COMPRESSIVE BEHAVIOUR OF COMPOSITE PANELS CONTAINING IMPACT-INDUCED DAMAGES AND HOLES: EXPERIMENTAL AND NUMERICAL ANALYSIS

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Abstract

The estimation of the residual strength of impact damaged composite structural elements is essential for substantiating their safety margin and/or residual life. This paper deals with an engineering assessment of the static residual strength of composite laminates with impact-induced damages acted upon by compressive loads. An integrated FEM-based Global-Local numerical analysis and experimental investigations procedure has been used which provided reliable predictions of the residual strength properties of actual impact damaged composite laminates. Theoretical and numerical studies have been developed for defining and developing an engineering analysis and assessment procedure and a related computational tool.
The proposed procedure is based on the integration of the following analysis phases: (1) NDE geometrical characterisation of damaged material volumes providing accurate characterisation of both in-plane damage extensions and through-thickness distributions, (2) reduction of the actual damaged material volumes to *equivalent holes*, (3) testing of *equivalent notched composite laminates* for the calibration of a tailored semiempirical model providing a direct and simple correlation between the residual strength and the damage size.

Introduction

The prediction of residual strengths of impact damaged composite structural elements is essential for substantiating the criticality of induced damages and for assessing in-service safety margin and residual life of load bearing composite structures. In order to design damage tolerant composite structures, several methods and approaches have been proposed for evaluating the behaviour and for predicting the residual strength of damaged composite laminates. The finite element method, is very powerful but requires comprehensive knowledge on the occurring damage and fracture mechanisms and effective expertise on accurate modelling and computational techniques[1,2,3]. FEM-based analysis tools are capable of providing reliable evaluations and predictions, irrespective of material systems and loading conditions but if damage propagations have to be simulated up to ultimate failure, they can be very time consuming and expensive. The assessment of the static uniaxial residual strength of both notched and impact damaged composite laminates is relevant to maintenance and health monitoring of structural systems and for practical engineering problems, simple and reliable predictive methods/tools are required. For this reason, semiempirical modelling techniques have been devised and proposed[4,5] but their efficacy and reliability is always doubtful because they do not take the elementary damage and fracture mechanisms into account. Semiempirical models, are very simple and inexpensive but they always need a tailored calibration as soon as either the material system or the loading condition change. In dealing with post-impact compressive strengths, it is of course possible to calibrate the semiempirical models by a direct best fitting of experimental data, but the reliability of the material/load dependent parameters is undetermined because of the uncertainty of post-impact experimental data. In fact, experimental evidences show that impact events with the same energy on alike specimens do not always occur with the same effects, in terms of damage patterns and sizes, and residual strengths carried out from tests on impacted specimens are generally affected by significant scattering particularly for compressive loading. Moreover, damage and failure mechanisms in fibre composite laminates must be properly interpreted as far as scale-up effects are concerned and appropriate extrapolation methods have to be devised for employing results of strength tests on small-scale specimens to actual structural components. Conversely, residual strengths of composite panels containing "standard notches", e.g. holes, are much more reliable because they are generally characterised by narrow scattering

and low standard deviations and scale-up effects also can be managed in a better way.
In this paper the applied approach is based on an Energetic Equivalence Criterion[13] for reducing impact induced damages to equivalent holes.

Physical Modelling Of Impact-Induced Damages In Composites

From experimental evidences, it can be observed that depending on both material systems and impact energy levels, different damage states can be induced in composite laminates. A possible classification of induced damages is the following one: (a) BVID (Barely Visible Impact Damage) - a slight damage is produced, both on front and back faces of the specimens, and an internal symmetrical delamination is also produced, (b) MEdium Damage (MED) - internal symmetrical delaminations are produced and an extra asymmetrical and more extended delamination of the back ply is also produced, (c) MAximum Damage (MAD) - internal extended symmetrical delaminations are produced together with an extended delamination of the back ply.
Damage patterns induced by Low and High energy impacts in composite laminates are schematically shown in Fig. 1.

