the scale effect.

## 5. Conclusions

A multiscale model has been developed to give a new insight into the scale effect in composite laminates. First an experimental program has been carried out checking the presence of the scale effect in all laminates tested, the presence of laminas with fibres aligned with the loading direction diminishing the effect.

A detailed stress analysis at mesoscale level has been carried out to try to detect any stress affection that may be in the root of the failures of the laminates. To this end an analytical approach has been followed to detect the appearance and effect of singular stresses. The analysis has indicated that, although verifying the presence of these type of stresses associated to the free boundary and to the presence of different values of the properties of the adjacent layers, the order of the singularity found is very low, the stresses associated not having any influence in the appearance of the failure. A detailed finite element analysis has also been carried out to check if the non singular terms of the stress state might be affected by the free edge and by the different properties of the laminas of the laminate, but the small alterations found do not seem to be in the root of the question under consideration.

Finally, a different scale of studying the composite has been visited looking for the scale effect influence on the incipient onset of failure, the debonding between a fibre and the surrounding matrix. A multiscale BEM model has been developed modeling at a mesoscale the laminas of the laminate as homogeneous and including a cell with a fibre and matrix where the debonding damage between the fibre and the matrix might take place. The results obtained from the analysis have shown that at this scale of the damage there is no influence of the scale effect on the onset of the damage, the debonding between fibre and matrix, as neither the nominal stresses nor the energy released by a potential debonding crack between fibre and matrix are affected by the proximity to the adjacent laminas.

All this means that there is no reason for finding, to the light of a double stress and energy criterion, different level of micromechanical damage for similar laminates, although affected by the scale effect. In other words, the level of load at which micromechanical damage, consisting on isolated debonding between fibres and matrix, is observed in experiments, must be very similar, this level of load not being controlled by the scale effect.

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