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Influence of open holes on composites delamination induced by low velocity impact loads

A.M. Amaro [a,*], P.N.B. Reis [b], M.F.S.F. de Moura [c], M.A. Neto [a]

[a] CEMUC, Department of Mechanical Engineering, University of Coimbra, Rua Luís Reis Santos, Pinhal de Marrocos, 3030-788 Coimbra, Portugal
[b] Department of Electromechanical Engineering, University of Beira Interior – UBI, 6200 Covilhã, Portugal
[c] Faculdade de Engenharia da Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

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ABSTRACT

The aim of this study is to evaluate the influence of holes on delamination induced by low velocity impact on glass/epoxy composite laminates. Plates containing one and two holes were tested and the resulting damage was compared with the one of plate without hole. A finite element analysis including a cohesive mixed-mode damage model was performed in order to better understand the interaction between the resulting delamination and the presence of holes. It was verified that presence of holes increases the energy absorbed by damage as well as the delaminated areas. Delamination profile is also affected owing to alteration of interlaminar shear stress profiles which are the main responsible for delamination between different oriented layers.

1. Introduction

Composite materials have been increasingly used because of their high specific strength and stiffness, good fatigue performance and corrosion resistance. However, in many cases, there are some problems in their application as consequence of the poor tolerance to damage.

Impacts at low velocity are the principal cause of in-service delaminations, which are very dangerous since they can affect dramatically the performance of composite materials and are difficult to detect visually [1,2]. Delaminations are prone to occur at interfaces between different oriented layers due to mismatch bending that lead to development of interlaminar shear stresses at those interfaces [3]. Under tensile loading the existence of the delamination promotes a drop of strength [4–7], but its size does not influence significantly the value of tensile strength [4]. Delaminations are also responsible for decrease on flexural properties of these materials [8]. It was verified that the most critical situation occurs when delamination is located close to the mid-thickness of the specimen, which can be explained by alterations induced by delamination on the shear stresses profile [9]. Additionally, an approximately linear relationship was found to describe the decrease of the maximum load as a function of increasing size delaminations [9]. Nevertheless, compressive strength is the most critically affected and is therefore considered to be a design limiting parameter [10]. This is essentially consequence of the different failure mechanisms that are induced by damage [11–13]. Effectively, delaminations induce premature buckling of the structures with the consequent drastic reduction on their compressive strengths.

On the other hand, open holes for electric wires, hydraulic pipes or assembly and maintenance are required in many structures. Their presence in a structure results in a high stress gradient at the vicinity of their edges. If the stress gradient around the hole is not dependent of the material for isotropic materials, the same it is not true for laminated composites because it will be dependent of the material constants, fibre orientation and laminate stacking sequence. This complex stress gradient result in a complicated failure mechanism near the hole and several studies can be found in literature to understand this phenomenon [14–19]. In terms of strength Xu et al. [20] concluded that the position of hole has a significant effect. For the tensile and compressive strength, the highest strength is obtained when the holes are in series. Concerning the shear strength the influence was observed to be small. The compressive failure mechanism of quasi-isotropic composite laminates with an open hole was experimentally and numerically studied by Suemasu et al. [19]. According with these authors, some accumulation of damage, such as fibre micro-buckling in the 0° layers and interlaminar delaminations in several interfaces, was observed before the final unstable fracture in the laminate with high interlaminar toughness, while sudden failure occurred in the laminate with low interlaminar toughness [19]. In fact, when composite laminates are subjected to loading, interlaminar stresses develop at the hole free edges and delamination may initiate depending upon the strength of the interface [21].

* Corresponding author. Tel.: +351 239790700; fax: +351 239790701.
E-mail address: ana.amaro@dem.uc.pt (A.M. Amaro).

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It is recognised by the open literature that laminated plates containing holes have been studied exhaustively in terms of tensile and compressive loading, but fewer studies can be found on the impact failure of composite plates containing holes [21]. Roy and Chakraborty [21] studied the response of the single and hybrid laminated composite plates with holes due to low velocity impact. They concluded that delaminations initiate at the interface from the inner free edges of the holes and with time, delaminations from two holes meet each other forming a big delamination area. On the other hand, kevlar/epoxy hybridization on graphite/epoxy laminate leads to reduced contact force and hence more impact resistance in terms of failure due to contact stresses, but the chances of delamination at the interfaces increase. For Luo [22] there are two parallel matrix cracks between the impact point and the hole. From the simulation, one crack (originating crack) initiates at the point of impact and propagates towards the hole whereas the other crack (rebounding crack) initiates near the hole edge and propagates towards the impact centre. In addition two more predicted cracks emanate from the far side of the hole and one of them appeared in the experiment. It is shown that the cracks can be initiated by either tension or shear or a combination of both. Experimental works developed by Green et al. [23] showed that the holes can induce matrix cracking in the lower lamina which is additional to that arising in the laminate without holes. These matrix cracks can extend from the region directly below the impact to the edge of the holes and in some circumstances further cracks can emanate from the far side of the holes. On the other hand, the simulation predicted that the presence of the holes can give rise to multiple cracks directly below the impact region which spread towards but not up to the holes, together with a crack emanating from the hole towards the impact region. Thus, whilst the computations are in qualitative agreement with the experimental evidence there is a need for further work in order to improve on the predictions [23].

