Composite Stiffened Panel Impact Damage Simulations And Parametric Studies

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Abstract

A finite element (FE) based analytical tool, Composite Damage Tolerance Analysis Code (Codac), has been developed at the German Aerospace Center (DLR), Institute of Structural Mechanics, over the past few years. It is a fast tool that can determine impact response, damage and residual strength of flat or curved, stiffened composite panels. The tool features Windows based, graphical user interface (GUI) forms for various modelling and analysis steps. A simplified 2-D modelling approach has been adopted by using eight-node, isoparametric, plate-bending elements and three-node, isoparametric, beam elements for skin and stringer modelling, respectively. Various failure criteria have been implemented for fibre breakage, matrix cracking and delamination. The tool is capable of showing the ply-by-ply progressive damage for different damage modes and performing delamination growth analysis in the postbuckling regime under quasi-static loading. Calculating the strain energy release rate at each in-plane strain increment and comparing this with the critical values determine the delamination growth. Comparisons of the simulation results against the available test data showed that Codac is capable of assessing impact damage rapidly with reasonable accuracy, although further improvement to the tool is necessary as not all predictions agreed closely with the test data. Parametric studies were performed to evaluate the tool's capability and to determine its critical parameters. It was found that impact damage prediction with Codac is sensitive to the meshing, lateral boundary conditions (free, simply supported or clamped), panel size and the impact energy. In the event of impact, delaminations typically occurred in plies located at the mid-plane or away from the impact face. Additionally, the first few plies at the impact side were dominated by fibre breakage at higher impact energies. This has been established as the phenomenon of low velocity impact in composite materials.

Nomenclature

E	elastic modulus
F	force
k	Hertzian contact constant
m	mass
R	radius
σ	normal stress
τ	shear stress
γ	Poisson's ratio
α	indentation depth

1. Introduction

Damage tolerance is of major concern in the design of laminated, fibre reinforced, composite structures due to their poor resistance to impact damage. Impact damage occurs when a foreign object causes through-thickness and/or in-plane fracture. In many applications, low velocity impacts are common, for example, when stones are thrown up from the runway hitting the wing of an aircraft, or damage occurring during the maintenance (i.e. tool drop). The effect of this damage can be greater than that of high velocity impact that creates a neat puncture of the component or indentation, especially if the damage goes undetected and grows under subsequent loading. It has been shown that the compressive strength can decrease dramatically due to impact damage in the composite laminates. In composite materials, impacts results in complicated damage in the form of varying amounts of delaminations between the plies, matrix cracks between the fibres, and fibre breakage. The first two damage modes are dependent on the properties of the resin, whereas fibre breakage is dependent on the fibre characteristics and is usually caused by higher energy impacts. Stiffness of the structure will decide the failure modes due the impact and different damage modes may exist alongside one another [1,2].

Matrix cracking occurs in composite laminates due to stress concentrations at the fibre-matrix interface. It is caused by compressive and tensile stresses on the impact contact and non-contact sides of the panel, respectively. Larger crack areas are normally caused by crack branching, in which case the cracks run in the direction normal to the general direction of fracture. Fibre breakage occurs when the fracture strain in the composite material is reached. It can also result from crack propagation in the direction perpendicular to the fibres. It should be noted that the fibre characteristics greatly influence the damage modes and hence the total energy to cause damage. Generally, a secondary damage mode, matrix damage will follow after the initial fibre failure. The fibre breakage may reduce the tensile strength, whereas the matrix damage may reduce the compressive strength of the composite laminates. Delamination usually occurs at the interface of two different ply orientations due to the stiffness mismatch. Impact on a composite laminate can produce multiple delaminations and can reduce the compressive strength significantly. Delamination produces sub-laminates and consequently reduces the local bending stiffness. Therefore, under compression and/or shear load, delamination can result in splitting of sub-laminates, i.e. local buckling at a lower applied load. Consequently, the delamination may propagate and lead to structural instability and premature failure. The shape of delamination is generally irregular, although elliptical or peanut shapes are usually observed. The major axis of the delamination is, in general, parallel to the fibre direction of the back face ply. Therefore, the delamination between any two plies is characterised by its length and width, which are taken to be the dimensions of the delamination in the directions parallel and perpendicular to the fibre direction in the back face ply [1,2,3].

