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Core crush criterion to determine the strength of sandwich composite structures subjected to compression after impact

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ABSTRACT

In this study a core crush criterion is proposed to determine the residual strength of impacted sandwich structures. The core of the sandwich is made of a Nomex Honeycomb core and the faces are laminated and remain thin. The mechanism of failure of this kind of structure under post-impact compressive loading is due to interaction between three mechanical behaviors: geometrical nonlinearity due to the skin's neutral line off-set in the dent area, nonlinear response of the core and damages to the skins. For the type of sandwich analysed in this study, initially the core crushes at the apex of the damage. Using a finite element discrete modelling of the core previously proposed by the authors, the load corresponding to the crushing of the first cell can be computed and it gives the value of the residual strength for our criterion. Some geometric and material hypotheses are assumed in the damaged area mainly based on non-destructive inspection (NDI). The criterion is then applied to tests modelled by Lacy and Hwang [Lacy TE, Hwang Y. Numerical modelling of impact-damaged sandwich composites subjected to compression after impact loading. Compos Struct 2003;61:115–128]. It is shown that the criterion allows a good prediction of the tests except in the case of very small dents. Several sensitivity studies on the assumptions were made and it is shown that using this approach, the criterion is robust.

1. Introduction

Sandwich structures exhibit static properties like high stiffness-to-weight ratio and high buckling loads that are of great importance in the aeronautics field. Although their properties have been known since the thirties, the current applications remain limited to secondary structures such as surface controls or floor panels or to a small number of primary aircraft structures such as the Beechcraft Starship (Hooper [2]). In fact, the limitations are linked to the cost and reliability of manufacturing (Sheahen et al. [3]), moisture problems and to the general lack of knowledge of the effects induced by impact damages (drop in strength up to 50% (Abrate [4]). To meet the requirements for certification, aircraft manufacturers mainly validate their components experimentally by using compression after impact tests (CAI) on representative specimens (Tomblin et al. [5], Castanié et al. [6]). This empirical method is costly and therefore reliable and not too conservative computation methods are needed. Moreover, impacts often occur in service or during maintenance operations and aircraft manufacturers should give rapid responses to the operating company. Thus, the objective of the present method is to provide a relatively simple and efficient finite element model integrating the core crush criterion.

The type of damages occurring during low velocity-low energy impacts are well known [7,8]: core crush, skin fractures or delaminations and a residual dent depending upon the energy level. During compression after impact using hemispheric impactors, generally speaking, the form of the print becomes elliptical and simultaneously the dent depth increases [6,9–11]. Then a crack appears at the summit of the ellipse causing the failure of the specimen except in the case of a redundant structural test rig. So the analysis of the tests shows that the phenomenon occurring during CAI is due to interaction between three mechanical behaviors:

- A geometrical nonlinearity due to the skin's neutral line off-set in the dent area.
- A nonlinear response of the core due to the crushed state and the classical "with peak" response of the undamaged area.
- The response of the skin due to its type of damage after impact: delamination or crack growth.

Theses nonlinearities are at the origin of the difficulties encountered to model the phenomenon. Some analyses were analytical and based on wrinkling type models like those of Minguet [12] or more recently Xie and Vizzini [13,14]. In 1997, Guedra-

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Degeorges [15] presented a nonlinear finite element model able to represent the evolution of the damage in the core during CAI by remeshing it. He pointed out the fact that the damage progression is linked to a compression over-stress that appears in the core and on the crush propagation line. Other finite elements models were proposed by Zenkert et al. [16] or by Lacy and Hwang [1,17]. In any case, the core is modelled by a continuum and the authors focused on the skin failures or wrinkling [18] to determine the compressive strength of the impacted sandwich.

Recently, after a phenomenological study [19,20], the authors have pointed out that during the compression of a low-density honeycomb core, due to a postbuckling mode of the cell walls, only the vertical edges of the hexagon cell take the compressive load. Thus, it is possible to model the core only by its vertical edges which leads to the creation of a grid of nonlinear springs in a finite element model. The compression law is based on a test on a sample of Nomex and can be enhanced by taking into account the effect of the interaction between the score and the skin [19,21]. This approach leads to a correct modelling of static indentation and dynamic impacts on sandwich structures with metallic skins [19,21]. Moreover, the approach was extended to the problem of compression after impact for the same kind of sandwich which enables the evolution of the residual dent and the ultimate strength to be predicted [19,22]. The core crush criterion was also proposed. The main results in this case will be detailed initially and then a nonlinear finite element using this approach will be proposed. Some materials and geometric assumptions will be assumed in relation to the tests and modelling of Lacy and Hwang [1] and NDI capabilities. Then a comparison with the tests results given by theses two authors [1] will be performed and finally, a sensitive study on the new proposed assumptions will be provided along with the conclusions and future perspectives.

