Modelling the failure of near-edge impacted carbon fibre-reinforced composite subjected to shear loading

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Abstract. The failure of an impacted carbon fibre-reinforced composite is analysed, where a double impact near the edge of a large centre hole and subsequent shear loading are simulated. Three levels of impact with energies of 15 J, 25 J and 50 J are investigated, along with an impact-free panel used as control. The numerical finite-element (FE) method together with cohesive zone modelling is employed. The composite material is represented by the three-dimensional ply-by-ply FE model. The numerical results of the impacts are compared with respect to the damaged areas as described in the FE model and it is found that only the 50 J impact causes the impactor to penetrate the composite. Subsequent shear loading shows two failures during loading. The first is caused by a local loss of stability in the impacted region whereas the second is a failure in the tension diagonal of the panel. The load carrying capacity, when compared to the impact-free panel, shows on average, a reduction of 37% at the first failure. The FE modelling technique utilizing the ply-by-ply 3D model and cohesive zone representing the ply interactions is successfully adopted to simulate the shear test of the near-edge impacted composite. However, the behaviour of the compression region including the impact zone does not entirely agree with that experimentally observed during the shear test. In future studies, the compressive strength and local loss of stability should be more precisely addressed.

1. Introduction

In view of their increasing application in transportation, civil industry, power industry, military and sport equipment, and more generally, in all types of light weight applications, the impact damage of composite materials has been extensively investigated in the past decades. For composite materials, prior to manufacturing, the design must take into account not only the loading conditions but also the reliability and serviceability of the composite part. Numerical methods have been used in the design process.

Simulating the impact damage in a composite material is not an easy task, since several impact characteristics such as the impact energy expressed in terms of the impactor mass and velocity, the impactor shape, and how these factors are related to the vibrational response of the composite must be taken into account. With respect to the velocities used in impact testing, there are three classifications: low velocity impact (considered to be up to 10 m/s) [1], high velocity (in the range ~ 20–50 m/s) [2], and ballistic impact (~ 900 m/s) [3]. Low impact velocities and energies often cause damage that is difficult to detect by visual inspection. The impactor does not penetrate the composite, but bounces back, causing under-surface and often back-surface damage. In this case, the delamination...
within the structure often develops around the impact zone. Such damages are commonly termed “barely visible impact damages (BVID)”. In contrast, ballistic impacts result in penetration of the surface, causing minor local delamination. In this case, it has been observed that the damage is concentrated at the impact and spreads from the entry face towards the exit face, during which the size of the damage increases linearly with distance [4].

Low energy impact damage is a major problem from the point of view of detection. High and medium energy impacts cause surface damages that can be detected relatively easily during inspection, but low energy impact damage mainly induces internal damage. Therefore, non-destructive inspection techniques (NDI) need to be used to detect such damage. For example, ultrasonic C-scan imaging or laser shearography have been successfully used in BVID inspection [5,6].

The investigation of impact damage often involves simulation techniques to predict the size and type of damage. Due to the above-mentioned reasons, a number of studies on BVID have been reported. However, most research groups have studied central impact damage [6-10], while near-edge impact has not been covered. Accidental impacts of various kinds can occur on several locations during manufacture and in-service. Near-edge or on-the-edge impact is severe in those zones of composite structure, where compressive in-plane loading is present [11]. This work deals with two impact damages created at points opposite to each other near a hole edge in a composite panel with a central large hole. The hole represents a lightening cut in the shear-loaded part, which can be the frame rib. The damages created by impacts at different energy levels are studied. The shear response following the impacts is also investigated, and it is generally expected that the load-carrying capacity is reduced following impact.