Some simple analytical and/or empirical expressions have been developed to predict the impact response of composite structures. However, by far the most promising techniques for predicting the impact behaviour are those based on the dynamic finite element (FE) method, which iteratively solves Newton's Second Law of Motion (i.e. Force = Mass x Acceleration). The solution is progressed from a known initial condition and incremented with small time steps to produce a sequential solution to the initial value boundary problem. The explicit FE method is able to solve time domain dynamic problems with geometric and material non-linear effects. The softening of materials and contact during impact can be handled by the explicit formulation with ease. However, the explicit method is computationally very expensive and is only used for problems involving short duration dynamic responses. The explicit algorithms are conditional stable; therefore a very small time step is required to achieve a converging solution. On the other hand, implicit algorithms are unconditionally stable, allowing bigger time steps to be used.

An FE based implicit analytical tool, Composite Damage Tolerance Analysis Code (Codac), has been developed at the German Aerospace Center (DLR), Institute of Structural Mechanics, over the past few years. Codac is used to rapidly determine impact response, damage and residual strength of flat or curved stiffened composite panels. It features Windows based graphical user interface (GUI) forms for various modelling and analysis steps. The tool is capable of showing the ply-by-ply progressive damage for different damage modes (i.e. fibre breakage, matrix cracking and delamination) and performing delamination growth analysis in the postbuckling regime under quasi-static loading. The purpose of this work was to verify the simulation results with test data and to evaluate the tool's capabilities through parametric studies.

2. Theoretical Background

2.1 General Modelling Approach

For the modelling of composite stiffened panels, Codac uses eight-noded isoparametric elements with five degrees of freedom (DOF) per node to model the skin and three-noded isoparametric beam elements with six DOF per node to model the stringer. Such a simplified approach to model the stringer means that Codac is unable to predict skin-to-stringer debonding, which is occasionally found in the vicinity of stringer impact. As a result, impact on the stringer region is currently not implemented in Codac. Development work is underway to model the stringer in greater detail with shell elements in order to predict the impact damage in the region. Figure 1 shows the representation of the composite stiffened panel with the FE modelling.

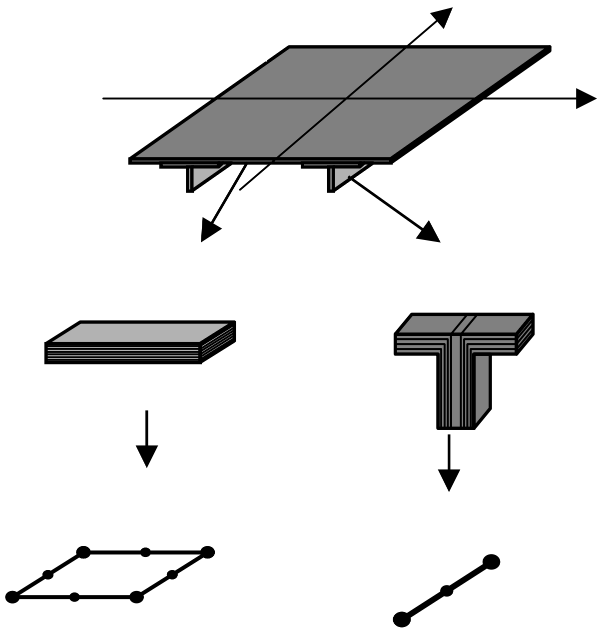


Figure 1 Composite stiffened panel finite element modelling approach in Codac

2.2 Impact Analysis

The method for transient impact analysis in Codac is a 2-D linear FE approach based on Hertzian contact law and Mindlin's plate theory that considers the transverse shear stress. The dynamic differential equation is given as follow, with the damping effects ignored [4]:

$$[K]\{u\}+[M]\{\ddot{u}\}+\{R\}=0 \tag{1}$$

Where [K] = global stiffness matrix
[M] = global mass matrix
{u} = displacement vector
{ü} = acceleration vector
{R} = impact load vector

The differential equation for the motion of the impactor is given as follows:

$$F_{impactor} = m\ddot{s} \tag{2}$$

Where m = impactor mass
$\ddot{s}$ = impactor acceleration

The impactor is assumed to be a point mass and is represented by a contact force between the impactor and the panel. The contact force is determined based on the Hertzian indentation law, given as follows:

$$F_{contact} = k_h \alpha^{\frac{3}{2}} \tag{3}$$

Where k_h = Hertzian contact constant
α = Indentation depth

The following equation is used to calculate the Hertzian constant, k_h [5]:

$$k_h = \frac{4}{3}\sqrt{R}\left(\frac{1-\gamma_S^2}{E_S}+\frac{1}{E_Z}\right)^{-1}\left(\frac{E_Z}{E_X}\frac{E_Z}{E_Y}\right) \tag{4}$$

Where R = radius of the impactor
E_S = Young's modulus of the impactor
γ_S = Poison's ratio of the impactor
E_X, E_Y and E_Z = Young's modulus of the laminate in the X, Y and Z directions

Direct integration can be used to solve Equations (1) to (3) if the initial conditions are known. The following direct integration methods are available in Codac: Linear Acceleration Integration, Newmark's Integration (default) and Wilson Theta Integration.

