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On the applicability of simple shapes of delaminations in buckling analyses

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ABSTRACT

The possibility to accurately analyse the buckling and postbuckling behaviour of plates with delaminations of irregular shapes by utilisation of circular or elliptic delaminations was studied. The behaviour of compressed plates with delaminations of irregular and corresponding smallest enclosing circular and elliptic shapes was predicted by computational analyses and compared in terms of buckling loads and maximum values of the energy release rates found along the delamination boundaries. The study indicates that utilisation of circular delaminations could provide highly inaccurate results. Moreover, for truly accurate analyses of the buckling and postbuckling behaviour of delaminated structures it seems to be inevitable to use as precise representation of the shape of delaminations as possible.

1. Introduction

It is well-known, that laminate structures with delaminations, i.e. regions, where there is no connectivity in between plies, could have substantially reduced load carrying capacity compared to sound structures. This applies especially if the structures are subjected to loads which may cause buckling of the delaminated sublaminates. That is why the phenomenon of buckling and postbuckling of delaminated structures has been addressed in a great number of studies. Majority of theses works is focused on the behaviour of delaminated beams or plates with through-the-width delaminations, but the behaviour of plates with embedded circular or elliptic delaminations has been addressed as well. Hence, it is already known how the buckling of such delaminated plates is affected by the size of delamination – see e.g. [1–7], by the through-the-thickness position of delamination [2,7], by the number of delaminations positioned through-the-thickness of laminate [6,8], by the ply orientation [2,9,10] and by the delamination orientation [6,9,11,12]. The growth of delaminations is affected by all the aforementioned parameters as well, but since the delamination growth is a complicated process which is also affected by other parameters such as the fracture mode mixity ratio and mutual ply orientation, the effect of most parameters cannot be easily separated and described. Nevertheless, some basic information about the growth of delaminations could be found in [13–15].

The important fact about the growth of delaminations is that they do not tend to grow in a self-similar way and therefore even a simple initial shape of delamination can change to a complex one [16,17]. Moreover, the shapes of delaminations found in laminated structures are often everything but simple – see e.g. [18–23]. Hence, it might appear that if the buckling and postbuckling behaviour of delaminated plates is to be studied by means of computational analysis, it would be desirable to take into account the complex shapes of delaminations. This approach, however, is not convenient for practical assessment of the load carrying capacity of delaminated structures since it complicates creation of computational models and also because the experience with the behaviour of structures with simple shapes of delaminations might not be directly applicable. Therefore, there is the question whether some simplified representation of the irregular shapes of delaminations could provide reasonably accurate prediction of the buckling behaviour of delaminated structures.

Hence, the present study was designed to evaluate the effect of the utilised delamination shape representation upon the predicted buckling and postbuckling behaviour of a delaminated plate. The study is based on the computational analyses of the buckling and postbuckling behaviour of plates with a single delamination which has either an irregular impact induced shape or a simplified circular or elliptic shape.

2. Analysis

2.1. Problem description

Behaviour of a delaminated square plate subjected to compressive load was studied. Dimensions of the plate were 80 mm × 80 mm × 1.83 mm. The plate was assumed to consist of aluminium

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alloy sheets interleaved with unidirectional carbon fibre/epoxy plies; the structure of the laminate is presented in Table 1. The plate was assumed to contain a single delamination of irregular impact induced shape, circular or elliptic shape at one of the three interfaces A, B or C (see Table 1).

All in all, seven different shapes of impact induced delaminations were utilised in the present study. The first six shapes of delaminations, in the following text denoted as #1–#6, were obtained by ultrasonic defectoscopic analysis of fibre–metal laminate plates which were subjected to low velocity impacts of a steel impactor with semi-hemispherical tip: three shapes corresponded to the plates with unidirectional layup [Al/0/0/Al/0/0/Al] and three shapes corresponded to plates with cross-ply layup [Al/0/90/Al/90/0/Al]. Since similar shapes of impact induced delaminations were presented in other studies, e.g. in [18–20,24–26], it could be expected that the outcomes of the present study could have broad applicability. However, it must be noted that also peanut shaped delaminations or delaminations with highly irregular shapes were reported in literature, e.g. in [21–23,27–29]. Since it would be unacceptable not to include the quite common peanut shaped delaminations in the present study, an extra delamination with this shape was used as well. The shape of this delamination was chosen to be similar to shapes presented in [27,29,30]. Moreover, since the buckling responce of plates with oblong delaminations is known to be strongly affected by the orientation of delaminations [6,7,9], two mutually perpendicular versions of the peanut shaped delamination, which corresponded to two different layups [Al/0/0/Al/0/0/Al] and [Al/90/90/Al/90/90/Al], were utilised in this study; the orientation of delaminations matched the orientation of the composite plies. These two instances of the same peanut delamination are in the following text denoted as #7 and #8.

