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Residual strength of GRP laminates with multiple randomly distributed fragment impacts

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Abstract

The residual tensile strength of glass fibre reinforced composites with randomly distributed holes and fragment impact damages have been investigated. Experiments have been performed on large scale panels and small scale specimens. A finite element model has been developed to predict the strength of multi-axial panels with randomly distributed holes. Further, an effective analytical model has been developed using percolation theory. The model gives an estimation of the residual strength as function of removed surface area caused by the holes. It is found that if 8% of the area is removed, the residual strength is approximately 50% of the un-damaged strength.

Keywords: A. Laminates B. Damage tolerance B. Impact behaviour B. Stress concentrations

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1. Introduction

In the design process of naval ship hulls a number of different structural requirements have to be considered. As an example, the hull needs to fulfil global stiffness and strength requirements, local robustness requirements and dynamic loading requirements such as hull slamming and underwater blast loading. In addition to fulfilling the different structural requirements, the hull weight has to be minimised in order to reduce the fuel consumption and thus increase the range and the maximum attainable velocity. As a consequence, fibre reinforced plastic materials and sandwich structures have gained particular interest since they have considerable lower material density than traditional metals yet comparable stiffness properties per unit weight and considerably higher strength per unit weight. This paper investigates the phenomenon of coupled blast and fragment impact loading of structures with the particular application of composite materials in naval ship hulls. The phenomenon of coupled blast and fragment impact loading is defined as follows. When an artillery shell detonates it generates a high intensity blast wave but it also produces a significant amount of fragments which travel at a high velocity. The blast wave velocity decays significantly faster than the velocity of the fragments and hence the longer the standoff distance, the more likely it is for fragment impacts to occur prior to blast loading of the structure. Nystrom [1] and Leipannen [2] have investigated the time of arrival for a blast wave and fragments as function of standoff distance. For a 250 kg general purpose bomb, with 50 weight percent TNT, the blast wave hit the structure simultaneously as the fragments if the standoff distance is approximate 5 meters. For a longer standoff distance, the fragments will hit the structure first, and for a shorter standoff distance, the blast wave will hit the structure first.

One of the primary effects of coupled blast and fragment impact loading is thus that the blast wave hits an already damaged structure and hence the residual strength of the structure is of great importance. The damages from fragment impacts typically have a variation in size and shape. The size of the fragments varies depending on the shell type and shell size and the impact velocity of each fragment is a function of standoff distance, shell type and shell size. The objective of this work is to present a cost-effective tool to predict the residual tensile strength of a typical fragment damaged multi-axial composite panel.

Previously, Kazemahvazi et al [3] showed that damages from fragment simulating projectiles can be approximated with drilled holes of the same diameter without giving a significant difference in the residual tensile strength of the structure. The accuracy of this approximation increases as the amount of 0-degree fibres in the laminates increase (where 0-degree is in the loading direction). For laminates with less than 30 percent of the fibres in the loading direction, the strength of the damaged plate is lower than the remaining net section strength. This further reduction in strength is mainly since the delamination, caused by the fragment simulating projectile, have a greater impact on the residual strength of the structure as compared to a structure with high amount of fibres in the loading direction (e.g. a unidirectional laminate). Further, the notch sensitivity of the composite material was investigated as a function of loading rate. It was found that the loading rate has a minor influence on the notch sensitivity of the material. Based on these assumptions it is possible to simplify the problem of fragment damaged panels subject to a high rate tensile loading to a panel with drilled circular holes loaded at quasi-static loading rate. The residual strength of laminates with randomly distributed

holes was investigated by Kazemahvazi et al [4]. A semi-analytical model was developed which predicts the residual strength of a unidirectional laminate with multiple holes with good accuracy. This model can be used to predict the strength of multi-axial laminates by assuming that when the 0-degree ply fails (the ply with the fibres oriented in the load direction) the whole laminate fails. This is a good estimate for laminates with high amount of fibres in the loading direction. One drawback with the proposed model in [4] is however that it requires information both on the amount of holes in the laminate as well as information about the hole pattern.