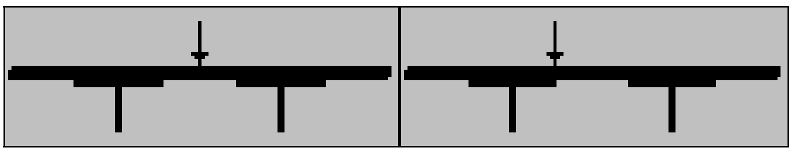
The various failure criteria available in Codac are summarised in Table 1. The default failure criteria used in Codac are Maximum Stress, Hashin Complete and Choi / Chang for fibre breakage, matrix cracking and delamination respectively. Every damage mode is evaluated with the application of its respective failure criteria in the FE model. The 8-noded plate element used in Codac is divided equally into four quarters, and each quarter of the element is used to represent the damage modes independently.

Table 1 Failure criteria implemented in Codac

Damage Mode	Criterion	Components of the ply stress tensor used
Fibre Breakage	Maximum Stress	σ_{11}
	Hashin	σ_{11}, τ_{13}, τ_{12}
Matrix Crack	Hashin Complete	σ_{22}, σ_{33}, τ_{23}, τ_{13}, τ_{12}
	Hashin 3D	σ_{22}, τ_{23}, τ_{13}, τ_{12}
	Hashin 2D	σ_{22}, τ_{12}
	Puck	σ_{22}, σ_{33}, τ_{23}, τ_{13}, τ_{12}
	Tang / Chai	σ_{22}, τ_{13}, τ_{12}
Delamination	Choi / Chang	σ_{22}, τ_{23}, τ_{13}
	Tang / Chai	σ_{22}, τ_{23}, τ_{13}
	Puck	σ_{33}, τ_{23}, τ_{13}
	Hashin	σ_{33}, τ_{23}, τ_{13}

3. Tool Overview

A FE model for the transient impact analysis can be created within the GUI form in Codac. It is possible to create flat or curved stiffened panels, which may have an arbitrary number of equally spaced stringers in the Y-direction. The stringers must be connected to the skin laminate either by co-curing or by adhesive bonding. Two types of stringers are implemented in Codac: T-shaped and trapezoidal. It is assumed that the impact location is at the centre of the panel in the X-direction. Therefore the mesh is refined in the X-direction, with the smallest element located at the centre of the panel and the size of the elements increased gradually towards the panel edges. There are two possible impact locations that can be selected: the mid-skin bay and the edge of a stringer, as shown in Figure 2. There are three options for the boundary condition (BC) definitions at the four panel edges: free, simply supported and fully clamped. The skin laminate lay-up and material type are also defined through a coding system in Codac. The material type is identified by the numerical code designated in the built-in material database. It is possible to add or modify the material properties through the material database GUI form. During the course of the transient impact analysis, the damage initiation and propagation during the impact event is displayed, together with curves for the force-time history and displacement at the contact point. The analysis can be suspended at any time in order to investigate the intermediate damage results and then resumed to complete the prediction of the entire impact event. The delamination area at each interface and the total overlayed delamination area are calculated. The three damage modes at each ply can be displayed graphically. It is possible to display the overlayed damage, as well as the ply-by-ply damage.



(a) Impact at skin bay (b) Impact at stringer flange edge

Figure 2 Two impact scenarios currently available within Codac: (a), (b)

4. Preliminary Validation

Studies were conducted with Codac on two types of composite flat panels: unidirectional tape and woven fabric. The dimension of the test panels were 150 mm x 100 mm, with a test region of 127 mm x 76 mm after the installation of a clamping picture frame. The test panel configurations used for the comparison studies are summarised in Table 2. The impactor diameter and mass was 12.7 mm and 0.522 kg, respectively. The FE model of the test panel, which consisted of 640 elements, was generated for the impact damage prediction in Codac. The tightly clamped BC was achieved by locking the four clamps tightly onto the picture frame. Therefore, no movement of the specimen was possible.