The simplified circular and elliptic shapes of delaminations were obtained by the algorithms for finding the smallest enclosing circle and smallest enclosing ellipse. These algorithms are implemented in the CGAL library [31]. These algorithms are based on the work by Welzl [32] and works by Gärtner and Schönherr [33,34]. All the original irregular shapes of delaminations as well as their simplified representations are presented in Figs. 1 and 2. It should be noted that the aforementioned algorithms represent a convenient way how to find unambiguous simplified shapes of delaminations.

In order to evaluate the effect of the out-of-plane position of delamination upon the buckling behaviour, each shape of delamination was used for three separate analyses of the buckling and postbuckling behaviour of a plate with a single delaminations at one of the three ply interfaces A, B and C – see Table 1. It should be pointed out that the structure of the laminate is closely related to the nature and extent of damage caused by the impact loading (see e.g. [18,22]), which fact is ignored by the introduction of a delamination with the same shape to the different ply interfaces.

2.2. Finite element mesh

The plate was modelled with four layers of 8-node layered continuum shell elements (entitled SC8R in ABAQUS) which employ the first-order shear deformation theory. Each of the two delaminated sublaminates was composed of two layers of elements; the layers of elements adjacent to the delaminated interface had either thickness of the composite layer or half of the thickness of the aluminium layer, depending on the actual material of the plies adjacent to the delaminated interface. Such element thicknesses were found to provide accurate results [35].

Because the virtual crack closure technique [36,37] was used to determine the energy release rate along the delamination boundary, the edges of elements adjacent to the boundary were made to be orthogonal in order to simplify evaluation of the results. The size of elements was chosen to provide accurate results for slightly irregular shapes of delaminations used in the present study. A sample finite element mesh is shown in Fig. 3. For highly irregular shapes, it would be necessary to use extremely fine mesh in order to satisfy the condition of self-similarity of delamination growth – a condition on which the virtual crack closure technique is based. More information about growth of arbitrary shaped delaminations could be found in [38,39].

Table 1
Structure of the laminate.

Layer	Thickness (mm)	Interface
Aluminium	0.4	A
Composite	0.1575	B
Composite	0.1575	C
Cluminium	0.4	D
Composite	0.1575	E
Composite	0.1575	F
Aluminium	0.4	

2.3. Boundary conditions

The utilised boundary conditions are depicted in Fig. 4. The plate was clamped along all its edges and one of the edges was uniformly displaced against the opposite edge. Since the three-dimensional continuum shell elements were used to build up the plate, some arrangements had to be made in order to simulate the plate boundary conditions appropriately.

Hence, the nodes on the boundary of the plate with the same inplane coordinates were constrained to lie on a straight line using the SLIDER type multi-point constraint implemented in ABAQUS. Moreover, an extra set of nodes was modelled along the plate edges on the mid-surface of the plate (see Fig. 5) and the movement of the nodes on the top, bottom and mid-surfaces was constrained by a set of linear equations – in the present case of a plate which is made of four layers of elements and which has clamped edges these equations take form of

$$\begin{aligned}
&u_\xi^1 - u_\xi^0 = 0\\
&u_\xi^5 - u_\xi^0 = 0\\
&u_\zeta^1 + u_\zeta^5 - 2u_\zeta^0 = 0\\
&u_\eta^1 + u_\eta^5 - 2u_\eta^0 = 0
\end{aligned} \tag{1}$$

where u_i^1, u_i^5 and u_i^0 are the displacements in the i-direction of the nodes on the top, bottom and middle surface, respectively. The appropriate in- and out-of-plane displacements were then prescribed at the extra set of nodes on the mid-surface.

2.4. Material

Both the metal and the composite were assumed to be linear elastic. The aluminium layers were assumed to be isotropic with Young's modulus of 72.5 GPa and Poisson's ratio of 0.34. The composite layers were modelled as orthotropic – corresponding material properties are listed in Table 2.

2.5. Contact constraints and imperfection

To prevent unrealistic overlapping of delaminated sublaminates, a surface based frictionless contact interaction was used between the delaminated sublaminates; the augmented Lagrangian contact algorithm was employed. The commonly used frictionless interaction was utilised because it greatly simplified evaluation of the energy release rate by the aforementioned virtual crack closure technique. It must be mentioned that this approach cannot