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Numerical/experimental evaluation of buckling behaviour and residual tensile strength of composite aerospace structures after low velocity impact

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ABSTRACT

A procedure for the characterization of low velocity impact damage and its effect on residual tensile and buckling behaviour of composite structures is presented. A simplified analytical method is used to enhance the damage simulation and a degradation model is introduced in the subsequent finite element analysis. Different degradation coefficients are defined for three impact energy stages. Two different types of analysis are performed using MD.Nastran software: the non-linear progressive failure analysis to estimate the residual tensile strength and the linear analysis to predict the critical uniaxial and shear buckling loads after impact. Tensile and buckling experiments are used to validate the present methodology. A good correlation is obtained for all the cases under investigation.

1. Introduction

Impact damage is a major concern during the design process of a new generation aircraft made of composites. Design techniques for metallic aircraft structures are well developed and accepted by the certification authorities. Certification requirements for composite structures are much more conservative and are covered by guidelines issued by airworthiness bodies such as European Aviation Safety Agency [1]. The certification of composite structures is accomplished using the so-called "building block approach", which requires tests on coupons, elements, and subcomponents until the full scale component. For composite structure the various damage types are classified into five categories of damage [1] by certification authorities based on visual/non-visual detectability. Different design load levels and different repair scenarios correspond to each type of damage. Barely Visible Impact Damage (BVID) is an allowed damage at which the aircraft structure must retain ultimate load capability for the entire life. Visible Impact Damage (VID) is a category of damage that should not grow or, if it occurs, should be slow or with an arrested growth. In this case the level of residual strength retained for the inspection interval is sufficiently above limit load capability in order to safely land on the nearest runway in case such an impact occurs during flight. In order to satisfy the requirement on ultimate load in presence of BVID damage, several theoretical–numerical studies and experimental monitoring of such damage are required.

S.X. Wang et al. [2] investigated low-velocity impact characteristics and residual tensile strength of carbon fibre composites laminates after impact through numerical and experimental methods. In that paper, impact force and residual strength of composite laminates were well predicted by FE model; it was created using a subroutine to enhance the damage simulation which included Hashin and Yeh failure criteria. Two different stacking sequences were investigated and the numerical degradation of residual tensile strength was compared with experimental results.

Caprino [3] arranged experimental tests to evaluate the residual tensile strength of AS4/3501 $(0/\pm 45)_{2S}$ composite panels. The results were utilized to develop a semi-empirical expression to predict the residual tensile strength of similar panels. After impact, all the specimens are visually inspected to evaluate the appearance of damage and identify the most relevant impact energy threshold. In both these studies the trend of residual tensile strength as function of the impact energy was divided into three stages. Stage one is lower impact energy degradation stage; stage two is the plateau trend and the last is a higher impact energy degradation stage.

In general, elastic instability is likely to occur during compression tests, especially for thin laminates, therefore the effect of impact damage on the buckling behaviour of advanced composite panels is another important aspect in designing aerospace structures.

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Nomenclature

α	Indentation	K_h	Hertzian contact stiffness
λ	Relative stiffness for composite laminated	K_y	Contact stiffness linearized
ν_i	Impactor Poisson coefficient	m_i	Impactor mass
σ_{ij}	Normal stress component on the composite lamina	M	Bending stiffness mismatch coefficient
τ_{ij}	Shear stress component on the composite lamina	M_k	Bending stiffness mismatch for k-interlamina
a	Characteristic dimension of samples	$\overline{Q_{ij}}$	Transformed reduced stiffness for a composite lamina
A_{DEL}	Total delaminated area	r	Global delamination radius
D^*	Effective bending stiffness	R_C	Contact area radius
D_{ij_K}	bending stiffness matrix component for the k-lamina	R_i	Impactor radius
D_{ij}	Component bending stiffness for composite laminated	S_{ij}	Strength value for shear component on the lamina
E^*	Effective contact modulus	t	Thickness of the composite laminated
E_{ij}	Transversal Young modulus for composite lamina	v_0	Impactor initial velocity
E_i	Impactor Young modulus	X_T	Tensile strength along to the fibre direction
E_{PERF}	Perforation value of impact energy	X_C	Compressive strength along to the fibre direction
F	Contact force	Y_T	Tensile strength normal to the fibre direction
F_{MAX}	Maximum contact force	Y_C	Compressive strength normal to the fibre direction
F_{PERF}	Perforation value of contact force	z_k	Lamina-k position trough the thickness of laminated
$\overline{F_{qsMAX}}$	Maximum non-dimensional quasi-static contact force	Z_T	Tensile strength normal to the ply plane
$ILSS$	Interlaminar shear strength	Z_C	Compressive strength value normal to the ply plane