Damage - Hole Energetic Equivalence Criterion

From fracture behaviour of laminates with impact-induced damages or holes and from continuum mechanics concepts, it is inferred that residual strengths of damaged laminates is higher then residual strengths of laminates containing holes of sizes equal to the mean damage sizes. In fact, the damaged material volume can be assumed as a layered elastic inclusion with perfectly bonded plies, with reduced stiffness but still having a load carrying capacity.
The analysis of stress-strain fields in a laminate containing a hole or an inclusion of equal size and with reduced elastic properties, reveals that both the stress concentration factor and the strain energy for the notched laminate are higher than those of the laminate containing the inclusion; it is then reasonable to consider an inclusion as a hole having a smaller size. In order to define an *equivalence criterion,* the main issue to be addressed is the choice of the physical parameter on the basis of which the equivalence is established. In the proposed approach, the Strain Energy (SE) has been chosen as the most consistent and relevant physical parameter. Generally speaking, referring to Griffith's theory of solid fracture[1], for any damage or fracture process occurring in both plates with inclusions or with holes, the SE can be suitably assumed as the "driving force" of fracture processes.

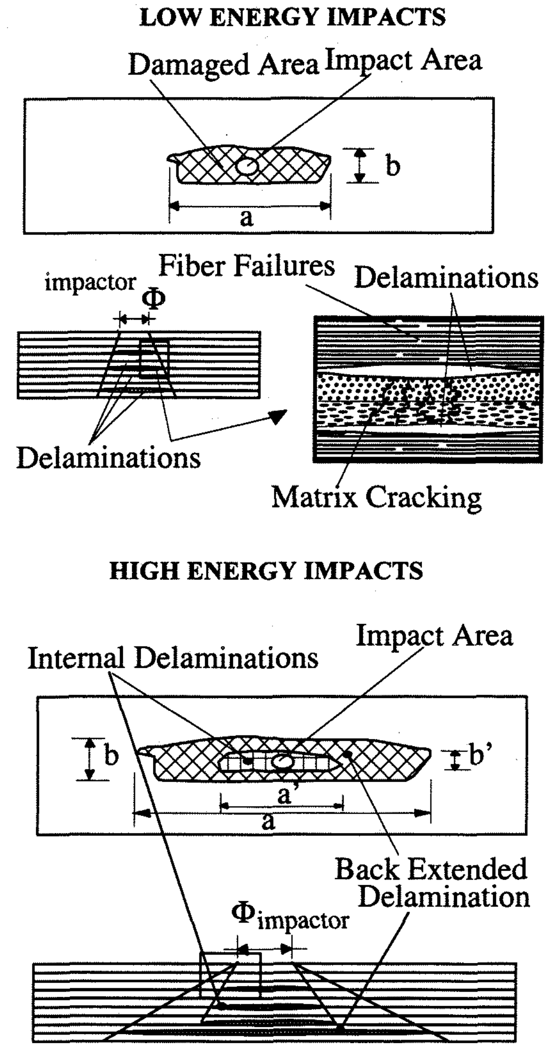

FIGURE 1 - Damage patterns induced by low and high energy impacts in composite laminates

Admitting that damage and fracture processes take place in the *process zone (PZ),* which is within an *intense energy area (IEA)* surrounding the damaged area (see FIG.2), it is inferred that damage and fracture processes make use of the strain energy gathered in the IEA, which behaves as a reservoir of energy.
The overall work of fracture can be evaluated by summing up the energy dissipated in each fracture mechanism occurring under compressive loading:

$$W_f = w_{mb} + w_{sc} + w_{db}$$

where w_{mb}, w_{sc} and w_{db} are the work of microbuckling, shear crippling and delamination buckling respectively. The statement of the proposed Energetic Equivalence Criterion (EEC) is: *an impact-induced damage is equivalent to a hole if both of them require the same work of fracture up to the ultimate failure. Because the* *work of fracture is extracted from the Potential Energy of Deformation (PED) stored within their respective intense energy area, IEA, a damage is equivalent to a hole if their individual PED, gathered within the IEA, are equal.* This statement is applicable only if the failure and damage mechanisms are the same for the impact-induced damage and the hole. The lay-up of the laminate considered in this study was $[0/45/90/-45/0_{1/2}]_{2S}$. By FEM-based Global-Local analyses of the elastic stress fields [6] it was verified that under compressive loading for such a laminate the interlaminar stresses are not critical and if the impact-induced delaminations are properly constrained for excluding delamination buckling, the prevailing elementary failure mechanisms are fiber microbuckling and shear crippling. Of course, in general delaminated composite panels acted upon by compressive loading, delamination buckling is one of the major fracture mechanisms.

