FAILURE MECHANISMS INVOLVED IN THE UNFOLDING FAILURE

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Abstract
Newer aircraft structures include composite laminates in stringers with a very high curvature in its section. Highly-curved zones of composite laminates are prone to delamination, denominated unfolding failure, when the curved part is loaded under an opening bending moment. This failure mechanism has been classically associated to the interlaminar tensile stresses. However, when applying a failure criterion based on those stresses to composite laminate a thickness-dependence of the interlaminar tensile strength is obtained, with higher strengths in thicker laminates. This thickness dependence has not a reliable explanation yet. It may be associated to defects such as porosity, although porosity should not be greater in thinner laminates. The present work aims to explain this thickness-dependence based on the idea of a second failure mechanism denominated induced unfolding. This failure mechanism considers the initiation of the crack as an in-plane failure, which, under a high enough interlaminar normal stress, turns into an interlaminar failure. This failure mechanism is validated by comparison with experimental results in two different ways: comparison of the stresses at the failure point and comparison of the crack locations through the thickness.

1. Introduction

The tendency to reduce the weight of aircraft structures and the fuel consumption is the main reason of the high percentage of composite materials included in the aeronautical structural components. This increasing use of composites resulted in the use of these materials in components with a higher curvature, such as L-sectioned or T-sectioned beams, which require the consideration of specific failure mechanisms. This is the case of the unfolding failure, a delamination caused when the curved laminate is loaded with a bending moment which tries to flatten the geometry.

When a laminate is loaded with an opening bending moment, its plies try to separate as the pages in a book, due to the different lengths of the plies in the inner and outer radius, which causes the apparition of interlaminar normal stresses (INS). Unfolding failure has been classically associated to these stresses. In this line, delamination failure criteria typically consider only interlaminar stresses. One of the most common delamination criteria for the unfolding failure is the Kim and Soni criterion [1], which considers and ellipsoid between interlaminar normal and shear stresses. Brewer and Lagacé [2] developed a similar criterion decoupling the compression and tension zones of the INS, considering two different ellipsoids. The advantage of this decoupling into two ellipsoids remains in the difficulties to obtain the interlaminar compression strength. In Brewer and Lagacé criterion, the interlaminar compression strength does not affect to the tension ellipsoid.

Only a few authors have considered the effect of the stresses in the in-plane directions in a delamination, such as Wisnom et al. [3]. Wisnom et al. obtain a matrix effective stress from the stresses in all the directions, included the stresses in the fiber direction which is pondered with the stiffness relation matrix-fiber. This effective stress is compared with the strength in the matrix direction.

Stresses prior to the failure criterion application may be obtained with Ko and Jackson's equations [4], which are an extension to composite laminates of the equations developed by Lekhnitskii et al. [5]. Ko and Jackson's equations are applied to determine stresses in curved laminates loaded under end loads and bending moment.

Since the unfolding is classically associated with the INS, the failure is highly dominated by the InterLaminar Tensile Strength (ILTS), which is obtained typically with a four-point bending test of a curved specimen [6]. Notwithstanding, when the four-point bending test is applied to quasi-isotropic CFRP laminates and the Kim and Soni or the Brewer and Lagacé delamination criterion is applied, a thickness-dependence of the ILTS is observed [7], where thinner laminates show lower ILTS.

This thickness dependence has not a reliable physical explanation yet, although sometimes it has been associated to internal defects such as porosity [8] or to the free-edge effect [9]. However, these effects should not be higher when the laminate is thinner.

In the present document, the thickness dependence is explained considering a different failure mechanism consisting in the propagation of the interlaminar crack from a preliminary intralaminar failure, in this case a matrix failure. This kind of failure has been previously analyzed by others authors such as Sun and Kelly [10,11] and Martin and Jackson [12]. The particular case shown in the present document is characterized by a pure bending moment, where no shear stresses are given in the curved zone and, therefore, the propagation of the in-plane failure as an interlaminar crack is not obvious.

Deeper information of this kind of failure may be found in González-Cantero et al. [13], where the competing failure mechanisms are analyzed in detail.

