Premature failures in standard test specimens with composite materials induced by stress singularities in adhesive joints

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Abstract

This work presents three examples of standard test configurations, involving composite materials, and the presence of stress singularities induced by adhesive joints which provokes premature failures, leading to underestimated strength values. Slight modifications of the local geometry, to remove, or reduce, in these critical points, the order of the stress singularities, have shown to give higher experimental failure loads, with almost double failure loads in the most striking cases.

The three examples covered in the present work are: a) the tensile and shear strength determination of a bimaterial interface, b) the off-axis tension test, for the intralaminar shear strength of unidirectional long fibre composite materials and c) the compression test of thick composite laminates. In two of the three cases, the premature failure occurs at the corner where the tab (which is necessary for the grip jaw faces of the testing machine) is bonded to the composite laminate, while in the third one the failure occurs at the bimaterial interface of the two materials, all of them involving an adhesively bonded joint and corner configurations with stress singularities.

With the use of a semi-analytical tool, developed by the authors, to calculate the order of stress singularities, slight and very local geometrical modifications have been successfully carried out to eliminate the stress singularity configuration. After the modifications, higher failure loads have been obtained in the tests carried out.

Keywords: Stress singularities; Off-axis; Compression strength; Bimaterial strength.

1. Introduction

In many laboratory mechanical tests for the characterization of composite materials, tabs at the ends of the sample are used to allow a smooth load application. Good laboratory practices and most of the test standards discard test results when failure occur at the tab, or near the tab, due to the uncertainty in the stress field and consequently in the test result. The tabs, which are typically bonded to the materials to be tested, generate complex configurations, where different materials meet, and induce stress concentrations or stress singularities, responsible for premature failures in the tests. Thus, the obtained strength in the test might not be fully representative of the real strength of the material. In the same context, the strength determination of a bimaterial interfaces is also problematic because the abrupt change in the material properties also induces stress singularities, altering the measured strength value of the bimaterial interface. The influence of the stress singularities in the initiation of failure has been extensively studied in literature and effort has been devoted in characterizing the singular parameters defining the singularity stress field [1,2], in adhesive joints [3-6], using statistic approaches [7], more recent numerical approaches using XFEM [8] or the coupled stress and energy criterion [9]. The effect of eliminating these critical points in the adhesive joints has a clear influence with the experimental results at failure [10]. It is not the aim of the present paper to give a comprehensive review of the works addressing the role of the singularity stress field in the initiation of failure of multimaterial corners, but only to show how, in some cases, standard test configurations with adhesive joints (between materials or between the material and the tabs) may have a premature failure induced by the stress singularity at these opoints.

The multimaterial configurations appear typically at the ends of the samples, where the tabs are bonded to the specimen. In these multimaterial corners, and considering a linear elastic analysis, the stresses are singular, these stress singularities depending on the mechanical properties of the materials and the local geometry and boundary conditions at the corner.

Due to the fact that the mechanical properties of the materials to be tested cannot be modified, in the present work it will be shown how slight modifications of the local corner geometry, where the tabs are adhesively bonded to the test specimen allow the singularity stress field to disappear (or to be reduced) and, consequently, the failure load to be increased, provided the failure is induced by these singularity stress fields. Thus, the real strength of the material, or the interface, being obtained.

In the present work, a brief description of the tool used to evaluate the singularity stress field will be introduced in Section 2. Then, three practical examples will be analyzed.

As a first example, in Section 3, the strength determination (in tension and in shear) of the bimaterial interface between a unidirectional composite material and an epoxy adhesive will be addressed. The correct determination of these strengths is a major problem to be able to predict failure in adhesive joints with composite materials.

A second example, in Section 4, the well-known off axis tension test, for the determination of the intralaminar shear strength of unidirectional composite materials will be analyzed. To avoid premature failures at the ends of the sample, at (or near) the bonded tabs, the study of the stress singularities appearing at these critical points will be carried out to propose corner configurations leading to the removal of the stress singularities.

A third example, in Section 5, will present the analysis of the thick laminates compression test, in which part of the compression load is applied by means of shear stresses at the tabs bonded to the specimen. It will be shown that slight modifications of the tab-end bonded to the specimen, leading to the reductions of the stress singularities at these points, has allowed the increment of the compression failure load.

In these three examples, it will be shown that the stress singularities appearing at the multimaterial corners generated at the adhesively bonded joints of the sample with the tabs are responsible of premature failures. When these corner configurations are adequately modified (in terms of the local geometry of the corner) to remove, or to diminish, the stress singularity field, the failure loads of the tests significantly increase.

2. Characterization of stress singularities

In all the examples covered in the present work, a similar configuration appears where different materials meet at the same point. In two of the cases, this multimaterial corner is generated by the adhesive bonding of tabs at the ends of the test samples, whereas in the other case, the multimaterial corner appears due to the direct adhesive bonding of two different materials. In these points, where the mechanical properties of the materials change abruptly and/or there is an abrupt change in the geometry, stress singularities appear. Taking a polar coordinate system (r,θ) centered at the corner tip, the asymptotic representation of the stresses can be expressed as [2]:

$$\sigma_{\alpha\beta}(r,\theta) = \sum_k K_k r_{\alpha\beta}^{-\delta_k} f_{\alpha\beta}^{(k)}(\theta) \qquad (1)$$

(1)

where K_k are the Generalized Stress Intensity Factors (GSIFs), $0<\delta_k<1$ are the order of stress singularities, and $f_{\alpha\beta}^{(k)}(\theta)$ are the characteristic angular shape functions. We will not consider here those few particular cases where the stress representation in (1) does not admit variable separation, for further information about these particular cases, see [11].