Table 2 Impact test panel configurations [7]

Test Panel ID	Lay-up and Material	Measured Thickness (Nominal) [mm]	Impact Energy (Measured) [J]	Boundary Conditions
F1C4	$[(0/90)_7]_s$, Fabric	3.12 (3.02)	5 (5.072)	Tight Clamp
F1C6	$[(0/90)_7]_s$, Fabric	3.13 (3.02)	10 (10.184)	Tight Clamp
F1C8	$[(0/90)_7]_s$, Fabric	3.12 (3.02)	16 (15.662)	Tight Clamp
T1A6	$[(0/90)_3]_s$, Tape	2.38 (2.40)	3 (3.073)	Tight Clamp
T1A8	$[(0/90)_3]_s$, Tape	2.45 (2.40)	8 (8.244)	Tight Clamp
T2B4	$[(0/90)_4]_s$, Tape	3.16 (3.20)	5 (5.072)	Tight Clamp
T2B6	$[(0/90)_4]_s$, Tape	3.32 (3.20)	10 (10.184)	Tight Clamp
T2B8	$[(0/90)_4]_s$, Tape	3.28 (3.20)	16 (16.420)	Tight Clamp

The Codac results were compared with the test data [7]. The Choi / Chang failure criterion was used to predict the delamination area. Table 3 shows that Codac has difficulty in predicting the damage area accurately in two cases (highlighted), while for most of the panels the measured and predicted overlayed delamination size differed by 15 % or less. The damage area of the woven fabric was predicted quite well for all impact energies, while the damage for the panels made of tape material was predicted well only in one case. The large deviations in damage area prediction for the two highlighted cases were due to the fact, that the Choi / Chang criterion used a semi-empirical approach, which was developed for impact energies of 10 to 40 J. It was more important to accurately predict impact damage for the higher impact energies, as the lower impact energies only produced tiny damage areas and their effects were almost insignificant on the structural strengths. Damage prediction with the Choi/Chang criterion also required the knowledge of a material system dependant parameter. The default value in Codac was used for both types of material, as the actual values of the parameter were not known. The damage prediction of the tape material could be improved if the correct parameter has been established. Two BCs were investigated in Codac in order to determine the correct condition representing the test. It should be noted that the test panel was placed in a picture frame and clamped at the lateral sides of the panel. It was found that the fully clamped BCs in Codac represented the test condition slightly better than the partially clamped BCs, as the simulation results have shown.

Table 3 Comparison of damage area predictions and test data

Test Panel ID	Damage Area [mm] (Percentage different with test data)		
	Test Data	Codac, with partially clamped boundary condition[1]	Codac, with fully clamped boundary condition[2]
F1C4	216	197 (-9 %)	206 (-5 %)
F1C6	421	434 (-3 %)	467 (-11 %)
F1C8	853	805 (6 %)	869 (-2 %)
T1A6	12	55 (-358 %)	80 (-567 %)
T1A8	497	149 (70%)	280 (44 %)
T2B4	8	106 (1225 %)	181 (2163 %)
T2B6	460	227 (51 %)	389 (15 %)
T2B8	1226	384 (69 %)	670 (45 %)

Table 4 shows the peak contact force comparison between the test data and Codac simulations. Codac has the tendency to overestimate the peak force. This was expected, because the influence of degradation was not taken into account during the impact analysis. A progressive damage model used to consider the softening effect of damage during the impact transient analysis has been incorporated for future investigations. Figure 3 show the damage shape and size predictions from the Codac and test data for panels T1A8 and F1C4. The shape of damage predicted by Codac for the panel T1A8 was dissimilar to the C-scan, where an elongated damage shaped was found, as shown Figure 3(a), whereas the impact damage

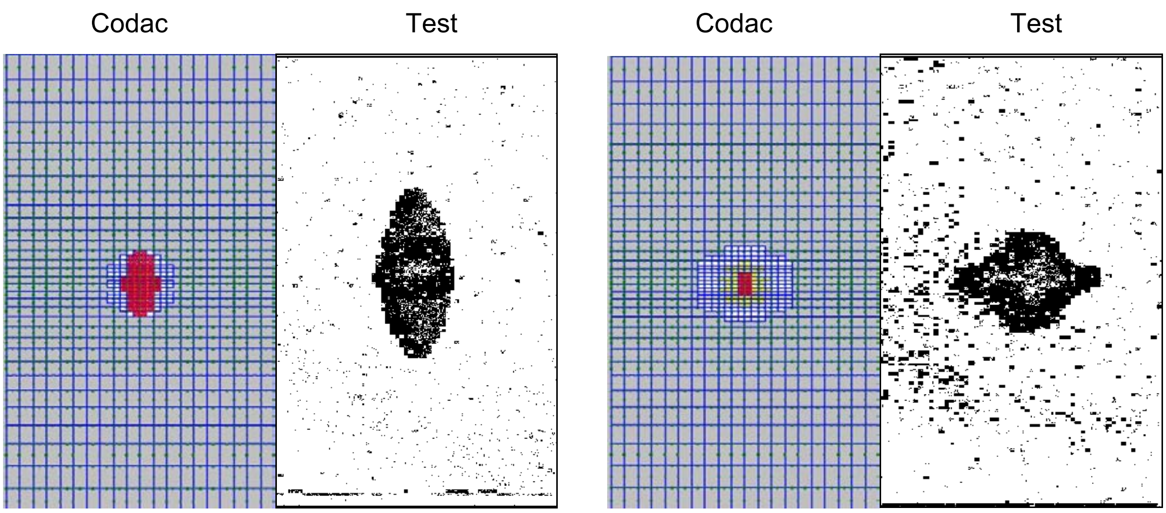
[1] Longitudinal sides simply supported and lateral sides clamped