2. Traditional unfolding vs. induced unfolding

The traditional unfolding concept assumes that failure is associated to the interlaminar stresses. The opening bending moment induces a stress state with dominant in-plane stresses and INS. However, the high strength associated to the in-plane fiber direction respect to that associated to the interlaminar direction causes that the interlaminar failure occurs in many cases previous to the interlaminar failure.

Due to the previous concept, the failure load of the specimens tested in the four-point bending test [6] is classically evaluated in the INS. In that way, the INS at the failure point is assumed as the ILTS, which will be denominated as apparent ILTS in the following, since this stress is supposed to be the only responsible of the failure. However, quasi-isotropic CFRP laminates have shown thickness dependence [7] of this apparent ILTS, which make us to question the validity of the traditional unfolding concept.

In the other side, the induced unfolding concept assumes that the interlaminar failure may be originated by a previous intralaminar failure, even when the interlaminar failure is initiated in the absence of interlaminar shear stresses that may help to change the crack direction to the interlaminar one. In the present case of a pure bending load, the 90º plies (which fibers perpendicular to the plane of interest, where the curved section is located) may fail by tension causing an in-plane matrix crack perpendicular to the interfaces with the adjacent plies. The propagation of this intralaminar crack may cause some interlaminar defects, and the interface of the ply with the non-90º adjacent plies are delaminated [14]. The appearance of the induced unfolding will be favored by the presence of high INS. At the same time, the presence of the intralaminar failure permits the onset of delaminations in presence of INS lower than the ILTS.

3. Experimental results

With the purpose of demonstrating the existence of the induced unfolding, Airbus Operations S.A. and TEAMS S.L. provided us some four-point bending test results over L-sectioned beams in CFRP composite laminates of UD plies with a ply thickness of 0.184 mm. Tests were carried out over six different kinds of specimens, with 6 coupons per kind of specimen. Stacking sequences of the specimens are summarized in Table 1.

Table 1. Specimens definition.

Name	Stacking sequence
SM1	[45 -45 90 45 0 -45 90 -45 45]
SM2	$[45\ {-45}\ 90\ {-45}\ 45\ 0\ 45\ {-45}]_S$
SM3	$[45\ {-45}\ 90\ {-45}\ 45\ 0\ 45\ {-45}]_S$
SM4	$[45\ {-45}\ 90\ 90\ {-45}\ 45\ 0\ 45\ {-45}\ 45\ {-45}\ 0\ 45\ {-45}]_S$
SM5	$[45\ 0\ {-45}\ 90\ 45\ 0\ {-45}\ 90\ 45\ 0\ {-45}\ 90\ 45\ 0\ {-45}\ 90\ 45\ 0\ {-45}\ 90\ 45\ 0\ {-45}\ 90]_S$
SM6	$[45\ {-45}\ 90\ 90\ 90\ {-45}\ 45\ 0\ 0\ 45\ {-45}\ 45\ {-45}\ 0\ 45\ {-45}\ 45\ {-45}\ 45\ {-45}\ 45\ {-45}\ 45\ {-45}]_S$

The failure load is obtained for each coupon, and the bending moment may be obtained from the failure load using a non-linear methodology such as the one defined in the ASTM procedure [6]. Interlaminar stresses for the calculated bending moment may be obtained by the use of the Ko and Jackson's equations [4]. However, the 90º plies stresses are very sensitive to the plane state considerations, so for a high accuracy in its calculation a 3D model, such as FEM, is required. In the present case, the three-dimensional model used is the developed by the authors in [15].

Table 2 shows the differences in the calculation of the INS of the Ko and Jackson's equations with assumptions of plane strain or plain stress with the 3D model [15]. In this stress, differences between Ko and Jackson with plane strain and the 3D model are negligible.

Table 2. $\sigma_{33,\max}$ values obtained with different models.

Specimen	K&J Plane Strain	K&J Plane Stress	3D model
SM1	0.5844	0.6663	0.5948
SM2/SM3	0.7437	0.9189	0.7421
SM4	0.9166	1.0218	0.9149
SM5	0.8565	0.8646	0.8565
SM6	0.9272	0.9481	0.9229

However, differences in the matrix in-plane stress, which are shown in Table 3, are much higher for some specimens. In particular, specimen SM1, due to the small asymmetry in the stacking sequence, show a 20% of difference between the value obtained with the 3D model and the value obtained with the Ko and Jackson's equations with plane strain.