In the present work we will use percolation theory [5] to develop a cost-effective phenomenological residual strength model. The model provides a closed form expression for the residual strength as function of the hole density (the amount of hole area / specimen area). The benefit of this model is that it provides a good first estimate of the residual strength using only one input variable (hole density). The drawback is, however, that the standard deviation of the strength estimations is larger (since the differences in hole patterns and shapes are not accounted for) and that a significant amount of experiments have to be performed to calibrate the model. To calibrate the model a number of experiments are performed on multi-axial laminates with randomly distributed holes. A finite element model is developed in order to make numerical experiments and get more experimental points for the calibration of the theoretical model. The approach is similar to that of Yanay [6] and Klein [7] with the difference of the constitutive materials and the numerical modelling technique. The article will be finalized by comparing the residual strength of large scale panels subjected to real

fragments damages from an artillery shell with the predictions made using the percolation theory model.

2. Small scale experimental protocol

2.1 Materials, manufacturing and specimen geometry

Glass fibre non-crimp fabrics [8] and vinyl-ester resin [9] have been used exclusively. Two types of laminate stacking sequences were used, a quadriaxial and a triaxial. Two layers of non-crimp fabric were used with areal weight fibre and stacking sequence as depicted in table 1. All laminates were manufactured using a vacuum assisted resin transfer moulding process (VARTM). In this process, the dry non-crimp fabrics are firstly stacked onto a flat and rigid stainless steel mould to form the desired thickness, shape and fibre lay-up. Secondly, the mould is sealed with a polyethylene vacuum bag after which the remaining air is evacuated and thus an atmospheric pressure of approximately 1 bar is put on the stacked non-crimp fabrics. Finally, the resin mix (Reichhold curing system D in [9]) is infused into the dry fabric and a vacuum pressure is maintained until the resin has cured at room temperature (typically 3 hours). The laminates are post-cured at 23°C for 7 days until full matrix strength is achieved [9]. The specimen geometry is shown in figure 1a. In the central patch of the specimen (an area of 50x50 mm) a number of circular holes were drilled. In order to distribute these holes randomly, a simple Matlab script was developed. The script is provided with a hole diameter (5 mm has been used in this case) and the approximate total hole surface area. The script then follows an iterative scheme where it randomly distributes x number of holes until the wanted total hole surface area has been achieved (starting with x=1 hole and adding 1 hole per iteration). The x- and y positions of the holes midpoint is

determined using the in-built “random” function in Matlab with a uniform distribution. A positional resolution of 1 mm was used meaning that the holes central point can attain 50 positions along the x-direction and 50 positions along the y-direction (a total of 50x50 positions over the full central patch). Holes were allowed to overlap meaning that the total hole area is not necessarily the number of holes multiplied by the single hole areas (an overlap results in a smaller total hole area). The total hole area was calculated by producing a bitmap where each hole is represented by a black circle on a white background. The image was then processed using “Matlab Image Processing Toolbox” in order to determine the amount of white and black pixels which finally gives the total hole surface area including potential overlaps. Figure 1b shows photographs of specimens with 5, 10 and 20 holes and table 2 summarise all hole configurations that were tested experimentally.

2.2 Test set-up and strain measurement

The experiments were performed in a screw-driven Instron machine at a nominal displacement rate of 2 mm per minute resulting in a quasi-static strain rate of 10^{-4} /s. The specimens were aligned so that the 0-degree fibres were oriented in the loading direction. Digital image correlation technique [10] was used for all experiments in order to measure a full strain field.

3. Description of finite element model

A finite element model was developed in the commercial FE-code package ABAQUS. Each specimen was modelled as a shell using the same geometry and hole patterns as the experimental setup. Each ply in the shell was given a thickness and ply orientation as

specified in table 1. The ply thickness was calculated by multiplying the measured total thickness with the percentage of fibres in the specific ply (supplied by material manufacturer). Constitutive material properties were taken as in table 3 for a unidirectional specimen. All stiffness and strength values in table 3 have been determined from experiments on un-damaged specimens. In-plane shear stiffness, G_{12} , was not measured experimentally but assumed to be approximately 2.8 GPa as specified in [11].