[2] Fully clamped at all edges

prediction on panel F1C4 compared well with test data, as shown in Figure 3(b). Codac did not manage to analyse each test panel with good agreement with the test data. However, it has demonstrated overall good abilities to rapidly predict impact damage.

Table 4 Impact test data comparison – peak contact force

Test Panel ID	Peak Force – Test panels [kN]	Peak Force – Codac [kN]	Percentage difference
F1C4	2.3	3.2	-39 %
F1C6	2.3	3.4	-48 %
F1C8	2.6	4.1	-58 %
T1A6	1.8	1.8	0 %
T1A8	2.4	3.0	-25 %
T2B4	3.1	3.4	-10 %
T2B6	3.6	4.9	-36 %
T2B8	3.6	6.2	-72 %



(a) Panel T1A8

(b) Panel F1C6

Figure 3 Comparison of damage area predictions for test panels T1A8 and F1C6

5. Parametric Studies

Parametric studies were conducted using Codac in order to evaluate the tool in greater detail. A two T-shaped stringer panel was used in the parametric studies, with the skin thickness of 2.25 mm, consisting of nine plies. The benchmark flat panel dimensions were 500 mm x 285 mm, which was used in all parametric studies except for the panel geometry studies. When a parameter was investigated, all other impact parameters were kept to the default values set in Codac.

The meshing density parametric study was conducted in order to assess its sensitivity to damage prediction. It was found that mesh density within the stringer region did not affect the results much. This was because all of the parametric studies, except impact location, involved impact at the skin bay and the impact damage was not expected to extend into the stringer region. The size and shape of the elements within the damaged region have a significant effect on the damage area prediction. During the meshing parametric studies the effect of the total number of elements on the computational time was also recorded. The computational time increased dramatically with the total number of elements in the model. The mesh density did not affect the predicted force time history or deflection at the impact point. It was found that a mesh with 1200-1400 nodes and elements of the size of about 5 mm x 5 mm in the expected damage area would lead to acceptable results in less than ten minutes on a modern desktop computer. The FE model with 468 elements was used in the parametric studies for its fast computational time and reasonable element size (i.e. the smallest was 6 mm) for predicting the damage area with good accuracy.

The impact energy level was investigated with the default impactor mass of 6.8 kg as well as a mass of 1 kg. The lighter impactor mass was used in order to investigate the impact energy at higher levels, i.e.100 J. It was found that the contact force increased with the impact energy, as shown in Figure 4, for the default impactor mass. The force-time history plots show a family of curves with a similar pattern for the same impactor mass. Figure 5 shows the delamination area comparison for the 1 kg impactor. Both cases have shown that the contact forces and damage area increased with the impact energy consistently.

