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Analysis of damage and interlaminar stresses in laminate plates with interacting holes

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ABSTRACT

In a laminate plate with an open hole, the damage initiation and progression and the interlaminar stresses that appear close to hole edge are modified when a second hole is made close to the first. The purpose of this study is to analyse the interaction between two holes when the plate is subjected to compressive loads. The Serial/Parallel Mixing Theory is used as the constitutive law of the composite, and a Continuum Damage Model is applied to predict failure initiation and propagation due to fibre microbuckling and matrix cracking. The model is validated using data from the literature. The developed model is able to predict the differences in the initiation and propagation of damage due to fibre microbuckling and matrix cracking in the area around the two holes. The variation of the distance between holes significantly modifies the damage due to both mechanisms. Also, the interlaminar stresses along the laminate thickness are changed. The results of this study can be applied to predict the critical distance between holes to avoid damage initiation by matrix cracking and microbuckling.

1. Introduction

The use of composite materials in the manufacture of structural components is widespread in many applications. High strength and stiffness with low density as well as the possibility of customizing the fabrication processes are the main reasons for a number of such applications. Lately, the necessity of providing optimized properties and novel possibilities has spread to the exploration of natural composite materials to complement traditional composite materials. Nanofibrillated or nanocrystalline cellulose from sugar palm fibres [1,2] have been used as reinforcements for a polymeric matrix [3] and can serve as application examples. Moreover, natural composite materials can even help to decrease emissions, reduce pollution and waste disposal impact as biodegradable reinforcement materials [4], or consider processes of properties optimization [5,6]. However, traditional composite materials such as carbon fibre/epoxy are still widely used due to their better mechanical properties and are far from being replaced in applications where strength and stiffness are the design requirements. Although the behaviour of these materials has been widely studied, the necessity of having proper models to explain the complexity of the stress states and mechanical properties still requires experimental approaches and computationally efficient numerical codes.

A hole in a laminate structure produces a stress concentration phenomenon in the area close to the edge of the hole that decreases the

mechanical strength or the stiffness of the laminate and therefore reduces the bearing capability of the structure.

Notches, holes and cut-out are mainly present in lightweight structures; and thus the prediction of the strength, failure modes, and damage initiation and propagation in open-hole laminates has a direct implication in the improvement of structural design. Several approaches can be applied to predict the initiation and progression of damage in a laminate, such as Fracture Mechanic models, Continuum Damage models or Discrete Damage models [7–14]. In many studies, the accuracy of these models has been validated using open-hole-laminate tensile tests [14–19]. This is because experimental tensile tests can be relatively easy carried out and enable comparing the features of the models in complex three-dimensional stress fields.

Among the different models proposed, the Serial/Parallel Mixing Theory (S/PMT) [20] as the constitutive law of the composite, and a Continuum Damage Mechanics (CDM) model based in Kachanov's proposals [21] can be used to describe the fibre and matrix damage. This approach can predict the behaviour of a laminate from fibre and matrix properties, without needing a complex formulation at a micromechanical level. In addition, it allows the use of different behaviours for compression and tension, or different constitutive equations for fibre and matrix. The S/PMT has been successfully applied to predict failure initiation due to microbuckling in laminates under compressive loads [22] and delamination [23]. It has also been used in fatigue and

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vibrations problems [24,25]. The S/PMT has not been used to study the influence of the interlaminar stresses in problems with stress concentration in situations where several holes are present.

In many cases in a structure, there are multiple holes close to each other. When a second hole is added to a single-hole laminate; both the in-plane stress concentration in the plane close to the holes and the global response of the laminate are modified. These two factors are a function of several parameters such as the relative position of the holes, relative sizes, etc. In the scientific literature, the effect of interacting holes in the in-plane stress concentration factor has been studied, analysing the influence of geometric parameters such as the distance between the holes and the relative radius between the two holes [26–30]. Another geometry parameter that has been studied is the angular position of the holes in relation to the load direction [26,29–31]. Also, the influence of ply orientations and the stacking sequence have been analysed [28,32]. Although two circular holes are generally selected, there are studies of the interaction of a greater number of holes [28] or even rectangular and elliptical holes [32–35]. Despite the studies cited, not enough information exists on the effect of interacting holes in the initiation and progression of damage.