2. Analysis

The finite element (FE) method, together with cohesive zone modelling technique, was employed for the analysis. A three-dimensional ply-by-ply model is used to represent a 3.4 mm-thick composite specimen comprising T700GC carbon fibres and the RTM6 resin matrix. Unidirectional layers (24 in number) are stacked in the sequence \([45/-45/45/90/-45/45\] \(_2\) /45/90/-45/45\], and a large 40 mm diameter hole is located at the centre of a square panel with a side dimension of 234 mm, as shown in figures 1 and 2. The dimensions were chosen to fit the picture-frame test apparatus used in VZLÚ laboratories and are close to specimens referred in [12]. The impactor-head radius was chosen to be 8 mm. Details of the model parameters are given in a previous report [13], wherein the behaviour of the model with respect to experimental observations is presented. In the model, a frictionless contact has been assumed. In the normal direction, the hard-kinematic contact algorithm was used between the impactor and plies, and among the plies themselves, the same algorithm was used as well.

![Figure 1. FE model of the composite panel for analysis.](image1)

![Figure 2. Details of the FE model, composite panel and impactor.](image2)

Progressive ply damage in fibre tension, fibre compression, matrix tension, and matrix compression as described by Hashin and Rotem [14] have been incorporated in the model; the material parameters are shown in table 1. \(E_{ii}\) and \(G_{ii}\) denote the Young's and shear modulus in direction \(ii\), \(\nu_{12}\) is Poisson’s ratio, \(X^T/X^C\) is the longitudinal ply strength in tension/compression, \(Y^T/Y^C\) is the transverse ply strength in tension/compression and \(S^L/S^T\) is the longitudinal/transverse shear ply strength. Damage evolution is
described by reducing the stiffness in the elastic matrix $C_D$ and the resulting stress $\sigma$ is computed from strains $\varepsilon$ using equation (1).

$$\sigma = C_D \varepsilon$$

The progressive cohesive zone damage with bi-linear law was also included; more details are given in a previous report [13].

| Table 1. Ply material properties. |
|----------------------------------|
| $E_{11}$ [MPa] | $E_{22}$ [MPa] | $v_{12}$ [-] | $G_{12}$ [MPa] | $G_{13}$ [MPa] | $G_{23}$ [MPa] |
| 110000 | 7400 | 0.3 | 4200 | 4200 | 4200 |
| $X^T$ [MPa] | $X^C$ [MPa] | $Y^T$ [MPa] | $Y^C$ [MPa] | $S^L$ [MPa] | $S^T$ [MPa] |
| 2300 | 1500 | 66 | 220 | 93 | 93 |

2.1. Impact testing
Low velocity impacts at the coupon level were tested using the falling weight apparatus simulating tool/equipment drop and BVID. Simulations of the impact were performed at three energy levels of 15 J, 25 J and 50 J, using an impactor velocity of 10 m/s. The energy of 50 J is recommended for tool/equipment drop by the military standard DEF STAN 00-970 [15]; the energy of 15 J is the experimentally determined value for impact causing BVID [13], and the energy level 25 J was considered so as to include an impact level between the two extremes. The impact was performed twice; the first impact was directed near the edge of the large hole at the diagonal and the second was directed to a location at the opposite side on the same diagonal. The duration of the impact was much longer than the time needed for elastic waves to reach the element boundaries, which means that the deflection and load would have a similar relation as in static loading. Even so, when studying BVID, the explicit integration scheme is most often applied [5,6]. Therefore, the impact stage was solved using the ABAQUS/Explicit solver. During impact, the specimen was supported at the outer squared margin with a coarse mesh to prevent deflection in the normal direction, whereas, the inner part including the hole was free to deflect during impacts on both sides. In-plane displacement was allowed with only the two opposite corners being constrained so as to hold the composite in the initial position during impact. The other analysis details are similar to those described in a previous report [13].

![Figure 3. Shear loading of the composite panel with a large hole; experimental arrangement; panel impacted with 15 J energy.](image)

![Figure 4. Experimental load-displacement curves for shear loading of impacted panels following impact with an energy of 15 J.](image)
included in the simulation to compare the effect of the impacts on the strength. The experimental load carrying capacity shows two rapid drops due to failures in the panel diagonals. The first failure is caused by material compression in the diagonal parallel to the loading force applied at the panel corners and the second failure is caused by a simple tension in the perpendicular diagonal. The experimentally measured load-displacement curves for the panel impacted with an energy of 15 J are shown in figure 4.