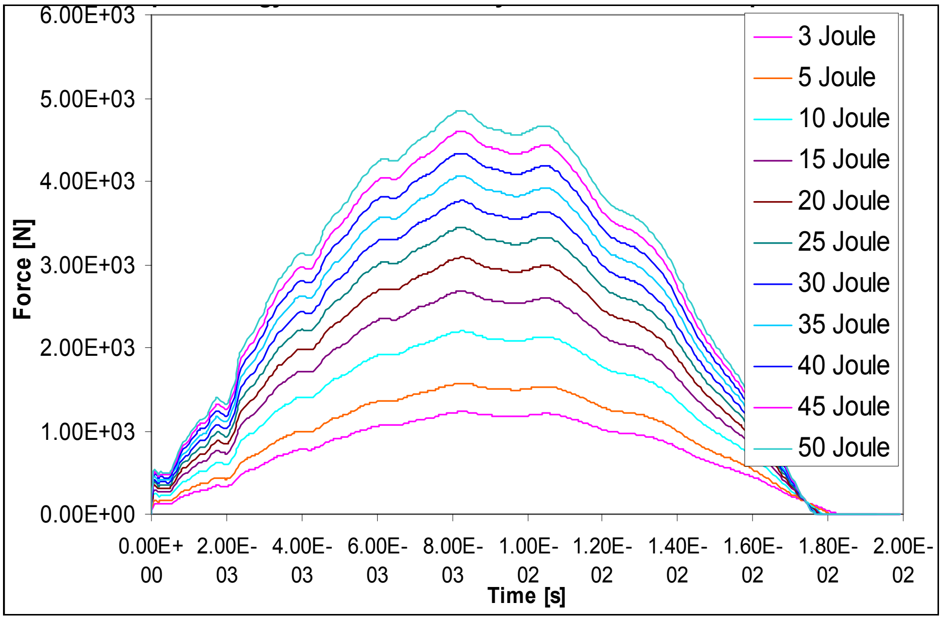


Figure 4 Force-time history plot for the default impactor with different impact energy

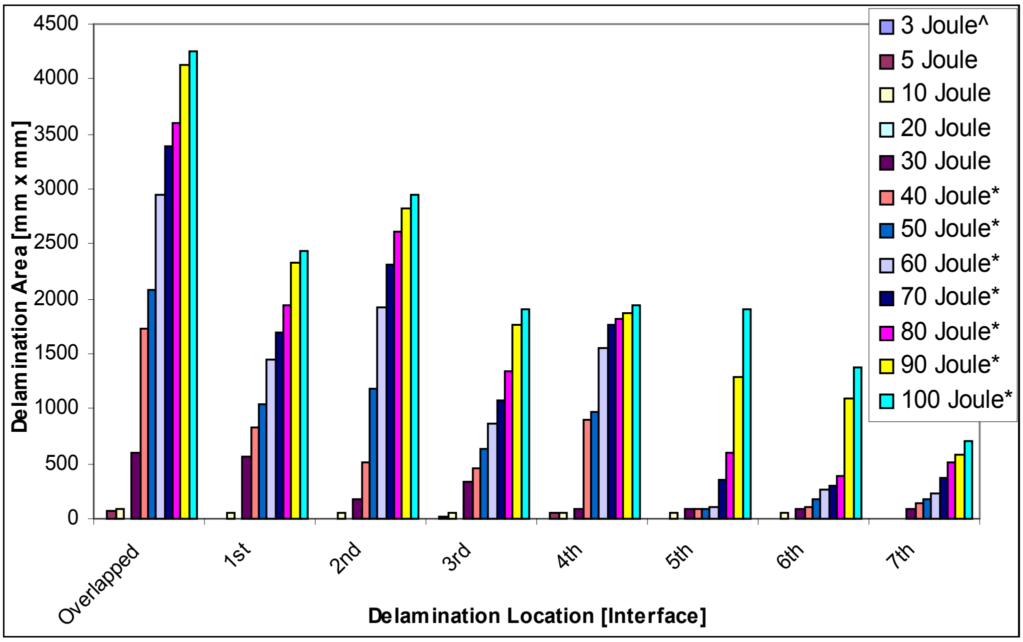


Figure 5 Delamination areas comparison with 1 kg impactor for different impact energy

Impactor masses of 0.5 kg to 20 kg were also investigated with the impact energy of 20 J. The higher impact energy was used in order to obtain reasonable damage regions for comparison purposes. It was found that the impact duration increased with the impact mass, while the contact force was not affected, as shown in Figure 6. It was also found that the delamination increased slightly with the impactor mass.

^ No damage was predicted in the model
* Edge delamination was predicted in the model

However, the delamination area prediction was not affected by the impactor mass ranging from 1 kg to 10 kg.