Ubaid et al. [30] used a tri-dimensional model to analyse a plate subjected to tension, with two holes in three configurations, series, parallel and oblique with respect to the direction of load application. They studied the damage around the holes to identify the point where matrix damage initiates in each configuration. They evaluated the influence of the distance between holes but only in the in-plane stress concentration factor. The effect is not clear when the distance between holes increases because an edge effect begins to appear when the holes approach the free edge of the plate due to the small size of the plate used.

The behaviour of an open-hole laminate under compressive or tensile loads is different. In compression, fibre microbuckling in the plies orientated at 0° is the governing failure mechanism. Depending on the stacking sequence, fibre microbuckling [26,36] or matrix cracking [31] appear first. Afterwards, the damage in the laminate grows, with a combination of failure modes (fibre and matrix damage that leads to delamination failure).

Suemasu et al. [36] studied experimentally the failure mechanisms of laminates with a hole subjected to compression loads. They evaluated the stresses and damage propagation close to the hole-edge using a numerical model. In all the configurations modelled, fibre microbuckling was the first damage mode that appeared.

Khedkar et al. [31] studied the same geometrical configurations as Suemasu et al. [36] and predicted the onset of damage for each failure mode by a relatively simple numerical model, identifying the ply and the angular position where the damage appears. The model was validated with experimental results, using the global response of the laminate and the strain field as variables for the validation.

In addition to the in-plane stresses, interlaminar stresses appear at the edge of the hole due to a mismatch in stiffness between plies with different orientation and the need to verify the boundary condition at the free edge [22,37]. In the literature, there are several works that study the interlaminar stresses in laminates in which there is only one open hole [22,36–37], but no studies have been found focused on the effect of the interaction between two or more holes in these stress components. Interlaminar stresses are dangerous since they can cause matrix failure and delamination as the stiffness and interlaminar strength of a laminate are relatively low [38,39]. For this reason, more information about this topic is required. To analyse this type of problems, three-dimensional models are needed.

In this work, the damage initiation and propagation in laminates with two holes subjected to a uniaxial compressive load is studied. The influence of the interaction between the two holes on the out-of-plane stress components is also evaluated. The S/PMT is used to estimate the constitutive behaviour of the composite and a Continuum Damage Model to describe the sequence failure by fibre microbuckling and matrix cracking. The model is verified in terms of strain in the area close to the holes using data from the literature. The influence of the relative

position between holes in both damage mechanisms and in the interlaminar stresses is analysed.

2. Model description

The model used in this work combines the S/PMT as constitutive law of the material and a CDM model to describe damage initiation and propagation. The model is implemented in a Finite Elements Method (FEM) custom code.

The damage model equations, as well as the constitutive law equations, are solved in every quadrature point in the FEM code by executing two iterative loops. The outer loop allows the external forces to be equal to the internal forces while the inner loop solves the S/PMT non-linear equations guaranteeing convergence. The FEM code and the iteration method are described by the authors of this work in [22].

The CDM model is based on the ideas proposed by Kachanov [21]. In order to describe the fibre and matrix degradation, the constitutive law proposed by Oller [40] is applied as described in Eqs. (1) and (2). This law uses an isotropic damage scalar model for every constituent and a scalar damage variable for fibre and matrix. In this way, the constitutive laws for both fibre and matrix can be written as:

$$\sigma_f = (1 - d_f) C_o^f \varepsilon_f \quad (1)$$

$$\sigma_m = (1 - d_m) C_o^m \varepsilon_m \quad (2)$$

Where σ_f , σ_m , ε_f and ε_m represent the stress and strain tensor components in Voigt notation for fibre and matrix respectively, C_o^f and C_o^m are the fibre and matrix elastic stiffness matrices and d_f and d_m represent the damage scalar parameters for each fibre and matrix constituent. The damage scalar parameter evolution laws are described by means of exponential softening functions (Eq. (3)) taken from Olivier et al. [41]:

$$d = 1 - \frac{c^{max}}{f(\sigma_o)} e^{A \left(1 - \frac{f(\sigma_o)}{c^{max}}\right)} \quad (3)$$