2. Core crush criterion

In this section, the key points of previous publication [19,22] are summarized. Compression after impact tests and modelling were carried out on specimens with brass skins and Nomex honeycomb reinforced at both ends (Fig. 1). These specimens were previously indented on a flat support. The finite element model made with Samcef software (by Samtech Group [24]) can be seen Fig. 2. The core was modelled by vertical springs located at the vertical edges of the cells. Its behavior was obtained experimentally from cycled compression uniform loading test on a small block of Nomex honeycomb (see Fig. 3) and implemented using special features of the software. The skins were modelled by Mindlin elements and the mesh is refined in the impact area. It was necessary to model both skins to obtain the true balance of forces between the skins during the compression loading. The boundary conditions represented some knifes of the test rig on the impacted skin. The unimpacted skin was fully clamped. This was necessary because the discrete modelling of the core cannot take into account the shear stresses in the core and any flexural behavior of the sandwich. Thus, the non linear response of the unimpacted skin reported by Lacy and Hwang [1] cannot be captured. However, this hypothesis was weak and this non linear response is due to the asymmetric aspect of the sandwich caused by the impact and it seems not to have any influence on the residual strength. To model the tests correctly, it was necessary firstly to compute the indentation loading and unloading (thus obtaining the residual dent, the plastic residual stresses in the skin and the core crush area and depth) followed by the compression after impact loading simulated by imposing the displacements on the edges of the two skins of the sandwich (Fig. 2). By doing so, the evolution of the dent and the residual strength were predicted with a high degree of accuracy [19,22]. It was noticeable that the compression after impact behavior of sandwiches with metallic skins was almost the same as sandwiches with composite skins.

The core crush criterion was found by analysing the reaction of the first uncrushed springs placed in the dent evolution direction about the major axis of the ellipse and in the circumference of the residual print (see Fig. 4). The reaction of these springs (1–3) is initially very weak and does not increase much during the appearance and the progressive extension of the ellipse. After a drop of the spring force which is probably due to the appearance of a little bump that stretches the springs, a sudden increase of the compression force is observed until it reaches the critical force (the peak) for the first spring at the periphery (no. 1). It is very interesting to note that the collapse of this first edge occurs only shortly before the abrupt progression of the ellipse, which takes place when the second edge (spring no. 2) situated on the major axis of the ellipse, collapses in turn. Numerically, it is shown here that the advance of the defect coincides with the physical phenomenon of local core crush. Therefore, the collapse of the first edge situated on the major axis of the ellipse modelled by its spring can be proposed as the criterion for determining the computed residual strength. This criterion should logically always underestimate the experimental residual strength but not too much since the ellipse generally appears just before the catastrophic failure of the specimens. In the next paragraph, the approach will be developed to the case of composite skins.

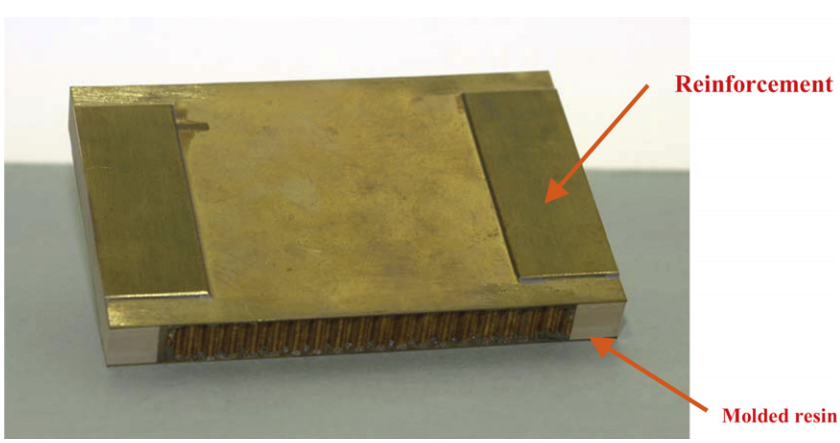

Fig. 1. Sandwich with metallic skins used for CAI Tests [19].