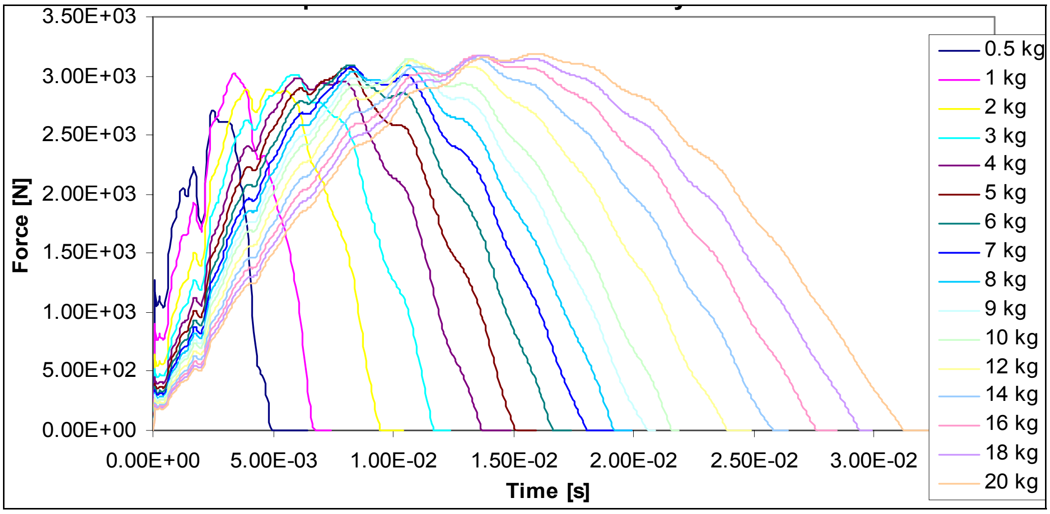
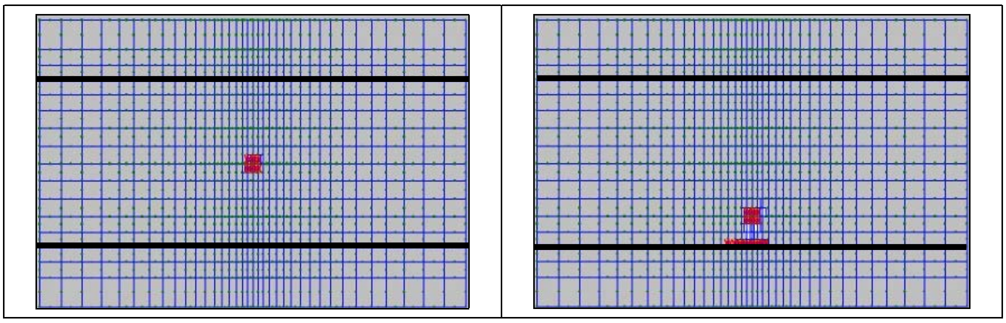


Figure 6 Force-time history plot for different impactor masses

Four different impactor diameters (i.e. 6.35 mm, 12.7 mm, 19.05 mm and 25.4 mm) and two types of materials (i.e. steel and aluminium) were investigated at 5 J and 30 J impact energies in order to determine their effects. It was found that the diameter of the impactor did not affect the force-time history curves at all. It also predicted exactly the same overlayed delamination area, with 105.0 mm^2 and 567.9 mm^2 for the 5 J and 30 J impact energies, respectively. However, there were very small differences when the delamination area at each interface was compared. It was found that the impactor material has no influence on the history curves and the delamination areas.

Impact energy of 5 J (default) 10 J and 20 J were used to investigate the effects of impact locations (i.e. mid-bay and stringer edge). The meshing density of the stringer region was increased to four elements in the panel lateral direction for the stringer edge impact. The damage area for the 5 J impact was relatively small, which made the comparisons difficult. However, it was found that the delamination area was larger when the impact occurred at the edge of the stringer regardless of impact energy. The impact at the stringer edge produced higher contact force with shorter duration. This was caused by the higher stiffness in the stringer region. Figure 7 shows the predicted damage for a 20 J impact at the mid-skin bay and stringer edge. The mid-bay and stringer edge impact produced 200 mm^2 and 292 mm^2 overlayed damage areas, respectively.



(a) Mid-bay impact (b) Stringer edge impact

Figure 7 Overlayed damage plots for the 20 J impact on different panel locations

The curvature of the stiffened panel on the impact damage was investigated. It should be noted that it was not possible to create a full cylinder with Codac. The damage behaviour of the panels with radius of 8000 mm and higher was very similar to the flat panel. The peak contact force was approximately 4 kN and the impact duration was approximately 18 ms. The predicted delamination area was also very similar, with the overlayed area approximately 380 mm^2. As the panel radius reduced from 8000 mm to 500 mm, the contact force increased and the impact duration reduced slightly. The delamination area also increased as the radius became smaller. At the smallest radius analysed, 500 mm, the peak contact force was 8.8 kN with the corresponding impact duration of 7.5 ms. The overlayed delamination area was 746 mm^2.

The total panel length and width were investigated in order to determine effect of panel size on the impact damage. It was found that the smallest panel with one stringer sustained the most damage, with an overlayed delamination area of 1157 mm^2. The damage area was reduced by over 50% when an additional stringer was added, without changing the panel length. It was interesting to find that a three-stringer panel with same length did not further reduce the delamination area greatly. The length of the panel also affected the damage area from impact. It was found that in the three-stringer panel, the overlayed delamination area reduced from 595 mm^2 to 350 mm^2 when the length was increased from 500 mm to 1000 mm. An additional stringer added to the 1000 mm long panel did not change the overlayed delamination area. The delamination area decreased when the length of the panel was increased, however, not with the additional stringer. The larger panel was more flexible and was able to absorb more impact energy elastically. Therefore the damage region incurred from the impact was smaller.