In this equation, c^{max} is the constituent compression strength, A is a constant estimated by using the approach proposed by Oller [42] and $f(\sigma_o)$ is the yield function. The model enables considering different damage thresholds in tension or compression by the weight function proposed by Olivier et al. [41] which defines the threshold of each constituent. The yield function is described through the Simo-Ju criteria [43] which is used in Eq. (4):

$$f(\sigma_o) = \varphi(r) \sqrt{\varepsilon C_o \varepsilon} \quad (4)$$

Where $\varphi(r)$ is the weight function written in terms of r in Eq. (5) and taken from [41]:

$$\varphi(r) = rN + (1 - r) \quad (5)$$

Thus r defines the relation between tensile and compressive eigenvalues of the stress tensor of each constituent, $N = \frac{\sigma_{comp}^{max}}{\sigma_{trac}^{max}}$ is the relation of the tensile and compressive damage thresholds, with σ_{trac}^{max} and σ_{comp}^{max} as the maximum stresses that can be applied without damage in tensile and compressive cases.

As indicated, the S/PMT developed by Ratellini et al. [20] was used as the composite constitutive law. This theory considers in fibre direction iso-strain or parallel behaviour for both constituents and iso-stresses or serial behaviour in the remaining directions for fibre and matrix. The S/PMT also considers that the composite is homogeneous and assumes a perfect kinematic agreement between fibre and matrix. The S/PMT equations provide expressions for the composite tangent constitutive tensor which enables representing the composite behaviour and iterates in the outer calculation loop.

3. Model verification

In a previous study, the model was applied to predict the damage by fibre microbuckling that appeared in the area around a single hole in a

Fig. 1. Numerical and experimental remote stress-strain (%) curves comparison. Experimental data taken from [26].

laminate subjected to compression [22]. In that work the model was validated with data from the literature. It was demonstrated that the model could accurately predict damage initiation due to fibre microbuckling and could reproduce the global response of the plate. In order to analyse the accuracy of the modified model used in this work (that includes two degradation mechanisms: fibre microbuckling and matrix cracking) to predict damage initiation and stress-strain behaviour in laminates with two holes, a comparison with experimental data from the literature [26] was carried out.

The selected configuration is a 245×50×3 mm laminate plate. Two holes are placed transversely to the load direction (Fig. 1) and centred symmetrically.

The same material used in the previous work [26] is selected: a carbon/epoxy Toray T800/Ciba-Geigy 924C laminate with a stacking sequence $[\pm 45/0_2]_{3S}$.

In order to discretize the domain, a model of approximately 6000 hexahedral elements is used. One end of the plate was fixed and at the other, a displacement is imposed to model the compressive load. The displacement was applied quasi-statically, increasing from zero to a strain level of 0.42%.

The longitudinal strain in the load direction is estimated as a function of the applied stress at three points: a point far away from the two holes

that represents the global stress-strain response (point 1), the midpoint between the two holes (point 2) and a point located at 1 mm from the edge of the right hole (point 3).

The model is able to predict the effect of stress concentration due to the two holes configuration represented in the left side of Fig. 1. The strains at points 2 and 3 are significantly greater than at point 1; the latter can be considered equal to the level of strain applied. The strain at point 2 is greater than at point 3. A non-linear behaviour is also found; according to the experimental evidence shown by Soutis et al. [26], this phenomenon is related to the presence of damage in the area between the holes. The major damage area is predicted by the model to be concentrated in the areas surrounding the two holes along the load direction, represented by a damage colour scale in Fig. 2. Furthest points present no significant damage. This is consistent with the experimental evidence presented by Soutis et al. [26], in which the damaged area has been observed by radiography.

The physical meaning of the areas where the damage parameter is high corresponds to areas where the material has lost the capability to support stresses [20,23] and, therefore, can be related to the inability to transmit shear in all the components that behave in serial (due to the hypothesis of iso-stress of the S/PMT). Although the delamination failure mode is not explicitly modelled in this work, the propagation

Fig. 2. Damage pattern in 45° plies, (a) overview and (b) area around the holes. Applied strain 0.42%.