Therefore, the aim of this study intends to improve the knowledge on low velocity impact response of glass fibre epoxy laminates containing holes. The effect of a single and two holes on the impact behaviour is discussed in terms of load–time, load–displacement, energy–time diagrams and evaluation of the damage. Experimental tests and numerical simulations were performed. The numerical approach is based on a three-dimensional analysis including a cohesive mixed-mode damage model implemented via interface finite elements [24]. The cohesive damage model includes a quadratic stress criterion to simulate damage initiation and a linear energetic criterion to model damage propagation under mixed-mode loading. The analysis of the experimental and numerical results provided fruitful conclusions about the influence of holes on the low impact behaviour of composites.

2. Materials and procedure

Unidirectional glass/epoxy composite laminate was used as testing material, considering the following stacking sequence $[45_2, 90_2, -45_2, 0_2]_s$. The volume fraction of E glass fibre is 0.45 and the laminates were processed using the autoclave/vacuum-bag moulding process. The processing setup consisted of several steps: make the hermetic bag and apply 0.05 MPa vacuum; heat up to 125° C at a 3–5° C/min rate; apply a pressure of 0.5 MPa when a temperature of 120–125° C is reached; maintaining pressure and temperature for 60 min; cool down to room temperature maintaining pressure and finally get the part out from the mould. The plates were manufactured in a useful size of $300 \times 300 \times 2.1$ mm^3.

The specimens used in the experiments were cut from the plates and the low velocity impact tests were performed using a drop weight-testing machine Instron–Ceast 9340. Fig. 1 shows the different specimens used and the mark X represent the impact position. The diameter of the holes is 4 mm. A 10 mm impactor diameter with a mass of 3.4 kg was used. The tests were performed on circular samples of 70 mm diameter and the impactor stroke at the centre of the samples obtained by centrally supporting the 100×100 mm specimens. The impact energy used was 6 J, which corresponds to an impact velocity of 1.88 ms^{-1}. For each condition, three specimens were tested at room temperature. After impact tests all the specimens were inspected visually in order to evaluate the size and shape of the projected delaminations.

3. Numerical analysis

A numerical analysis based on finite element method was also performed in order to better understand the phenomena that explain the observed experimental behaviour. A three-dimensional analysis including cohesive zone modelling was used to simulate the rising of delaminations at interfaces between different oriented layers [24].

The cohesive mixed-mode damage model is based on a quadratic stress criterion to simulate damage initiation

$$\begin{aligned} &\left(\frac{\sigma_I}{\sigma_{u,I}}\right)^2 + \left(\frac{\sigma_{II}}{\sigma_{u,II}}\right)^2 + \left(\frac{\sigma_{III}}{\sigma_{u,III}}\right)^2 = 1 \quad \text{if } \sigma_I \geqslant 0 \\ &\left(\frac{\sigma_{II}}{\sigma_{u,II}}\right)^2 + \left(\frac{\sigma_{III}}{\sigma_{u,III}}\right)^2 = 1 \quad \text{if } \sigma_I \leqslant 0 \end{aligned} \tag{1}$$

where σ_i (i = I, II, III) represent the stress components in each loading mode and $\sigma_{u,i}$, (i = I, II, III) are the local strengths. When the above criterion is satisfied, a linear softening relationship between stresses and relative displacements is assumed at the integration points. The definition of the ultimate relative displacement corresponding to complete failure is realised through the linear energetic criterion

$$\frac{G_I}{G_{Ic}} + \frac{G_{II}}{G_{IIc}} + \frac{G_{III}}{G_{IIIc}} = 1 \tag{2}$$

where G_i (i = I, II, III) are the strain energy components and G_{ic} the respective critical values. When this criterion is satisfied at a given integration point, total failure occurs, thus simulating delamination growth. Shear and normal tensile stresses vanish at the integration point, being only able to transmit normal compressive stresses. The cohesive damage model is implemented on Abaqus software by means of the User Subroutine tool. More details about the used model are presented in [24].

One aspect that deserved special attention was the modelling of the quasi-isotropic stacking sequence of the laminate $[45_2, 90_2, -45_2, 0_2]_s$. This laminate is constituted by seven groups of equally oriented layers which mean that delaminations can arise at six interfaces. In a three-dimensional numerical analysis it would be necessary to consider seven layers of solids elements separated by six layers of cohesive elements. However, it is known that delaminations are inexistent or very small at "upper" interfaces, i.e., at interfaces proximal to impacted surface, owing to development of normal compressive stresses [3]. Consequently, the ten upper layers of the laminate were homogenised considering the classical

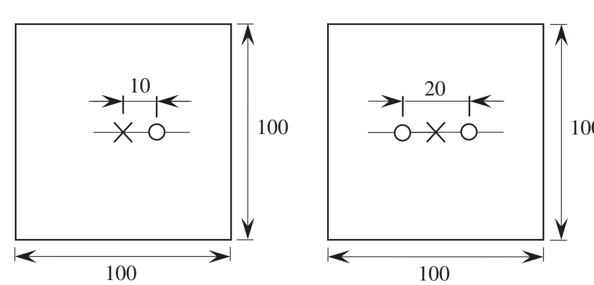

Fig. 1. Specimens' geometry (dimensions in mm).