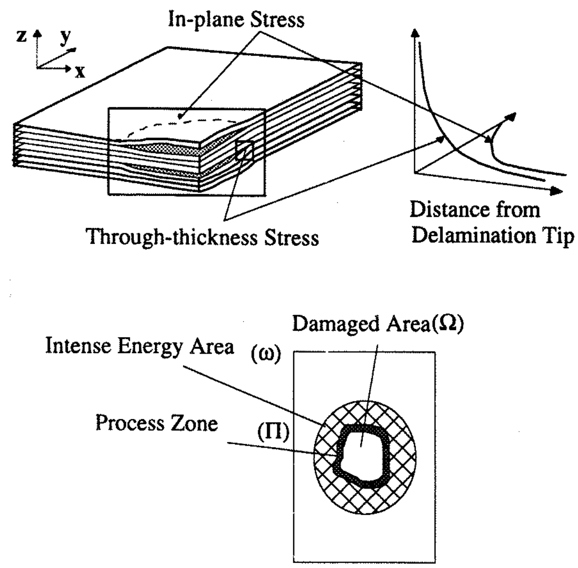

FIGURE 2 - Damage and fracture model

<u>Engineering Assessment of Impact Damaged Composites Laminates: Basic Philosophy</u>

The objective of the study was to define and validate an analysis procedure and a related computational tool for assessing the static residual strength of impact damaged composite laminates. The following requirements were established for the procedure/tool: (a) it must be simple and reliable, (b) it must provide predictions with a high confidence, (c) it must be capable of accounting for damage and fracture mechanisms and (d) it must be capable of handling geometry and scale-up effects. For accomplishing these requirements, it was decided to combine a FEM-based Global-Local analysis procedure and a semiempirical models calibrated via tailored experimental tests.

By the FEM-GL analysis the damage and fracture mechanisms as well as scale-up effects can be properly modelled and analysed and hence the material and/or load dependent factors can be taken into account. On the other hand, the semiempirical model provide a very simple and direct relationship between the static residual strength and damage sizes. The overall analysis procedure for the residual strength assessment is shown in Fig.3.

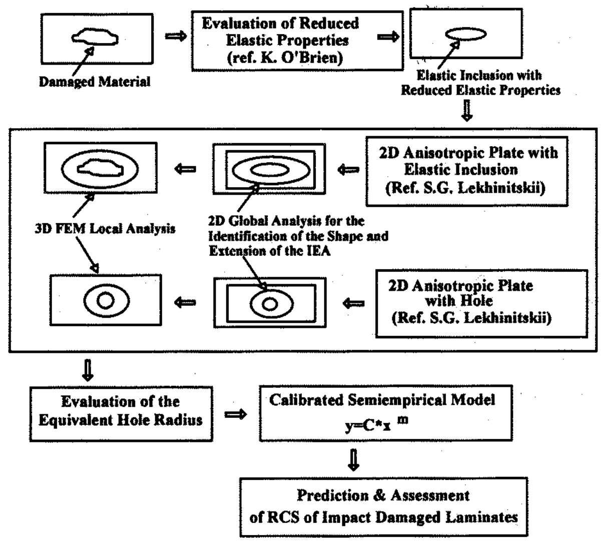

FIGURE 3 - Analysis procedure for assessing the static Residual Compressive Strength (RCS)

For developing the GL analysis, a tailored computational model was implemented for identifying the IEA around the impact-induced damages and holes. The IEA is determined by the boundary of the stress riser at hand, i.e. the damaged material volume or the hole, and the boundary defined by points in which the maximum in-plane stress components assume a value differing by a small percentage difference from the corresponding applied far-field stress.

<u>Experimental Program</u>

The experimental tests (see Fig. 4) were carried out to obtain as much data and information as possible in order that all the different data (US-NDI, AE, Strain Measurements, Load vs. Displacement) can provide complementary information during the analysis and assessment phases.
As received specimens were first analysed by US-NDE technique for characterising their "initial defective status".
Then, specimens were subjected to "falling weight" impacts with three different energy levels.
Preliminary impact tests were carried out in order to define the applicable energy levels. The energy

levels were defined by looking at the amount of the induced damages. Impact damaged specimens were then analysed with C-scan technique for characterising the damaged material volume in terms of both in-plane extensions and through-the-thickness distributions of impact-induced delaminations.
After the ND damage identification, specimens were tested in compression in order to measure their residual strength, with a INSTRON 4505 Static Testing Machine. An antibuckling frame was used to inhibit both the global buckling of the laminate and the local buckling of the sub-laminates generated by the impact-induced delaminations.
After ND damage identification and having the geometry of each damaged material volume, a FEM-based Global-Local analysis was carried out for estimating the radius of an *"equivalent hole"*.
For establishing the equivalence between the impact-induced damage and the hole, an energetic equivalence criterion was defined.
Tests have been carried out for measuring the compressive strengths of alike notched and un-notched specimens, i.e. containing holes with different radius and without holes. On the basis of such experimental residual strengths, a semiempirical model was calibrated establishing a direct relation between the compressive residual strength and the hole radius.
All the tests have been monitored via strain-gages and Acoustic Emission (AE) measurements. The AE monitoring was carried out during all the loading history up to 80 % of the ultimate failure load. The purpose of strain-gages measurements was to monitor both the uniformity of the applied load and buckling events. The load vs. displacement curves were also registered up to ultimate failure.