For the evaluation of the order of stress singularities, a code developed by the authors has been used. This code allows any number of linear elastic materials (isotropic, orthotropic, anisotropic…) with perfect adhesion or frictional interfaces between materials, and different boundary conditions at the external faces of the wedge (stress free, fixed, symmetry,…). Detailed information about the implementation, capabilities and features of the code can be found in [1, 2].

As mentioned previously, in the three examples included in the present work, the local modifications have been applied to the geometry, in the very close neighbourhood of the corner, slight geometrical changes which do not alter the global load-path behaviour of the test but significantly alter the local singularity stress field, have been applied (when possible) to secondary elements of the samples, such as the tab material or the adhesive used to bond the tabs.

3. Tensile and shear strength of bimaterial interfaces

An essential value for the failure prediction in adhesively bonded joints (in the absence of interface cracks between both materials) is the nominal strength of the bimaterial interface between the adhesive and the adherent. In fact, two strength values are typically needed, the tensile strength and the shear strength.

The use of standard tensile, or shear, test coupons with the two materials, each material on one half of the specimen, generate bimaterial corners with stress singularities [12-15]. Without any further caution, the failure of the specimen may be drastically influenced by these stress singularities, and the obtained strength value could significantly differ from the real one.

The case under study in this first example, in the present work, consists on the interface between a unidirectional carbon fiber laminate (CFRP, AS4-8852) and a structural epoxy adhesive (FM-73M0.6). The mechanical properties of these two materials are: E_{11}=141.3 GPa, E_{22}=E_{33}=9.58 GPa, G_{12}=G_{13}=5.0 GPa, G_{23}=3.5 GPa, ν_{12}=ν_{13}=0.3, ν_{23}=0.32 for the composite material (where subindex "1" refers to the fibre direction) and E=3.0 GPa, ν=0.35 for the adhesive.

For both test coupons, the tensile test and the Iosipescu test, a bimaterial corner with two solid wedges of 90º with perfect adhesion in the common interface, appears along the lateral contour where the two materials meet each other.

With the mechanical properties introduced above and using the tool for the singularity stress characterization developed by the authors [2], there is only one singularity term with a value for the stress singularity exponent of δ=0.219697 [15].

The local geometrical modification in the bimaterial corner consists in a slight machining in the adhesive side (much easier to be machined than the composite material) to get a bimaterial configuration with a 90º wedge in the composite material side, and an adhesive wedge with an angle α ($0<\alpha<90$) necessary to remove the stress singularities. Using the developed tool by the authors, the orders of stress singularities where calculated for different angles α, obtaining δ=0 for a=65º (Figure 1) [15].

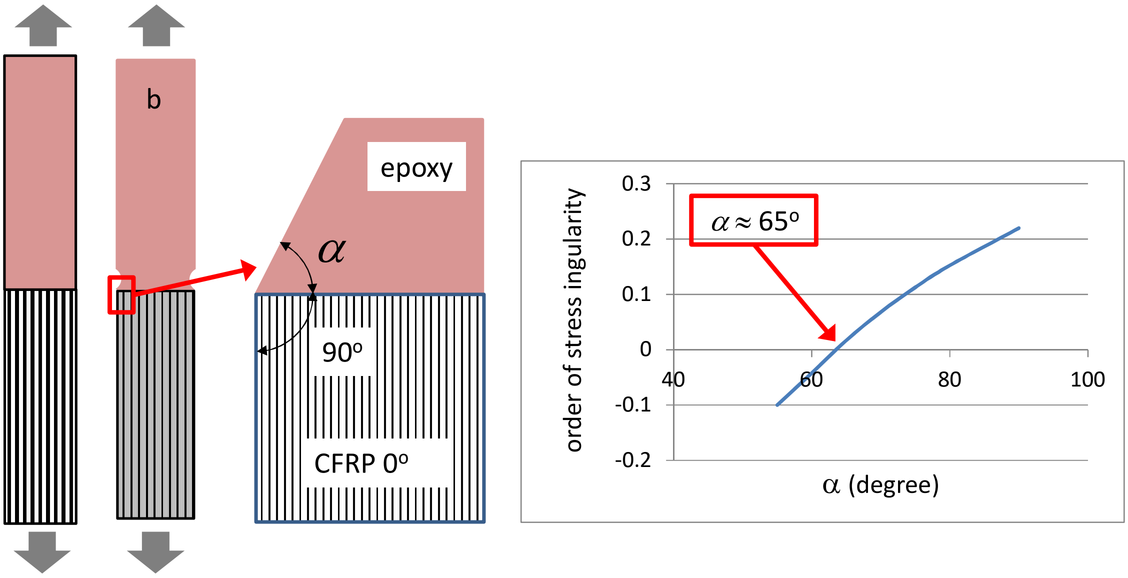


Figure 1. Order of stress singularities for the modified bimaterial corner configuration.