Although the shear test is essentially quasi-static, it was also simulated by means of the dynamic FE code ABAQUS/Explicit. The explicit solver was used in view of the fact that if an implicit FE code was used, high material and geometrical nonlinearities were observed, resulting in severe convergence difficulties. Accordingly, a displacement loading was applied at the two opposite corners of the plate that was sufficiently slow and smooth, so as to maintain the kinetic energy lower than the internal energy of the system.

3. Results

3.1. Numerical results of the impact
Impacts were applied individually in succession on opposite sides close to the edge of the hole. It is seen that different energy levels result in different types of damages. The 15 J impacts cause BVID and the impactors bounce back. In addition, the damage caused by both the impacts is almost the same in shape and size, which indicates that there is no influence of the previously applied impact on the second one. That the two 15 J impacts are independent is demonstrated by comparing the two delamination and damaged areas both numerically and experimentally [13]. The 25 J impact is more severe, but no penetration of the impactor is predicted numerically; here too, the impactors bounce back. The damaged and delaminated area is increased compared to the 15 J impact. The layers below the impact point are damaged, in contrast to the 15 J impact, where the damage occurs mainly within the top half of the layers. Increasing the impact energy up to 50 J leads to the penetration of impactors. During 50 J impact, the edge bends in a manner similar to that observed for impact at lower energy levels, but the elastic energy is not sufficient to stop the impactor. At a certain displacement, the back-surface tension is high enough to break the back layers. The resistance of the material against the movement of the impactor disappears, causing the impactor to penetrate and pass through the composite.

![Figure 5](image1.png) ![Figure 6](image2.png)

**Figure 5.** Delamination zone after impacts at energies of 15 J, 25 J and 50 J; Abaqus damage post processing parameter SDEG\textsubscript{min} = 0.999.

**Figure 6.** Ply damage zone after impacts with energies of 15 J, 25 J and 50 J; Abaqus damage post processing parameter DMICRTMAXVAL\textsubscript{min} = 0.999.
Viewed from the top, the area of damage in the layers appears to be comparable in size for all the different energies used. However, going through the layers, it is seen that only the upper half of the layers is damaged under 15 J impact, whereas, during impact with 25 J energy, all the layers are broken and the detached back layers are damaged. The 50 J impact causes severe damage in all the layers during the penetrating process of the impactor through the composite. The delamination increases with higher energy impacts, but the 25 J and 50 J impacts cause similar delamination. During post processing, full damage and delamination are assumed at damage parameters of 0.999. The comparison of the damaged area and delamination for the different energy levels of impacts are shown in figures 5 and figure 6. The area of damage caused by the 50 J impact overlaps that caused by the 25 J impact, and the 15 J impact area is shown at the top. In figure 6, the “square” shape shows lamina damage of the back layers caused by the supports. At this location, the damage is through matrix tension failure mode according to Hashin’s failure criteria [14]. The clamping applied during the impacts simulates a connection of the part to the surrounding structure. In the absence of clamping, the response of the specimen could be totally different, but for example, the wing rib is constrained around its perimeter as well, which means that the boundary conditions have been applied correctly. The surrounding white colour indicates that in the other elements no exceeding of the damage parameter is observed.

The cross-sections of the impact area after impact for all the energy levels are shown in figure 7. Although the increased displacement of the damaged elements with energy of impact is clearly seen, the damaged area as viewed from the top is similar for the 25 J and 50 J impacts, as mentioned above. During the 25 J impact, the back layers are damaged almost as severely as in the case of 50 J impact, when the impactor penetrates the composite case. The damage also develops in the normal direction through the composite and does not spread in the plane. Thus, it seems that when increasing the impact energy to over 25 J, no new elements are damaged and the damage in the affected elements only progresses further.