Specimen Configuration

Experimental tests, on laminate stacking sequence $[0/45/90/-45/0_{1/2}]_S$, which are objects of a joined research program with a helicopter company, are in progress.
Actually, only preliminary results of characterisation of impact-induced damages (impact energy levels, NDE characterisations) are available.
Specimens were manufactured by the autoclave lay-up technology and using UD high strength carbon fibres (T300) pre-impregnated with epoxy REC resin system (43%) and cured at 125°C.
Three different specimen's geometries were defined as reported in Tab.1.

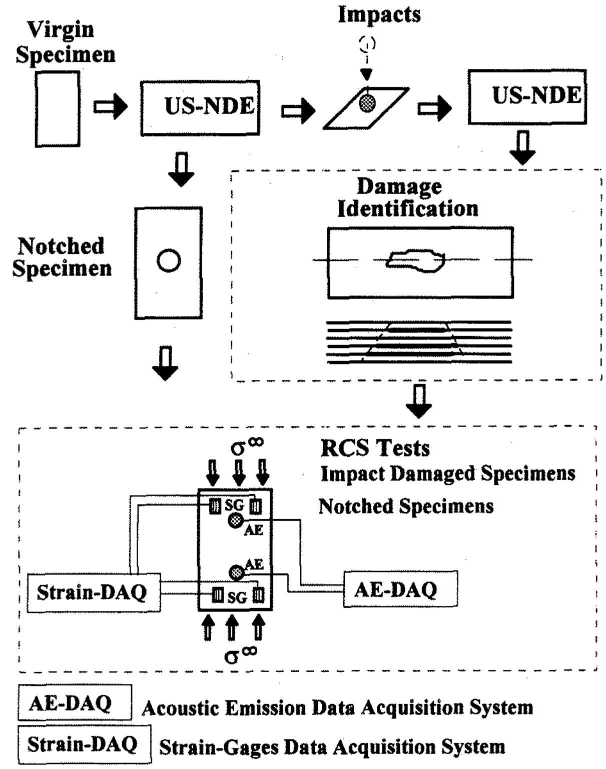

FIGURE 4 - Experimental program

Type of Specimen	Width (W) mm	Length (L) mm	Gauge Length (GL) mm
Impact	200	300	100
Un-notched	60	300	100
With hole	100	300	100

Tab.1 - Type of specimens and associated geometry

Impact Tests

Impact tests used for composites are those previously developed for plastics and are performed using the following configurations :
- bars in tension
- beams in flexure
- plates in flexure

The impact is variously by :
- spring/air driven projectile
- falling weight
- swinging pendulum

Impact tests were conducted with the "FALLING WEIGHT" modality, combined with specimen in a flexed plate configuration, that corresponds more closely to the modalities of damage we want to analyse(14), compared to common techniques as Izod or Charpy pendulum. It is worth stressing that impact testing, if it is to be used in design, should produce similar types of damage to those occurring in the practical application: in the extreme, such as bird strike on aircraft, it might