In Figure 2, the modified coupon and the original one for the tensile test (left hand side of figure 2) and for the Iosipescu coupon (right hand side of figure 2)

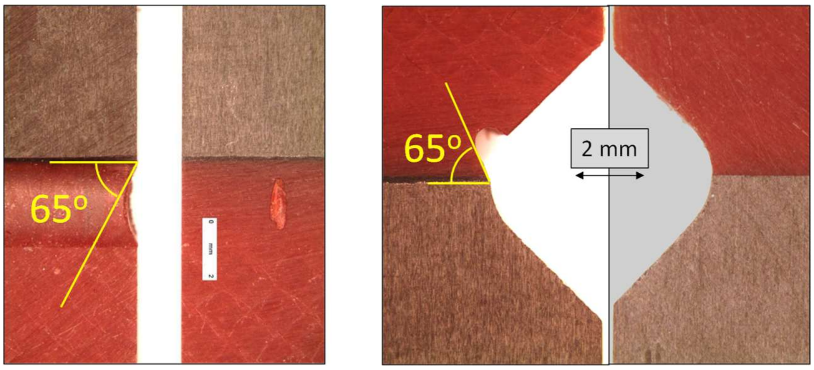


Figure 2. Details of local geometrical modifications to remove stress singularities in tensile test coupons (left hand side) and Iosipescu coupons (right hand side).

In the case of the tensile coupon, the slight local machining consists, as can be seen in Figure 2, in a perimetral machining using a 3 mm (in diameter) tool which only removes 0.2 mm in depth, generating a 65º angle wedge in the adhesive side. In the case of the Iosipescu coupon a notch was done at the interface (1 mm depth).

Two configurations were tested in tension and the same two in shear. The first one having the composite material with the fibres oriented perpendicularly to the interface, and a second one with the fibres parallel to the interface. Both orientations of the fibre makes the bimaterial corner to be different, but the order of stress singularities are the same, due to the orthotropic nature of the composite material, as obtained in [15].

The test results for the tensile case, with the composite material with the fibres perpendicular (and parallel) to the interface are shown in Figure 3a, (and 3b) respectively. The configuration CFRP 0º-Adhesive, is the case with the highest differences between the samples in the original form, without the local modification (and with stress singularities) and the modified samples, with the local notch (without stress singularities). The tensile strength almost duplicates when removing the stress singularity. In the case CFRP 90º-Adhesive, the removal of the stress singularity also increases the failure load but this increment is only around 22% (35% if results from sample “Modified-2” is not taken into account (it has a much lower failure load that the other three samples).