In order to model the onset and progression of damage the in-built damage model for fibre reinforced composite materials was used. This is based on the failure criteria developed by Hashin [12] and Matzenmiller [13] and is described in more detail by Lapczyk et al [14]. The energy release rates were not measured experimentally but an initial estimation was used from Lapczyk et al [14] and then calibrated to values that provided the best overall fit to the experimental results (for a range of hole configurations). Further a small material viscosity, $\eta=0.0005$, was used. In an implicit analysis (quasi-static) the viscosity parameter only has minor effects on the global load-displacement response but improves the convergence rate of the simulation significantly. A more detailed discussion on this is given by Lapczyk et al [14].

A mesh convergence study was performed and an element size of approximate 0.2 mm was required in the vicinity of the hole in order to get sufficiently high resolution of the stress field (and thereby a converged value for the specimen strength). Figure 2 shows an example of a mesh for a specimen with a large number of holes.

4. Summary of results from small scale experiments and FE-simulations

In order to validate the quality of the finite element predictions, all the hole configurations which were tested experimentally were also simulated numerically. This section presents a summary of these comparisons by investigating the global force-displacement behaviour as well as comparing the full strain field measurements.

FE-simulations were benchmarked against experimental observations for a variety of hole densities and hole configurations. Figures 3-5 show examples of comparisons between FE-simulations and experimental observations. The specimens in these examples have 5, 10 and 20 randomly distributed holes respectively. It is observed that the FE-model is able to predict the global load-deflection response with good accuracy. Comparisons between the full strain fields also show good agreement, both in terms of areas of strain concentrations and the quantitative level of strains. There are however a few observations worth highlighting.

Looking at hole configurations 5-1 and 10-1 (figures 3 and 4), it is observed that the initial stiffness of the laminates is well predicted but at higher displacements the FE model shows lower stiffness than experimental measurements. In the FE model, damage of the specimen initiates at approximately 5000 N for 5-1 and 3200 N for 10-1 which is followed by a distinct softening in the load-displacement response. The softening behaviour of the FE model is related to the specified energy release rates described in previous section. As these are not measured directly and calibrated over a large range of experiments, some discrepancies is observed.

Looking at the strength predictions, a good agreement is found (within ~5%) for both the 5-1 and 10-1 hole configurations. The 20-1 hole configuration (figure 5) however shows a larger discrepancy. This discrepancy is attributable to the practical difficulty of machining multiple holes which are located near or on top of each other. The holes in the FE model are “machined” perfectly, leaving more undamaged material in between the holes to the right hand side of the specimen. It can be observed from the pre-test photographs (figure 1b) that small cracks have formed between the holes on the right hand side of the 20-1 specimen which are believed to cause the premature damage.

A summary of all benchmarking FE-simulations are found in figure 6. The majority of the simulations show good agreement with the experimental observations. However, a few hole configurations show somewhat larger discrepancy between experimental results and finite element predictions (e.g. Quad 5-1 and Tri 5-5). One reason for the higher discrepancy for some hole configurations is that each hole configuration was only tested once. Given the nature of the problem, a large spread of the experimental results is expected which can result in high discrepancy between experimentally measured strength and the strengths predicted by the FE-model

The developed FE-model was used in order to generate a bulk mass of residual strength data as input for the statistical strength prediction model described in section 5. The benefit of using numerical experiments is that the time consuming process of manufacturing specimens with a large number of holes is reduced. The drawback is however that there will be somewhat larger uncertainties in the input data. In total, more than 40 different hole configurations were simulated for the two laminate configurations

(Quad and Tri) resulting in more than 80 numerical experiments. The numerical experiments followed a scheme where the random hole patterns, generated by the Matlab script described above, was added to the Abaqus finite element model using a Python script. The “specimen” was then loaded until failure was reached and the peak load was recorded manually in the Abaqus CAE environment. Each numerical experiment had an average calculation time of 8 hours. Figure 2 shows an example of a specimen with 110 holes used for a numerical experiment.