mean an exact simulation, such as firing dead birds from a gun at aircraft parts. There is a practical advantage of the flexed plate method, consisting of the fact that the preparation of specimens is relatively undemanding because carelessly produced edges are unlikely to affect the result; in contrast the impact resistance of a flexed beam is sensitive to the qualities of the edges.
Above all we must notice that, at a constant impact energy $E=1/2\ M\ V^2$, is possible to change two parameters: impactor mass and impact velocity.
If the velocity is changed then it is important to say that the specimen is subject to different stresses that can lead to various consequences even if impact energy is held constant. Impact response can be divided basically in two parts: structural and local. To the former is associated the flexure of the specimen due to the action of the striker transmitted along the structure by means of transverse elastic waves (which have different propagation speed for each harmonic and are distorted during propagation); to the latter is associated the local compression transmitted by means of longitudinal waves (that are not distorted along the specimen and have a velocity independent of frequency). By experimental evidence and numeric analysis is obtained that the response is the more local and the less structural, the more is the value of impact speed, with decreasing influence of boundary conditions and increasing importance of the phenomenon of mechanical waves propagation and consequent variation of damages showed by specimens. At low incident velocities, impact damage tends to be mainly splitting damage parallel to the fibres such as intralaminar splitting within the plies and delamination between the plies. At higher velocities, there are time constraints on the impact event leading to higher energy densities, higher stresses near the point of impact, a greater incidence of fibre breakage and possibly a restricted area of damage.
Impact tests were conducted with the CEAST T.C.F.W. (Temperature Chamber Falling Weight): A steel rod mounting a 12,7 mm-diameter hemispherical tup at the front end, with total mass of 1 Kg, is dropped on the specimen from an height determined by the impact velocity (and hence energy level) we are interested in; the specimen are clamped at both ends on each side and lay on an annular support. An anti-rebound device is used to prevent multiple impacts to the test specimen. The entire fixture complies with ASTM D3029 (impact resistance of rigid plastic sheeting by means of a tup). A timing flag and a light gate system are used to obtain the velocity of the rod just before impact (different from theoretical value $V=(2gh)^{1/2}$ because of the presence of friction along the travel of impactor).
The striker is fitted with a force transducer constituted by four semiconductor strain gages forming a common Whetstone bridge in full-bridge configuration.
The derived data relates to the striker. It is assumed that this reflects the situation in the specimen by assuming that the striker and the specimen are in contact throughout the test.
Observing the diagrams (FIGG. 5,6) so obtained interesting information can be drawn:
the maximum contact force increases as the impactor velocity increases, whereas the duration of impact decreases; the basic shape of the force time signature changes if there are fibre failures.
It is possible to determine the damage incipience from the impact force-time history.

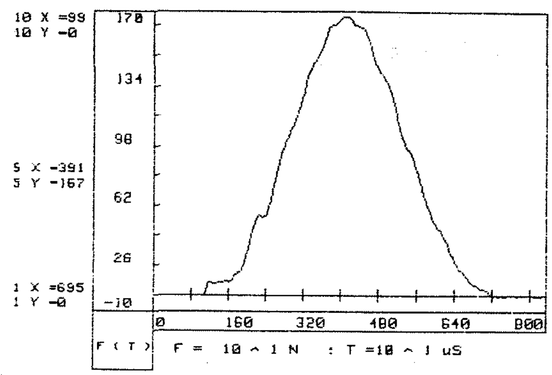

FIGURE 5 - Impact Energy E=3.5 J

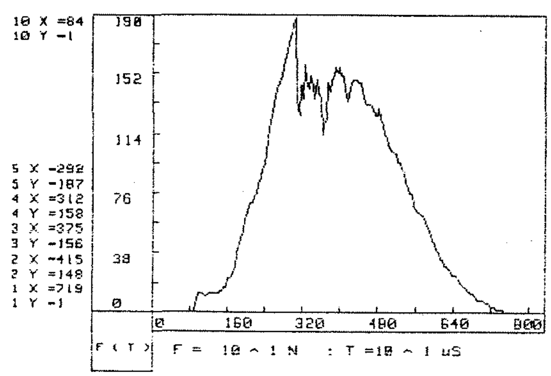

FIGURE 6 - Impact Energy E=5.4 J, fibre failures in the back ply

NDE Characterisation of Impact-Induced Damages

Figure 7 shows a local zoomed C-scan pictures as an examples of the results. The load axis is oriented along Y-axis.
Through C-scan it is possible to identify the damaged area, ply by ply, for all the laminate's thickness.