Table 3. $\sigma_{22,max}$ values obtained with different models.

Specimen	K&J Plane Strain	K&J Plane Stress	3D model
SM1	0.8443	3.6978	1.0638
SM2/SM3	0.9722	2.6575	0.9687
SM4	1.1667	2.4186	1.1632
SM5	0.7863	1.0465	0.7895
SM6	1.0834	1.7527	1.0769

3.1. Evidences based on the stress state at failure

First evidences of the existence of the unfolding failure are given by the stress state of the curved laminate at the failure load. Figure 1 shows the maximum INS (non-dimensionalized with the matrix in-plane strength, S_{22}) respect to the number of plies of the laminate, N_p.

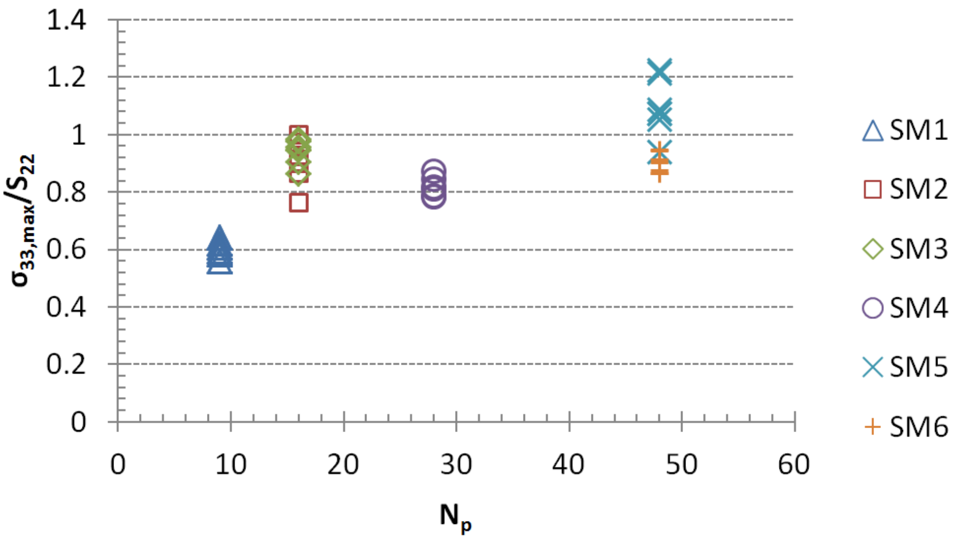

Figure 1. Apparent ILTS of the coupons.

The thickness dependence of the apparent ILTS is observed, where the thinner laminate has almost a 50% apparent ILTS in comparison with thicker ones. However, the tendency is not so clear since specimens with the same thickness have significant deviations in the value of the apparent ILTS.

Conversely, Figure 2 shows the maximum stress in the matrix in-plane direction at the failure load, non-dimensionalized with the matrix in-plane strength, which is given generally at the 90º plies, respect to the number of plies.