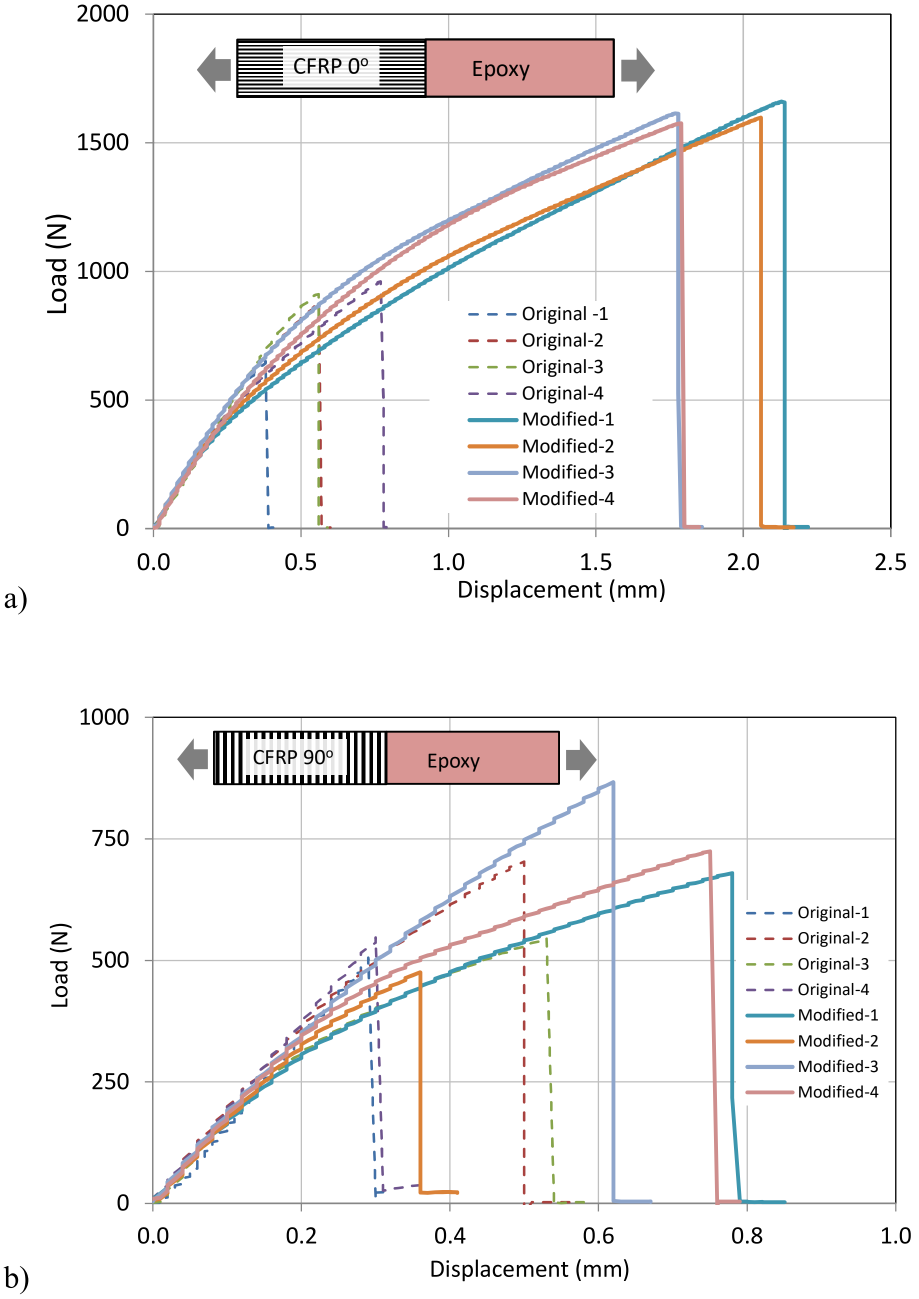


Figure 3. Tensile test results for the coupons with (thick lines) and without (thin lines) bimaterial corner modification, a) CFRP 0º-Adhesive and b) CFRP90º-Adhesive.

Shear tests using the Iosipescu specimen did not show significant differences between samples with and without modifications. While the tensile test specimens present the stress singularity all around the perimeter of the bimaterial interface, the shear test configuration only present the main singularity shear stresses in the thickness side of the specimen. Thus, the removal of the stress singularity field in both samples has a dramatic effect in the tension test samples but a negligible effect in the shear test samples.

4. Off-axis test. Intra-laminar shear strength in unidirectional composite materials.

One of the most used standard tests for the intra-laminar shear strength determination is the off-axis test. In this test, the fibres are not parallel to the loading direction, and it is well known the problems associated to this test regarding the influence of the displacement boundary conditions at the grips, generating non uniform stress states all along the test coupon. In fact, in the last years, new proposals and modification of well-known tests are still being proposed in literature to characterize this mechanical property [16,17].

There are different approaches to solve these problems [18], among which Sun & Chung Proposal [19] stands out, with the use of oblique tabs at the ends of the coupon coinciding with the iso-displacement lines in the longitudinal direction of the sample.

The problem with this test lies in that the shape (inclination) of the tabs depends on the mechanical properties of the material, including one (G_{12}, shear modulus) to be obtained in the test.

In addition to this effect, the solution of the problem, including the determination of the longitudinal iso-displacement lines, depends on the orientation of the fibers, which could be different than 10º.

In summary, for each fiber orientation (θ) out of the tension axis of the sample, the longitudinal iso-displacement lines, and consequently, the optimum angle of the tabs (ϕ) is different.

This effect, well-known in literature, will be supported in the present work using an approach of singular stresses. Assuming perfect clamping in the whole tab area inside the grips, a scheme of the problem is shown in Figure 4, where the so-called corners A and B represent the locations where the singular stresses are expected to appear [20].

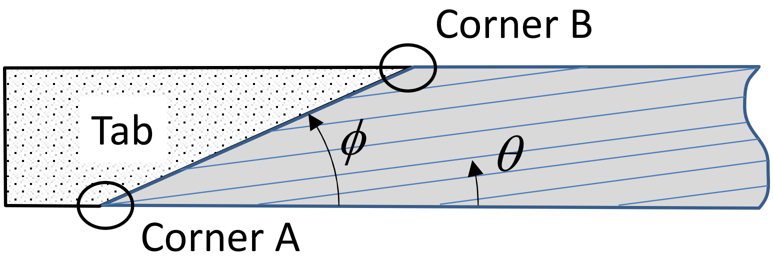


Figure 4. Corners with potential stress singularities at one end of the off axis specimen.

These two corners are similar in geometry, single-wedge material with the same boundary conditions, clamped at the tab and stress-free at the lateral side of the sample. The differences between both corners lay in the wedge angle itself and the relative fiber orientation with respect to the global geometry.

The presence of these singular stress corner configurations may affect, mainly, to the shear strength determination. The premature failure of the sample induced by the presence of these singular stress states could give rise to an underestimated experimental value of the shear strength of the material.

The analysis carried out in the present work has determined the order of stress singularity for each fiber orientation (θ) and tab angle (ϕ) and try to explore if there is a combination of both parameters leading to the removal of the stress singularity configuration at these corners.

Although there are two corners with stress singularities in the test configuration, the internal structure of the material makes that only failures initiated in corner A could progress along the matrix, in shear, and generate a catastrophic failure of the sample. Failures initiated in corner B necessarily need, for the failure to progress, the failure of the fibers, which is unlikely to occur when compared with the other failure path only affecting matrix failure, as the strength affecting the fiber failure is at least one order of magnitude higher than the strength associated to the matrix failure. Thus, in what follows, only results associated to corner A will be presented.

In Figure 5, the orders of stress singularities for corner A for several different orientations of the fibers ($5^{\circ} < \theta < 26^{\circ}$) and different tab angles (ϕ) are shown.