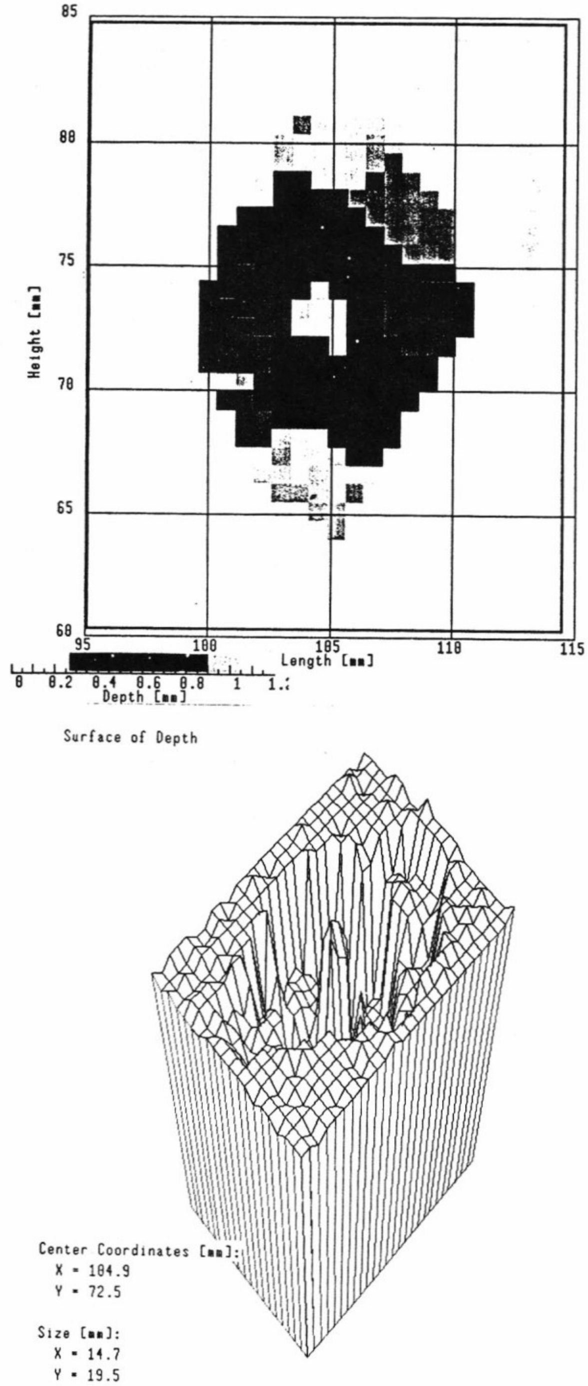

FIGURE 7 - ND Characterisation of impact induced damages

Impact Energy Level and Related Damages

Three different levels of impact energy damage were defined corresponding to an equal number of extents of the internal delamination caused by the impacts and assessed by C-scan plots obtained by the ultrasonic ND inspection:

1. BVID (Barely Visible Impact Damage) 1.5 J
2. MED (MEdium Damage) 3.5 J
3. MAD (MAximum Damage) 5.0 J.

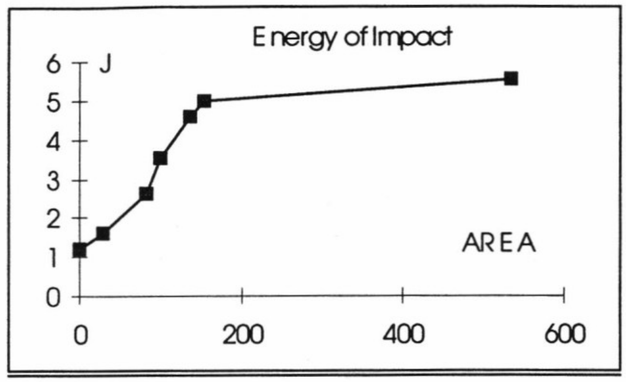

FIGURE 8 - Levels of Impact Energy vs Damage's Area

Numerical Models and Results

FEM analyses provide useful insights into the stress-strain and energy fields and by appropriate "zooming" techniques very detailed computations can be performed. Because of singularities and steep gradients affecting the local stress fields, a FEM-based GL procedure [7,8] was applied. The global analyses have been carried out by using analytical solutions of anisotropic plates containing elastic inclusions or holes [9]. The reduced elastic properties of inclusions have been estimated by applying the model proposed by K. O'Brien [10], which is based on the classical laminate theory. From global analyses the boundaries of IEAs and the related displacement boundary conditions have been evaluated. The local analyses have been carried out by defining suitable 3D finite element models where displacement boundary conditions, representing the actions of the "outer region" on the "inner region", have been enforced. In modelling impact damaged laminates, i.e. containing delaminations, kinematic contact elements have been used but contact friction between sublaminates was not considered.
It must be remarked that within the IEA surrounding the damaged material or the hole the stress fields are affected by local steep gradients (in-plane stress components) and even singularities (through-thickness stress components). Therefore, the contribution of these stress components to the PED is significant and the FEM-GL analysis must be developed by suitable models in order to carry out accurate estimations.
Since each layer of composite panel is meshed with 3D brick elements in order to estimate correctly the global PED a large number of degree of freedom are necessary.
This mean a considerable increase in terms of work space and computation time. For these considerations a sub-structuring technique is employed to perform a local analysis and then to evaluate the strain energy.