Freitas et al. [4] determined the mechanisms of the damage growth of impacted composite laminates when subjected to compression after impact loading. It was detected that delamination at low impact energies had little effect on the tensile strength but significantly reduced the compressive strength. The residual compressive strength is influenced by the delaminated area which is a function of the impact energy but is also dependent on the distance between the delaminated area and the lateral borders of the specimens. This conclusion means that available bi-dimensional models for the calculation of delamination growth due to compressive loads cannot be applied on specimens with a small percentage of delaminated area where a three-dimensional analysis is needed [4].

Ghelli and Minak [5] performed several low velocity impact tests on coupons of the same thickness but two different geometries (rectangular and circular) according to ASTM standards. The adopted experimental conditions led to global buckling of the specimens during CAI (Compression After Impact) tests. The study highlighted several peculiar phenomena of interest, like influence of impact damage on critical buckling load and buckling shape.

S.S. Saez et al. [6] studied the residual compressive strength of different lay-up of laminated composites both numerically and experimentally. They obtained the trend of the average compression strength as a function of the impact energy, compared to non-impacted specimens. All the tested laminated panels showed a similar trend: a fairly sharp reduction at low impact energy and less reduction when the impact energies increase. Failure of damaged laminates under uniaxial compression load was caused by local buckling of the sub-laminates originated in the impact. Among all the specimens, quasi-isotropic laminates showed better damage tolerance, since their normalized strength reduction was smaller at all the impact energies tested.

The present paper reports a simplified procedure to identify the response at low velocity impact and evaluate, in a first approximation, the effect on the tensile and compressive structural behaviour. The validity of the proposed methodology is verified by experimental and numerical comparisons. The procedure is based on five steps: 1. Identification of the maximum contact force; 2. Characterization of the damage dimensions; 3. Identification of possible delaminations; 4. Damage modelling; 5. Numerical analysis and experimental comparisons.

2. Analytical model

The impact response of structures can be evaluated by numerical approach or by analytical methods. The numerical approach typically uses the finite element method which allows the discretization of the impactor and target structure. Using the FEM numerical approach it is possible to study the impacts at different energies, considering the time response of the structure. However, in the preliminary stages of the project, simple low-order analytical models describing the key impact parameters and their effect on residual strength are preferred.

2.1. Characterization of impact

The model developed by Christoforou and Yigit [7–10] is used to evaluate the maximum contact force, indentation depth and contact radius for a low velocity impact on a composite laminated plate. The analytical model considered in [7] is valid for a special orthotropic laminated composite plate subjected to lateral loading, including transverse shear deformation. In the case of low velocity impacts, the contact models are traditionally based on the Hertzian Contact Law [11] expressed as:

$$F = K_h \cdot \alpha^{3/2} \tag{1}$$

where the local indentation α is defined as the difference between the displacement of impactor and the deflection of the target structure at contact point. In this paper the Hertzian stiffness for the laminated composites plate (Eq. (2)) is defined following the approach introduced by Yang–Sun and Carvalho–Soares [11,12]:

$$K_h = \frac{4}{3}\sqrt{R_i}\left[\frac{1-\nu_i^2}{E_i} + \frac{1}{E_{zz}}\right] \cong \frac{4}{3}\sqrt{R_i}E_{zz} \tag{2}$$

where the Young's modulus of the fibre-reinforced composite normal to the impact plane (E_{zz}) is considered equal to the Young's modulus of the composite lamina in the in-plane matrix's direction E_{22}. For most composite materials the local response is dominated by the elasto-plastic phase of the contact law which is usually linear as in [7,8]. A linearized contact law can be written as:

$$F(\alpha) = K_y \alpha \tag{3}$$