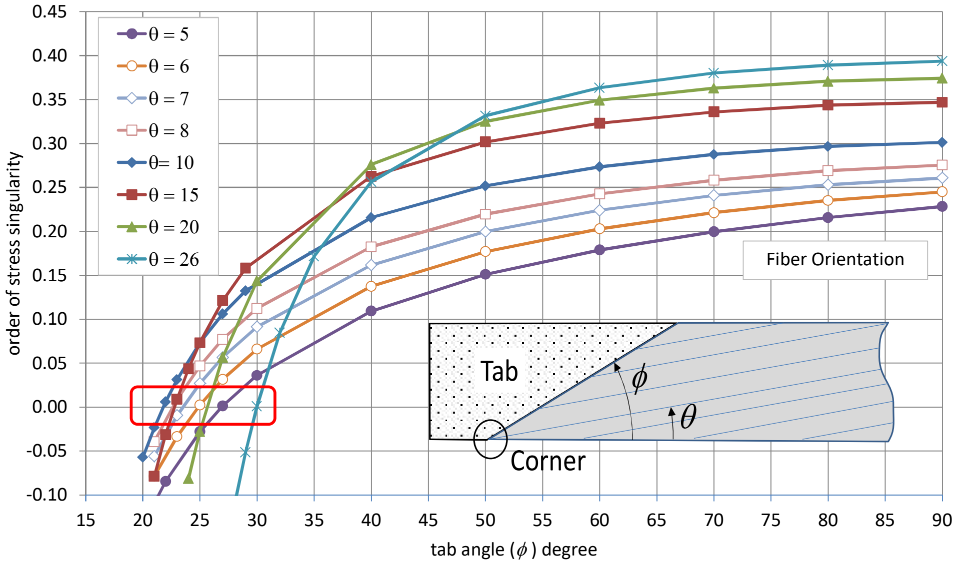


Figure 5. Results of the orders of stress singularities for the off axis tension test with different combinations of fiber orientation and tab angle.

The right hand side of Figure 5 corresponds to test configurations with standard straight tabs (ϕ=90º). As the tab angle is reduced, and depending on the fiber orientation, it is possible, for all combinations of ϕ and θ to eliminate the stress singularity configuration, these combinations of ϕ and θ included in the red box in Figure 5.

Some examples of the tab angle (ϕ) which makes the stress singularity disappear and the theoretical tab angle associated to the longitudinal iso-displacement (u_x=cte), for each fiber orientation (θ) are summarized in Table 1.

θ (º)	ϕ u_x=cte (º)	ϕ no-singularity (º)	Deviation (º)
5	29.6	27.0	-2.6
10	23.1	22.0	-1.1
15	24.2	22.5	-1.7
20	27.5	26.0	-1.5

Table 1. Values for the tab angle, for u_x=cte and to remove the singularity.

The differences between the theoretical tab angle values ϕ to coincide with the longitudinal iso-displacement lines and the tab angle values to remove the stress singularities are low in all cases (below 3º in all fiber orientations), the lowest deviation corresponding to the fiber orientation θ=10º, with a tab angle value of ϕ=22º. This could be considered as the optimum test configuration for the off axis tension test.

5. Compression strength determination in thick composite laminates.

In general, unidirectional composite laminates need the use of end tabs for the application of external loading. In particular, for the determination of the compressive strength in thick unidirectional composite laminates the test sample has a much larger dimension in the tabs than in the free space between tabs, where the sample is expected to be in pure compression (avoiding buckling) and fail.

Besides the direct compression at the end of the samples, an important part of the compression load is applied, in the thick composite laminate samples, by means of shear stresses along the tab area. Although there are standards to carry out this type of tests [21,22], different alternatives and proposals for this test have been proposed [23]

The problem with this test lies in the premature failure at the corner generated by the composite laminate to be tested and the end of the tab, see Figure 6a (corner detail in 6b). A lateral compression is applied in the tab area and when the grips get closer, a significant shear loading is generated along the tab-composite interface which finally results in a pure longitudinal compression in the central part of the sample (the free part of the sample, outside the grips). The original tab configuration, with a 90º tab wedge bonded to the composite sample, originates a stress singularity field and premature failures. The modification proposal in [23] consists in slightly modifying the local tab end, see Figure 6c, using a scarf angle of α=45º at the end tab and filling the free space with epoxy adhesive, also with an angle of β=45º in the contact with the sample.

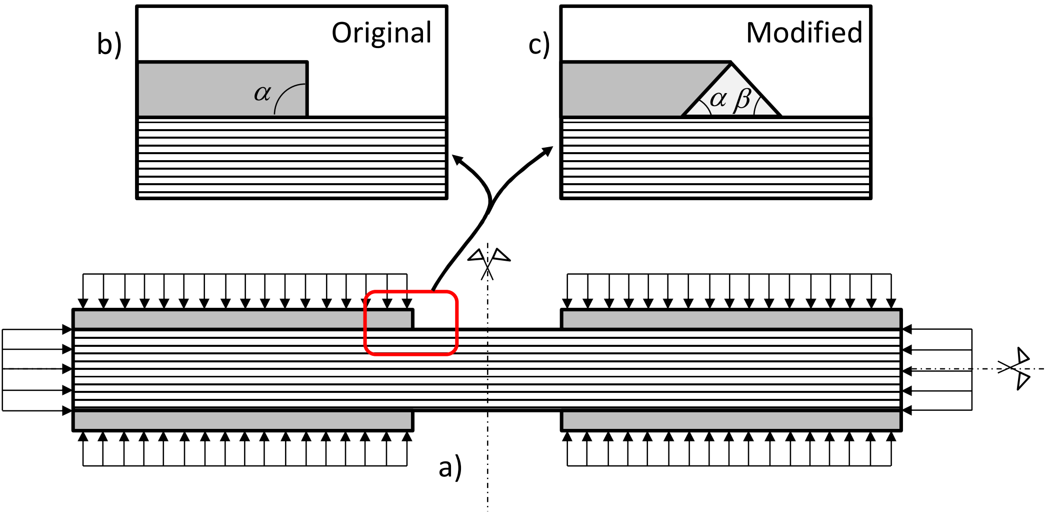


Figure 6. a) Compression test configuration, b) detail of the end-tab original configuration, c) detail of the modified end-tab configuration.