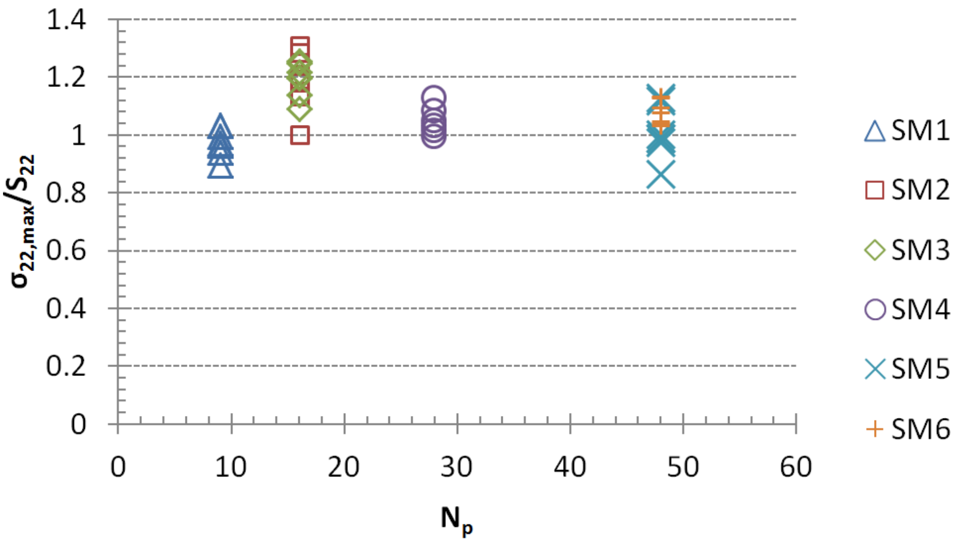

Figure 2. Maximum stress in the matrix direction of the coupons.

The stress state agrees with a failure originated by the in-plane stress in the matrix direction instead of a failure initiated by an INS.

Supposing that the strength in the in-plane matrix direction, S_{22}, and that the ILTS have the same value, most coupons should have failed due to the induced unfolding, and only SM5 may have failed by traditional unfolding.

3.2. Evidences based on the location of the delamination observed

Second evidences of the existence of the unfolding failure are given by the location of the delamination cracks through the thickness. Traditional unfolding and induced unfolding are initiated by different stresses and, consequently, failure should be initiated in different locations. While the maximum of the INS is typically reached below and near the mean radius, the maximum of the in-plane stress is obtained near the inner radius.

Tested coupons present several delaminations, being impossible to determine which of them appeared first in the failure of the sample.

However, if one of the above mentioned mechanisms has taken place, at least one of the delamination cracks present in the failed sample should be located in the position predicted by that failure mechanism.

Consequently, the analysis have been carried out over all the coupons, obtaining the percentage of coupons of each kind of specimen containing a crack in the position predicted by the traditional unfolding, and the percentage of specimens containing a crack in the position predicted by the induced unfolding.

All specimens have presented a 100% of correlation with the position predicted by the induced unfolding. However, the correlation with the traditional unfolding is much lower. The most representative specimens are specimens SM4, where only a 29% of the specimens have a crack where predicted by the traditional unfolding, and specimens SM6, where a 43% of the specimens have a crack where the traditional unfolding predicts.

An example of a SM4 coupon is depicted in Figure 3, and an example of a SM6 coupon is depicted in

Figure 4, where the stress distributions are superimposed in the pictures. In both cases it can be appreciated that there are no delamination cracks in the location predicted by the traditional unfolding, although there are cracks near to the predicted position. Additional images are shown in [13], where the differences are higher.

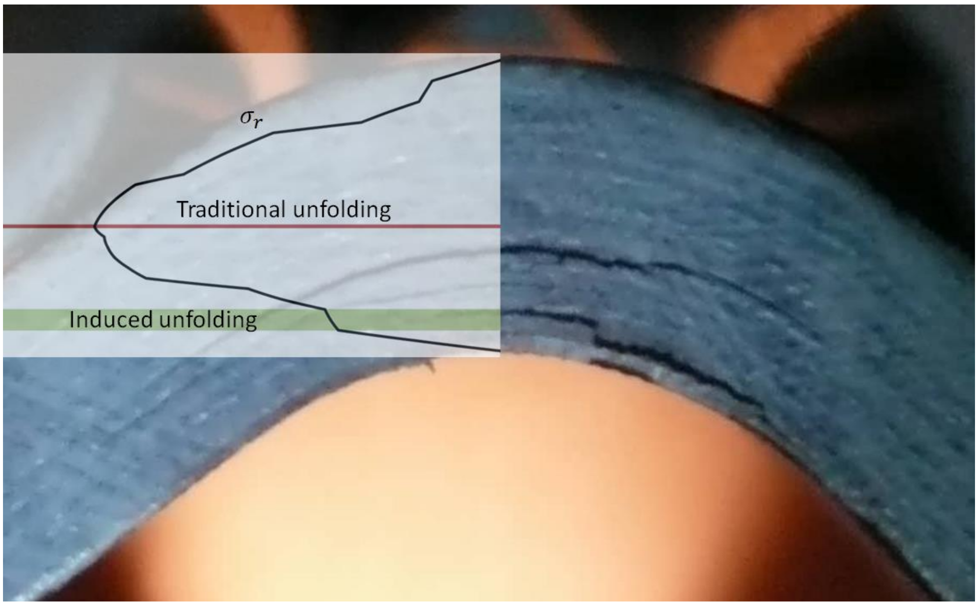

Figure 3. Location of the delaminations in a SM4 coupon.