Fig. 3. Fibre damage variable progression for increasing strain levels, (a) strain 0.298%, (b) strain 0.322% (c) strain 0.345%, (d) strain 0.368%, (e) strain 0.391%, (f) strain 0.414%.

of matrix damage could be identified with the initiation of damage by delamination, as proposed by Martinez et al. [23]. The damaged area estimated by the model is similar to the experimental damage shown in [26].

The accuracy of the model in predicting the global response of the plate is excellent (point 1, Fig. 1). The estimate for the other two points was considered good enough. The positions of the three points are estimated from the data of [26], not enough information is available about the exact position of the strain gauge at point 3 (hole edge). A slight de-

viation of the position of the gauge implies a high variation of strain due to the stress concentration phenomenon in this area. Additionally, the gauge has physical dimensions, so its measurement can be considered an average value of strain; by contrast, the numerical value is a point value.

Fibre and matrix damage onset can be localized through model predictions. Fibre damage initiates in the thickest group of 0° plies closest to the symmetry plane of the laminate, according to Fig. 3.

The strain level (0.79%) for which this damage mode appears corresponded to point 2 on the curve of Fig. 1 in which the

Fig. 4. Matrix damage variable progression for increasing strain levels, (a) strain 0.298%, (b) strain 0.322% (c) strain 0.345%, (d) strain 0.368%, (e) strain 0.391%, (f) strain 0.414%.

non-linear behaviour starts. When the applied strain increases, the fibre damage in the central block of 0° plies grows, and also appears in the other plies with the same orientation closer to the top and bottom plies. The fibre damage in $\pm 45^\circ$ plies is negligible. By contrast, matrix damage appears first in all $\pm 45^\circ$ plies simultaneously, and when the applied strain increases, also in the 0° plies (Fig. 4). Both damage modes progress mainly in a direction perpendicular to the load application.

In view of these results, the model can be assumed accurate enough to predict both the global response of the laminate and the evolution of fibre and matrix damage in the area close to the holes-edges.

4. Results and discussion

Once the model was verified, the influence of the hole-interaction is studied. Two configurations are compared (Fig. 5): a plate with a centred

Fig. 5. Laminate geometry configurations used in this study.

hole used as reference (configuration 1) and a plate with two holes of the same diameter (configuration 2), one centred (hole 1) and another located transversely to the load direction at a distance d (hole 2). Four values of d are considered: 1.1, 1.2, 1.4 and 1.5 times the diameter ($\emptyset$) of the hole. In all cases, sufficiently large plate dimensions are selected to ensure that the edge effect did not interact with the effect due to the second hole when the distance d increased (Fig. 5). A value of strain (0.42%) equivalent to the maximum load shown in Fig. 1 is applied.

4.1. Analysis of the influence of distance /hole-diameter ratio in fibre and matrix damage

The distance between the holes has a significant influence on the fibre and matrix damage extension. In configuration 1, the damage distribution is symmetrical on both sides of the hole (points A and B). This symmetry has been observed experimentally in laminates with a single hole subjected to compression [26]. When a second hole is considered (configuration 2), the symmetry in the damage on hole 1 disappears. The damage increases at the closest point (point B) to hole 2 (Figs. 6 and 7, b to e).

For a distance of 1.1 times the hole diameter, the extension of the damage to the same level of applied strain is significantly higher in all plies in configuration 2 than in configuration 1 (Fig. 6b and 7b), especially in fibre damage. In configuration 2, with $d = 1.1\emptyset$, damage parameter values are close to unity so the presence of the second hole causes the failure of the laminate. By contrast, the damage in configuration 1 is smaller and do not produce the failure of the laminate for the same applied load. The damage in the matrix extends in the plane of the laminate to the whole area between both holes (Fig. 7b), whereas the fibre damage is restricted to the plies at 0° although it extends in the plane of the ply. For a distance of $d = 1.5\emptyset$, the fibre and matrix damage is smaller than in the case of a hole distance 1.1 times the diameter. Also, the matrix damage is located close to the hole edges.