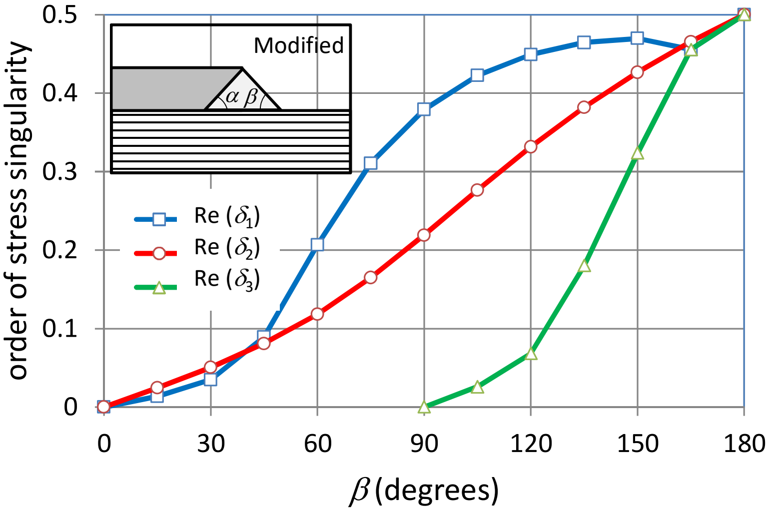
The experimental evidence shows that the proposed modified geometry has higher failure load values in compression. As the epoxy adhesive is more compliant, the lateral compression is clearly generating a less severe stress field at this critical point. Now, using the tool developed by the authors for the stress singularity characterization, a parametric analysis will be presented to check if a different geometrical alternative with a lower stress singularity field can be achieved and might lead to a higher compression strength value.

The mechanical properties of the composite material, the material used for the tab and the adhesive are: composite material (T300/914, E_{11}=129 GPa, E_{22}=E_{33}=8.4 GPa, G_{12}=G_{31}=4.2 GPa, G_{23}=3 GPa, ν_{21}=ν_{31}=0.02, ν_{32}=0.4), tab material, made of glass fibre reinforced plastic (E_{11}=27 GPa, E_{22}=29 GPa, E_{33}=7 GPa, G_{12}=7.4 Gpa, G_{23}=G_{31}=4 GPa, ν_{21}=0.2, ν_{31}=ν_{32}=0.3) and the adhesive (E=2.87 GPa, ν=0.27). As in the previous cases, the mechanical properties of the tested material can not be changed, but in the analysis not only the geometry of the corner is changed but also the mechanical properties of the material used for the tab.

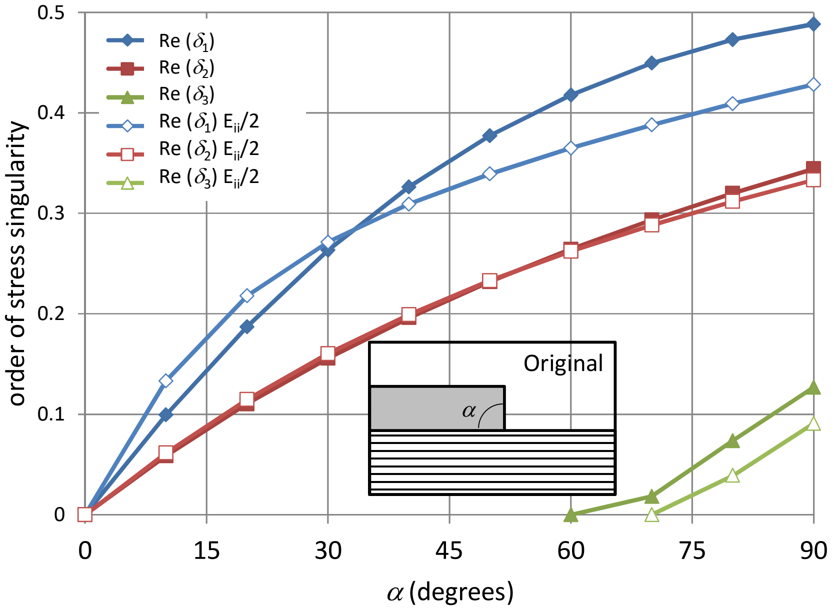
When modifying the original tab end geometry (Figure 6b) to the modified geometry (Figure 6c), a new corner configuration appears. In Figure 6b, there is a bimaterial corner beteween the material to be tested and the tab bonded to the material. In Figure 6c, two corners appear, the first one is a bimaterial corner between the adhesive and the composite material (angle β), the second one is a tri-material corner composed by the composite material, the tab material and the adhesive (angle α). The modification of the original corner configuration now leads to two different singularity problems, which will be sumarized below.