In figure 7, the distorted elements under 25 J and 50 J impact can be seen. There seems to be an interpenetration of the elements, but this is the consequence of the contact algorithm, where master nodes can penetrate the slave surface. The effect is seen after leaving the impactor when the nodes of master and slave surfaces do not match each other due to the different displacements of the element caused by damage development. During impact, the corresponding contact nodes are very close and this effect does not appear. However, the stiffness of severely damaged elements is too low, which in reality behaves as ply failure, and penetration of the layers occurs as well. Using smaller elements could help but would increase the cost.
3.2. Numerical results of shear loading

Shear loading following impact is characterised by two failures along the diagonals of the panel, as determined experimentally. The behaviour as determined using the numerical model during the shear loading is also characterised by two failures in the diagonals, as shown in figure 8. When using the 3-D ply-by-ply model, the sensitivity to impact energy levels is well demonstrated, but the behaviour of the load-displacement curve does not fully correspond to that observed experimentally [13]. The rapid loss of stability in the impacted zone loaded in compression, which is observed experimentally, was not simulated precisely by the model. A progressive development of failure was observed in the simulation. Nevertheless, the load at which the development of compressive failure starts agrees well with the corresponding experimentally determined value. Thus, the model is inconsistent in the description of the local loss of stability in the compression region. The reason for this may be in the micro-mechanism of failure. Hashin’s model does not adequately take into account, the micro-buckling of the fibres in the compression zone. A more sophisticated model could predict a more realistic behaviour in compression, for example, the LARC failure model developed at the Langley Research Centre [16]. However, certain parameters to be used in the modelling remain very difficult to determine and thus, their implementation into commercial FE codes is not fully satisfactory.

The load-displacement curves following impacts are similar, as shown in figure 9. The first failure in the compressive zone is influenced by the impact, but the second failure in the tension diagonal occurs at approximately the same load level, since it depends particularly on the fibre strength under tension. The initial parts of the load-displacement curves are identical to that observed for the impact-free panel. However, starting from approximately half of the maximum load of the impact-free panel, the curves for the impacted panels start to deviate due to the damage developed in the compression zone. The damaged zone and the delaminated area resulting from higher energy impacts, do not differ much, and therefore, their responses to the loading are similar. The load levels at the first and the second failure are presented in figure 10 with respect to the maximum load of the impact-free panel. In this case, the compression and tension failures occur at similar load levels, but the load level at the first failure is slightly higher. Contrary to the impact-free case, the load level at the compressive failure of impacted panels is lower than that at tension failure. Thus, for the impacted panels, compressive and tension failures occur on average at 37% and 15% lower load level, respectively.

![Load-displacement curves determined using the numerical model](image1)

**Figure 9.** Load-displacement curves determined using the numerical model

![Failure load levels due to shear loading; FE simulation.](image2)

**Figure 10.** Failure load levels due to shear loading; FE simulation.
4. Conclusion
The impact damage and subsequent resistance to shear loading were investigated numerically and the effect of impact energy was studied using a combination of a 3-D ply-by-ply FE model and the cohesive zone technique. Impacts of three energy levels and an impact-free panel were analysed. An impact energy of 50 J caused the penetration of the impactors, but the damaged zone in the plies was comparable to the impact caused at the energy level of 25 J. The delamination area increased with impact energy, but the delamination areas were similar for impact energy levels of 25 J and 50 J.

Numerical results showed, as expected, that the impact-free panel can carry a higher shear load than the impacted panels. During loading, two failures occurred; compressive failure occurred in the panel diagonal parallel to the applied load and tension failure occurred in the second diagonal. The response on the loading in the load-displacement curve was similar at low loads, but for loads greater than 0.5, the of impact-free panel failure load the curves of impacted panels deviated. The load at the compressive failure was on average 37% lower than that for the impact-free panel. Only the 50 J impact caused the impactor to penetrate the composite, but the reduction in load-carrying capacity was similar to the case with no penetration. The 15 J and 25 J energy impacts caused damage, which can be considered to be BVID.

Numerical investigation of the near-edge impact and subsequent shear loading showed the effect of the impact on the load-carrying capacity of a composite panel with a large hole. Following impact, the load-carrying capacity was dramatically reduced. The danger of BVID near the edge of the central hole was clearly demonstrated. The loss of load-carrying capacity as a result of BVID, was as severe as in the case where penetration by the impactor occurred.

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