The maximum damage in fibre and matrix, along the laminate thickness, is calculated at four points: A, B, C, and D. Point A and B are located in hole 1, and points C and D in hole 2. Points A and D are the furthest apart, and points B and C the closest (Fig. 5). The ratio between this damage and the equivalent values in configuration 1 at points A and B is estimated (and called fibre and matrix damage ratio). A distance ratio ($d/\emptyset$) is also defined, dividing the distance between holes and the hole diameter. The change of damage ratio as a function of the distance ratio is represented in Fig. 8.

A significant increase in the fibre damage ratio when the distance between holes diminishes, is found. The influence of distance in the fibre

damage ratio is similar to results reported by other authors on the in-plane stress concentration factor at the hole edge [30,31]. For a distance ratio equal to 1.1, the damage ratio is 1.6 at point B and 1.4 at point A (Fig. 8a). There is also an evident non-symmetry of the damage ratio between points A and B, the difference between these values decreases when the distance increases. The fibre damage ratio at the second hole, at points C and D, does not match exactly the ratio at points A and B of hole 1 for a distance ratio of 1.5. Assuming that for this distance there is less interaction between holes, the damage must be similar to the case of two isolated holes, and thus the damage at points A and C, and B and D should be equal. Probably the differences could be due to the non-centred position of hole 2. This effect is more significant when the distance between holes increases.

At a distance close to 1.5 times the hole diameter, the fibre damage at points A and B are very similar to the damage in the case of a single hole. This behaviour is different from that observed in the in-plane stress concentration [26,30,31]. For this parameter, higher stress concentration appears in the case of two holes, even for distance ratios greater than 2.5.

The influence of distance on the damage in the matrix is less significant than in fibre damage. At points A and B, for a distance ratio of 1.1, the damage ratio is slightly greater than one, decreasing when the distance increases. There are also few differences between the equivalent points at both holes (points A and C, and points B and D). The matrix damage relationship with distance is approximately linear.

Not only are the damage parameters modified when the distance between the holes changes, the level of strain in which the damage initiates is also different. In Fig. 9, the curve of remote stress versus strain at an intermediate point between the two holes (point 1 in Fig. 5) is shown. When the distance between holes decreases the strain at which non-linear behaviour appears (related to damage initiation) diminishes. For a distance ratio of 1.1, the strain is 0.794%, and for a distance ratio of 1.5, the strain is higher than 1.02%.

4.2. Analysis of the influence of distance/hole-diameter ratio on interlaminar stresses

At points B and C, the variation of interlaminar stresses in the thickness direction is estimated. Figs. 10 to 12 show only the results for configuration 1 and configuration 2 for distance ratios equal to 1.1 and 1.5, given that these ratios are considered the most representative. In all stress components, oscillations are observed at those points located at the interfaces between the plies.

Fig. 6. Fibre damage distribution at holes edges. (a) configuration 1, and configuration 2: (b) $d = 1.1\theta$, (c) $d = 1.2\theta$, (d) $d = 1.4\theta$, and (e) $d = 1.5\theta$.

Fig. 7. Matrix damage distribution at holes edges. (a) configuration 1, and configuration 2: (b) $d = 1.1\varnothing$, (c) $d = 1.2\varnothing$, (d) $d = 1.4\varnothing$, and (e) $d = 1.5\varnothing$.

Fig. 8. Damage ratio at points A, B, C and D as a function of distance $d/\varnothing$ ratio. The damage ratio is obtained by dividing the damage parameters in configuration 2 by the equivalent parameters in configuration 1. (a) Fibre damage, (b) Matrix damage.

Fig. 9. Stress-strain curves at point 1 for several distance ratios.

Fig. 10 shows the variation of the stress component σ_{zz} along the laminate thickness at points B and C. The presence of a second hole and the distance at which it is located modify this stress component. In the case of a second hole located at a distance $d = 1.1\varnothing$ from the first, σ_{zz} increases at point B with respect to the configuration 1 in all ply interfaces except in the mid-plane interface where this stress is almost equal to those in configuration 1 (Fig. 10b). The stress distribution at point C is lower than at point B. For a distance $d = 1.5\varnothing$, the stress σ_{zz} is compressive along all the laminate thickness, both at point B and C (Fig. 10c). This stress distribution is smaller at point B than at point C and also smaller than in the other cases. At point C, the stress distribution is smaller along the laminate thickness, except in the mid-plane.