5.1 Bimaterial corner

The orders or stress singularities for the bimaterial corner between the composite material and the adhesive fillet, corresponding to Figure 6c, are shown in Figure 7a in terms of the angle β. The proposal in [23] is for β=45º which corresponds to a δ=0.089. The original corner configuration has a tab angle of 90º, with a corresponding order of stress singularity of δ=0.488 (see Figure 7b), is a scarf angle of 45º is made in the tab material, to make it comparable with the scarf geometry of the proposed geometry, at least in terms of geometry, but with a different material, the order of stress singularity is δ=0.35. Thus, the proposed modification has a much less severe stress singularity field in this point. In Figure 7b, the orders of stress singularities have also been calculated for a more compliant tab material (E_{ii}/2, i=1,2,3).



a)



b)

Figure 7. Order of stress singularities for the bimaterial corner in: a) composite-adhesive corner, b) composite-tab corner.

5.2 Tri-material corner

The proposed modified geometry in [23] generates a new corner with three materials, the composite laminate, the tab material and the adhesive, corresponding with Figure 6c and an angle α=45º. This is a so-called closed-corner, as all the materials are perfectly bonded, with no external faces.

The orders of stress singularities for this corner are shown in Figure 8. The lines with dots represent the values of the orders of stress singularities with the actual mechanical properties of the materials. An alternative evaluation has been made using for the tab a more compliant material, with the three young modulus half of the original values of the tab material ($E_{ii}/2$, i=1,2,3).

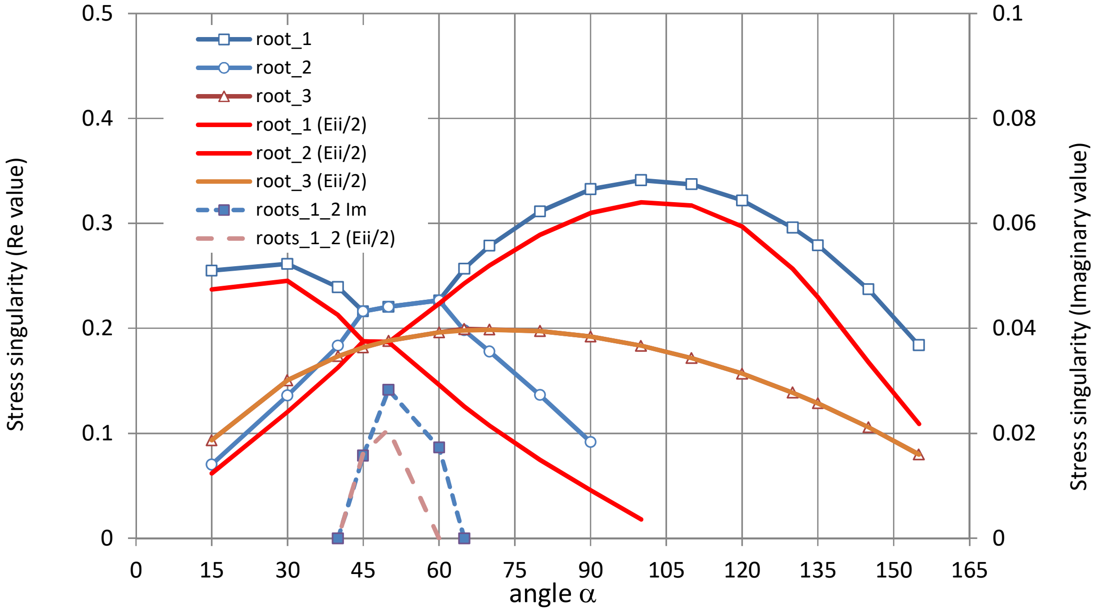


Figure 8. Order of stress singularities for the tri-material corner in the modified geometry.

For both cases (with the original values and half values of the stiffnesses) there are two configurations with low values for the order of stress singularities. The first one for α=45º, which coincides with the proposed corner configuration in [23]. There is a second alternative with lower values for the stress singularities, for α>155º which might generate some difficulties in the tab machining and bonding process.

In [23] there are no data for other corner configurations different that α=45º, but the one with α=45º gives rise to lower stress profiles. It has to be taken into account that nominally, with a linear elastic analysis, the stresses at these corners are unbounded, and the stress singularity analysis carried out in the present work could lead to a better understanding of the most favorable stress fields at these points.

The proposed modification reduces (but not completely removes) the order of stress singularity from δ=0.488 corresponding to the original 90º tab configuration (without adhesive filling), to δ=0.22 corresponding to the modified 45º configuration at the three-material closed corner, with adhesive filling.

The use of compliant materials ($E_{ii}/2$, i=1,2,3) for the tab also reduces the order of stress singularities, as shown in Figure 8 (continuous lines)

6. Conclusions

In the present paper three examples of standard test specimens have been introduced where the adhesive bonding generates multimaterial corners, with nominal singular stress fields, giving rise to premature undesirable experimental failures. The slight modification of the local geometry, in the three cases, has shown that the order of stress singularities can be removed (or at least diminished) and the failure loads have been increased, the real strength values of the test configurations being more realistically determined. In some of the cases, the failure load has been almost doubled when removing the stress singularity configuration.