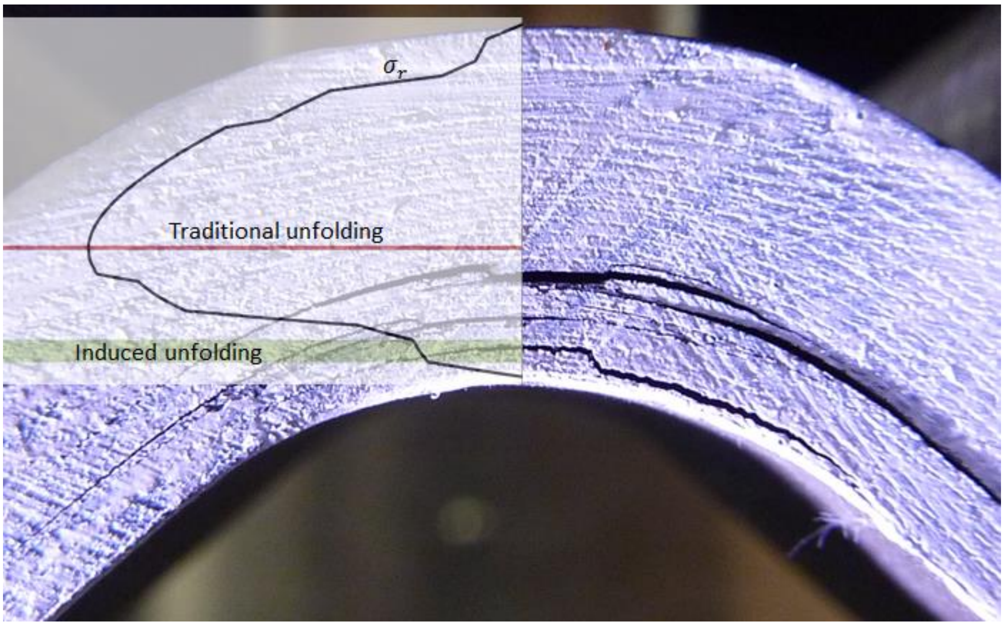

Figure 4. Location of the delaminations in a SM6 coupon.

Respect to the other kinds of specimens, SM5 has a 70% of agreement with the traditional unfolding and SM2 and SM3 (which have the same stacking sequence) have a 100% of agreement with the traditional unfolding. SM1 is difficult to analyze due to the small thickness, and a 100% of agreement with the traditional unfolding has been deduced.

4. Conclusions

Curved composite laminates are prone to delamination when they are loaded under an opening bending moment, a failure mode denominated unfolding failure. This failure has been classically associated to the interlaminar normal stresses (INS). However, results obtained in the four-point bending test for CFRP curved laminates imply a thickness dependence of the interlaminar tensile strength (ILTS).

This thickness dependence may be associated to a failure initiation due to in-plane stresses, in the present case a matrix failure in the in-plane directions. The matrix failure causes an intralaminar crack which, under a high enough INS propagates interlaminarly. This kind of failure has been denominated induced unfolding failure, to distinguish it from the traditional unfolding failure.

The present work shows some evidences of the existence of this failure mechanism. The evidences are based on two different experimental observations.

The first observation is based on the failure load, which let us to calculate the stress state and compare the maximum INS and the maximum matrix in-plane stress. Thickness dependence is observed in the maximum INS, since the maximum in-plane stress normal to the fibers is almost constant.

The second observation is based on the delamination crack location, comparing the location predicted by both traditional and induced unfolding with the delamination observed in the samples. The induced unfolding has presented a much higher agreement in the delamination location than the traditional unfolding.

Results from the present work are not conclusive since there are many delamination cracks and a deeper analysis is required, which will be done in future researches.

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