The distribution of stress σ_{xz} along the laminate thickness in configuration 2, has opposite signs at points B and C (Fig. 11b and 11c). In configuration 2, with $d = 1.1\varnothing$, this stress component is higher than in configuration 1 at positions close to the laminate surface, being smaller

in positions close to the ply interfaces. When $d = 1.5\varnothing$, the stress σ_{xz} is smaller than in the other two cases, both at point B and point C, even at positions close to the laminate surfaces.

The stress σ_{yz} also has different signs in configuration 2 at points B and C for both distances between holes (Fig. 12b and 12c). The stress distribution at point B along the laminate thickness for a distance $d = 1.1\varnothing$, is equal or slightly smaller than in configuration 1 in all ply interfaces. The stress at point C is similar to the stress at point B, although of opposite sign. For a distance $d = 1.5\varnothing$ the stress at point B is also similar to that in configuration 1, but the stress at point C is higher than in the previous case.

Thus, the presence of a second hole modifies the interlaminar stress-distribution along the laminate thickness in the area around the hole, increasing or decreasing the stresses at the first hole when the distance between holes is modified. Nevertheless, fibre and matrix-damage initiation and propagation or in-plane stresses are more significantly modified than interlaminar stresses.

a)

b)

c)

Fig. 10. Stress σ_{zz} distribution along the laminate thickness. (a) configuration 1, (b) configuration 2: $d = 1.1\varnothing$, (c) configuration 2: $d = 1.5\varnothing$.

a)

b)

c)

Fig. 11. Stress σ_{xz} distribution along the laminate thickness. (a) configuration 1, (b) configuration 2: $d = 1.1\varnothing$, (c) configuration 2: $d = 1.5\varnothing$.

Fig. 12. Stress σ_{yz} distribution along the laminate thickness. (a) configuration 1, (b) configuration 2: $d = 1.1\varnothing$, (c) configuration 2: $d = 1.5\varnothing$.

5. Conclusions

In the present study, a laminate plate with two interacting holes subjected to compressive loads is studied. The influence of the distance between the holes in interlaminar stresses, damage initiation and damage propagation are analysed. Two configurations are selected, one with a centred hole and the other with a second hole located transversally to the load direction. Two failure mechanisms are modelled, fibre microbuckling and matrix cracking, using a CDM model and the S/PMT as the constitutive law of the composite. The proposed model has been implemented by the authors in custom FEM code. The main results found can be summarized as follows:

- The distance between the holes significantly modifies both fibre and matrix damage extension; when the distance diminishes, the damage increases. This effect is less significant in matrix damage than in fibre damage.
- Fibre damage is located in the 0° plies and extended in each ply plane with this orientation as the distance between the holes decreases. By contrast, matrix damage extends in the whole area between the holes and in all ply-orientations, although it initiates in the $\pm 45^\circ$ plies.
- The presence of the second hole produces a non-symmetrical damage distribution. The highest damage is located along the thickness in the area between both holes close to the hole-edges. Additionally, the strain level at damage onset diminishes as the distance between holes reduces.
- σ_{zz} close to the nearest edges to both holes is compressive along the thickness (except for the quadrature points near the external plies) and increases due to the second hole in all areas far from the mid-plane interface.
- In the same area, σ_{xz} and σ_{yz} , change sign along the thickness in each ply-interface. The interlaminar stresses close to each hole have opposite signs at the same ply-interface. The presence of the second hole produces an increase in σ_{xz} near the laminate surface while it is lower near the mid-plane. Regarding σ_{yz} values, the effect of the second hole is less significant in this case, producing more similar values to the single-hole case.

Declaration of Competing Interest

I declare that this manuscript is original, has not been published before and it is not currently being considered for publication elsewhere. The manuscript has been read and approved by all authors.

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