Since, actually, the after impact compressive tests results are not available for the $[0/45/90/-45/0_{1/2}]_S$, the comparison of the numerical results is carried out with the experimental results of the stacking sequence $[0/45/90/-45/0_{1/2}]_{2S}$, which was object of previous experimental tests[6,15].
For the panel topology considered in this work (with a max. 4 delaminations) two different sub-structured models have been carry out. The first with 6 superelements: one representative of anti-buckling stiffeners, the others representative of the five sub-laminates.
The second model is composed of 10 super-elements. The local model is divided in two regions: inside and outside the delamination front. Five super-elements are representative of the inner region, four are representative of the outer region and the last of the anti-buckling guides.
In Tab. 3 the results for these two sub-structured models are compared with full model.
For a fixed work space sub-structured models can run with larger number of d.o.f. than the full model. This mean that sub-structured models have a greater reliability in term of strain energy than full model.
Moreover sub-structuring technique allows a considerable saving in CPU time respect the complete model.
In fact in a non linear analysis (this analysis is non linear for the presence of contact elements), it can substructure the linear portion of the model so that the element matrices for that portion need not be recalculated every equilibrium iteration.
The convergence of the sub-structured results toward the experimental value confirm their high reliability.

Ref.	Max. del. Size in x axis (mm)	max. del. size in y axis (mm)	location trough the tick z axis (mm)	σ_r (MPa)
A_2/173	27.2	25.6	0.6/1.2/1.8/2.4	276.27
A_2/172	28.8	28.8	0.6/1.2/1.8/2.4	258.87
A_2/166	28.8	27.2	0.6/1.2/1.8/2.4	275.38

Tab.2 - Mechanical and geometrical characteristics of the post-impact specimens

Ref.	Mod. FEM	d.o.f. N.	Master	CPU (sec)	Req (mm)	σ_r (MPa)
	no sup. el.	11550	-	6369	9.40	266.56
A_2/273	6 sup. el.	15460	10791	4569	9.35	267.80
	10 sup. el.	22740	6578	3890	9.25	270.70
	no sup. el.	12706	-	6763	9.95	254.06
A_2/273	6 sup. el.	16850	11435	4793	9.90	254.50
	10 sup. el.	24578	6722	3998	9.82	255.60
	no sup. el.	12376	-	6499	9.80	256.76
A_2/273	6 sup. el.	16675	11376	4678	9.76	257.56
	10 sup. el.	24321	6667	3951	9.70	260.90

Tab.3 - Comparison between sub-structured models and full model

There is an other important effect, related to the delamination through-thickness position, to be considered in the local FEM 3D modelling. Depending on the interface at which the delamination is initiated, the sub-laminate may have a coupled membrane-flexural behaviour giving rise to warping effects. Such warping effects must be carefully taken into account because they can give rise to contact phenomena between the sub-laminates and they can also be critical as far as the local delamination buckling is concerned. In the present study, this problem has been considered to some extent by using contact elements without friction. Fig. 9 shows two 3D FEM models of a totally delaminated laminate, containing four delaminations. Without using contact elements, interpenetration phenomena take place loosing the physics of the phenomenon. Fig. 10 shows the out-of-plane displacement contour plot obtained by 3D finite element model of a delaminated specimen with anti-buckling constrains.
The bulging of the delaminated portion of the specimen under the anti-buckling stiffeners is evident.

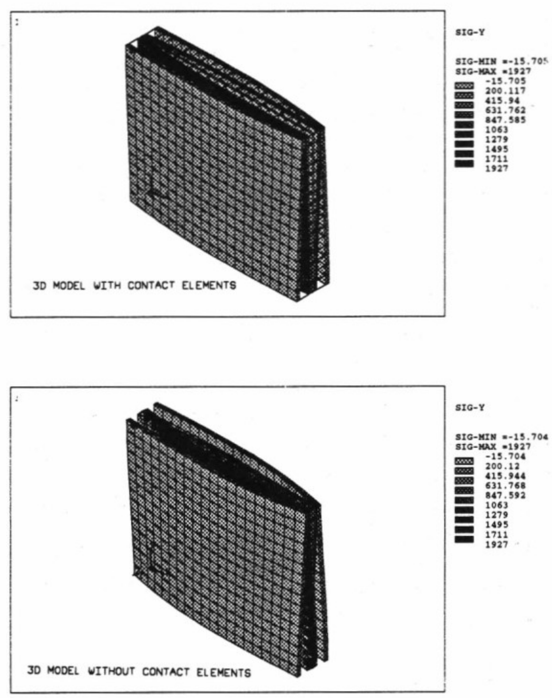

FIGURE 9 - 3D FEM modelling of a totally delaminated laminate showing warping effects