The three cases studied in the present paper are practical problems of mechanical characterization of materials and interfaces between materials, thus, a correct determination of the strength is of outmost importance.

The three studied problems are: a) the strength determination (in tension and shear) of the bimaterial interface between two materials, b) the intralaminar shear strength determination (of axis test) in unidirectional composite materials, and c) the compression strength in thick composite laminates.

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References

[1] A. Barroso, V. Mantič, F. París. Singularity analysis of anisotropic multimaterial corners. International Journal of Fracture 119 (2003), 1-23

[2] V. Mantič, A. Barroso, F. París, Singular elastic solutions in anisotropic multimaterial corners. Application to composites. Chapter 11 of the book: Mathematical methods and models in composites. 425-495. (2014). Imperial College Press. Editor: V. Mantič.

[3] Chen, Z., Adams, R.D., Da Silva, L.F.M. The use of the J-integral vector to analyse adhesive bonds with and without a crack. International Journal of Adhesion and Adhesives 31 (2011), 48-55.

[4] A. Barroso, V. Mantič, F. París. Representativity of the singular stress state in the failure of adhesively bonded joints between metals and composites, Compos. Sci. Technol. 69 (2009), 1746-1755.

[5] Akhavan-Safar, A., da Silva, L.F.M., Ayatollahi, M.R. An investigation on the strength of single lap adhesive joints with a wide range of materials and dimensions using a critical distance approach. International Journal of Adhesion and Adhesives 78 (2017), 248-255.

[6] Rastegar, S., Ayatollahi, M.R., Akhavan-Safar, A., da Silva, L.F.M. Prediction of the critical stress intensity factor of single-lap adhesive joints using a coupled ratio method and an analytical model. (2018) Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications (in press).

[7] Towse, A., Potter, K.D., Wisnom, M.R., Adams, R.D. The sensitivity of a Weibull failure criterion to singularity strength and local geometry variations. International Journal of Adhesion and Adhesives 19 (1999), 71-82.

[8] Stein N., Dölling S., Chalkiadaki K., Becker W., Weiβgraeber P. Enhanced XFEM for crack deflection in multi-material joints. International Journal of Fracture 207 (2017), 193-210.

[9] Talmon l'Armée A., Becker W. Coupled stress and energy criterion for composite failure: Pointwise versus averaged evaluation of the stress criterion. Mechanics of Advanced Materials and Structures (2019), DOI: 10.1080/15376494.2018.1519618.

[10] Zhao, X., Adams, R.D., Da Silva, L.F.M. Single lap joints with rounded adherend corners: Experimental results and strength prediction. Journal of Adhesion Science and Technology, 25 (2011) 837-856.

[11] Sinclair, G. B. Logarithmic stress singularities resulting from various boundary conditions in angular corners of plates in extension. Journal of Applied Mechanics 66 (1999), 556-559.

[12] B. Lauke, A. Barroso. Notched-butt test for the determination of adhesion strength at bimaterial interfaces, Compos. Interface 18 (2011), 661-669.

[13] B. Lauke, Doubly-curved interfaces for adhesion strength testing, Compos. Interface 18 (2011), 121-133

[14] C. Wetherhold, G.F. Dargush. Improvement of adhesive strength at a bimaterial interface by adjusting the interface angles at the free edge. Theor. Appl. Fract. Mec. 77 (2015), 69-73.

[15] A. Barroso, B. Lauke, V. Mantič, F: París. Tensile and shear strength of bimaterial interfaces within composite materials. Composite Science and Technology 124 (2016), 81-88.

[16] M. Gude, W. Hufenbach, M. Andrich, A. Mertel, R. Schirner, Modified V-notched rail shear test for shear characterisation of textile-reinforced composite materials. Polym. Test. 43 (2015), 147–153.

[17] K.W. Gan, T. Laux, S.T. Taher, J.M. Dulieu-Barton, O.T. Thomsen. A novel fixture for determining the tension/compression-shear failure envelope of multidirectional composite laminates. Compos. Struct. 184 (2018), 662–673.

[18] J.C. Marín, J. Cañas, F. París, J. Morton. Determination of G12 by means of the off-axis tension test. Part I: Review of gripping systems and correction factors. Composites Part A 33 (2002), 87-100.

[19] C.T. Sun, I. Chung. An oblique end-tab design for testing off-axis composite specimens. Composites. 24 (1993), 619-623.

[20] J.C. Marín, J. Justo, A. Barroso, J. Cañas, F. París. On the optimal choice of fibre orientation angle in off-axis tensile test using oblique end-tabs: Theoretical and experimental studies. Composite Science and Technology 178 (2019) 11-25.

[21] ASTM D 6641/D 6641M Standard test method for determining the compressive properties of polymer matrix composite laminates using a combined loading compression (CLC) test fixture. American Society for Testing and Materials, 2001.

[22] ASTM D 3410/D 3410M "Standard test method for compressive properties of polymer matrix composite materials with unsupported gage section by shear loading". American Society for Testing and Materials, 2001.

[23] J. Dogra, J.M. Hodgkinson, P. Robinson, S.T. Pinho, Development of a compression test for thick composite laminates: finite element analysis. 16th International Conference on composite materials, Kyoto, Japan, (2007).