Codac provides three BC options: free, simply supported and clamped for each side of the panel. Various combinations of BC were investigated to determine the effect on the impact damage for the 20 J case. It was found that all the BC combinations showed similar force-time curves, except for two cases, as shown in Figure 8. These two cases were longitudinal sides clamped, lateral sides free, and longitudinal sides simply supported, lateral sides free. Free BCs resulted in a different dynamic response of the panel. The peak contact force and impact duration varied slightly for the other BCs. The constraints on the lateral sides of the panel seemed to be more sensitive towards impact damage in comparison to the longitudinal sides, as it produced the highest delamination area when it was fully clamped and lowest delamination area when it was free of restraints.

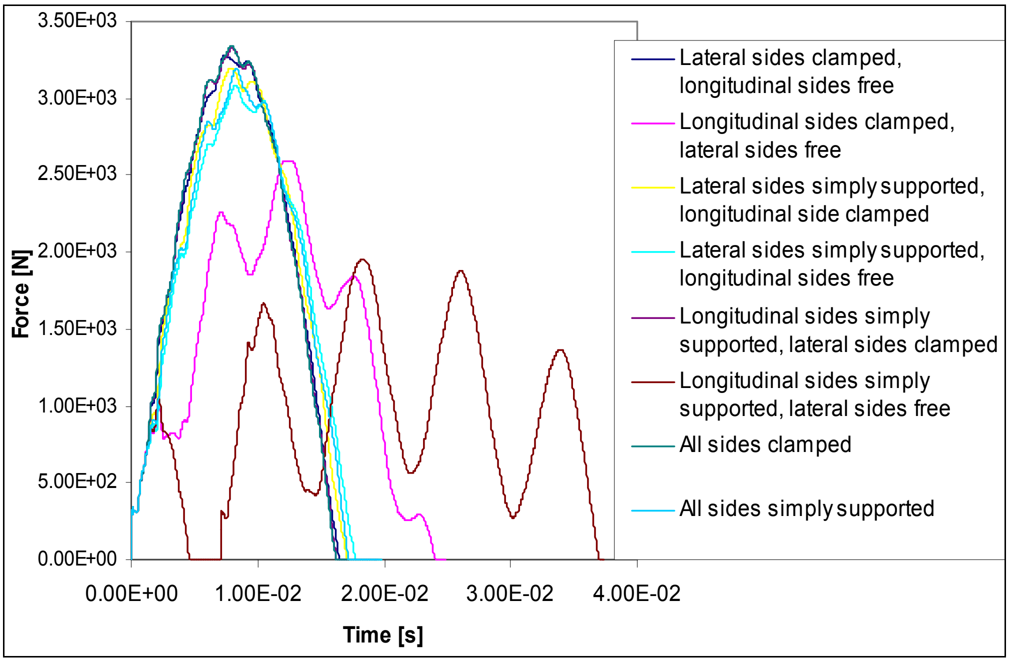


Figure 8 Force-time history plot for different boundary conditions

6. Conclusion

Codac is a fast and practical tool to determine the impact damage of composite panels. The complete impact damage assessment implemented in Codac is basically coherent with the general requirements for an engineering procedure. The methodology includes: (1) a FE model to predict impact damage; (2) application of failure criteria; (3) a scheme to store information about damage characterisation; and (4) an algorithm for the residual strength analysis of a laminate with delaminations. Although Codac is designed to analyse the impact damage rapidly, the computational time depends on the FE model size and the computing resources. 1200-1400 nodes are usually sufficient to model a typical stringer-stiffened panel reasonably well and the analysis time for the impact damage prediction is within ten minutes with typical computational resources currently available on a desktop computer. The development of the tool is continuing to improve the capabilities and further verify the impact damage predictions.

Comparisons of Codac analysis results with test data showed that it was able to predict the impact damage with reasonable accuracy. The transient impact analysis results matched satisfactory. The size of the damage area matched very well for the fabric material. However, Codac had underestimated the delamination area for the tape specimens due to the inaccurate material system parameter assumed in the delamination failure criterion. In the parametric studies, it was found that several parameters were more sensitive to the impact damage prediction than others. The most sensitive parameters were: impact energy, panel size and BCs. In the event of impact, delaminations typically occurred in plies located at the mid-plane or away from the impact side of the panel. Additionally, the first few plies at the impact side were dominated by fibre breakage at higher impact energies. This has been established as the phenomenon of low velocity impact in composite materials.

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