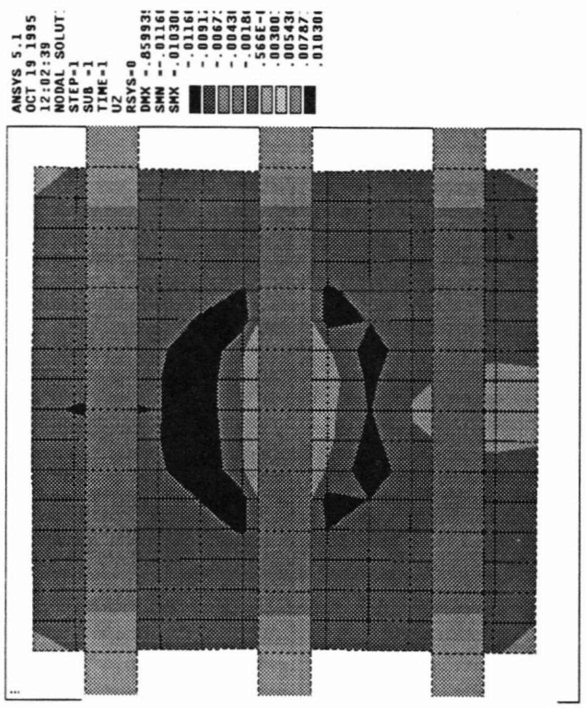

FIGURE 10 - Out-of-plane displacement contour plot

Residual Compressive Strength Tests

The semiempirical model used in this study is based on LEFM concepts[11], and it was formulated following the approach proposed by Waddupons[12]. Assuming a crack-like defect within the composite laminate and by applying the LEFM theory failure occurs when:

$$K_{IC} = \sigma_C (\pi C)^m \quad (2)$$

where: σ_C is the far-field applied stress, $2C$ is the crack length and m is a material dependent constant. Assuming that the final failure of an un-notched laminate is due to an intrinsic defect of size $2C_0$, the behaviour of an un-notched laminate can also be analysed in terms of fracture mechanics:

$$K_{IC} = \sigma_0 (\pi C_0)^m \quad (3)$$

where σ_0 is the typical strength of the material. From Eqns (2) and (3) the following relationship is obtained:

$$\frac{\sigma_C}{\sigma_0} = \left(\frac{C_0}{C}\right)^m \quad (4)$$

representing a power-type model with two unknown material dependent parameters, C_0 and m. Fig. 11 shows the correlation of compression post-impact residual strengths data obtained by experimental tests and by the proposed analysis procedure. The differences between the numerical residual strengths and experimental residual strengths on the impacted specimens are acceptable, with a max. error of the 4%.

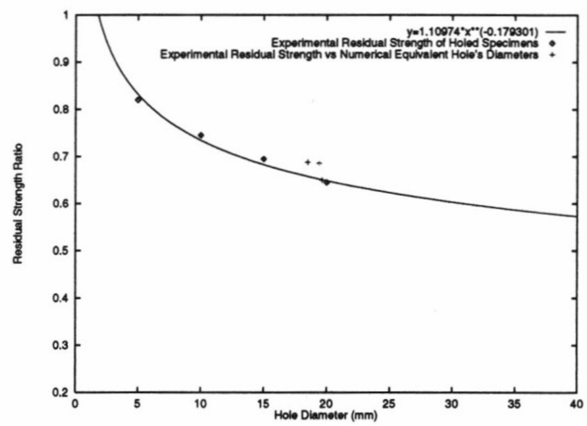

FIGURE 11 - Correlation between the numerical results of the proposed model and experimental post-impact analysis

Discussion & Conclusions

A combined analytical, numerical and experimental analysis procedure for assessing the static residual strength of composite laminates containing impact-induced damages was developed. The proposed analysis procedure allows to carry out very accurate and highly confident calibration of semiempirical model for post-impact residual strength predictions by using residual strength data carried out by testing laminate containing equivalent holes. The combination of FEM based analysis and semiempirical modelling allows to take damage and failure mechanisms into account providing an analysis tool with an underlying physical basis. The adopted substructuring analysis allows to reduce the CPU time. The proposed analysis procedure has been validated only for a specific laminate configuration and material system under compressive loading. Residual strengths obtained via equivalent hole concept have been correlated with a semiempirical model calibrated using residual strength data of alike laminate containing holes and it was found a good correlation. The proposed modelling and analysis procedure can be improved by taking the progressive nature of failure into account and by modelling both the delamination buckling and contact phenomena.

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