5. Phenomenological modelling of residual strength

Percolation theory has been used in order to develop a fast and effective model to predict the residual strength of laminates with randomly distributed holes. The normalized fracture strength, F , as function of hole density, P , can be described by [6,7],

$$F(P) = k \left(\frac{P^c - P}{P^c} \right)^{2.2} \left[1 - m \left(\frac{P^c - P}{P^c} \right) + n \left(\frac{P^c - P}{P^c} \right)^2 \right] \quad (1)$$

where k , m and n are fitting coefficients. P is the hole density, i.e. the total area of holes divided by the total area of the plate. P^c is the percolating threshold. It is defined as the hole density at which the plate will have zero strength. For an infinite plate this value is 0.64 (64 % area of holes). Since the model is only based on one variable, P , no consideration is taken to changes in residual strength as function of different hole patterns. Further, if the fitting of equation 1 is performed solely on numerical simulations – potential deviations in residual strength due to deviations in material properties will not be captured.

Using the assumption of an infinitely wide plate, so that $P^c = 0.64$, and employing a least square fit to the experimental and FE-simulation data points, the solid curve in figure 7 is obtained. The solid line is fitted to all experimental and numerical data for both laminate configurations giving the fitting coefficients (equation 1); $k = 1.397$, $m = 1.858$ and $n = 1.392$. The solid curve in figure 7 now shows the normalized strength as function of the hole density. The crosses are data points from Quad laminate experiments and the diamonds are Quad laminate strength predictions by numerical simulations. Further, the circles are data points from Tri laminate experiments and the squares are Tri laminate strength predictions made using the numerical simulations. To get an estimation of how well the model predicts the in-data variations, the coefficient of determination, R^2 , was calculated for each curve fit. The curve fit presented in figure 7 has a coefficient of determination of, $R^2 = 0.94$, which means that 94% of the variations in the in-data is captured by the model ($R^2 = 1$ means that all points lie on the model curve). The remaining variation is e.g. caused by the difference in hole patterns, voids/defects in materials and difference of laminate properties (all of which not accounted for in the developed model). It can be observed that the deviation in strength is larger for lower hole densities, e.g. $P = 0.05$, as compared to higher hole densities, e.g. $P = 0.25$. This difference in deviation is likely due to the sensitiveness to hole pattern shape for different level of hole densities. For low hole densities, the shape of the hole pattern can have significant impact on the remaining net section area. Looking for example at the hole pattern shape of configuration 5-1 (figure 1b) it is seen that the remaining net section is high (since the holes are located on top of each other) to be compared to other five hole configurations where the holes are located next to each other resulting in significantly lower remaining net section area. For

higher hole densities, the remaining net section area is approximately similar as the shape of hole patterns change.

Using the percolation theory estimation shown in figure 7, it can be observed that the residual strength is approximately 50% of an un-damaged panel for a hole density of 8%. At a hole density of 15%, only one third of the undamaged panel strength remains.

If the data for the Tri laminates is separated from that of the Quad laminates (and vice versa) a better fit is obtained, see figure 8. The percolation theory prediction in figure 8 fits the experimental and numerical data with a coefficient of determination of, $R^2 = 0.97$. The fitting coefficients in this case are $k = 1.247$, $m = 1.640$ and $n = 1.185$. Comparing the performance of Quad and Tri laminates separately it is observed that the Quad laminates show slightly higher residual strength at low hole densities compared to Tri laminates which explains the improved fit when the data sets are separated. For the large scale experiments (presented in section 6), Tri laminates have been used and analytical predictions are therefore made using the percolation theory model for Tri laminates only.

6. Large scale experimental protocol

6.1 Materials and test set-up

A total of 14 sandwich panels of dimension 1200 by 800 mm were exposed to real fragments from a fragmenting shell. The panels were placed in a circle around the shell at various distances, see figure 9a. The sandwich panels had face sheets made from glass-fibre reinforced composite laminates with triaxial reinforcement and vinyl-ester matrix (same as the ones used in the small scale experiments). Sandwich panels were used in

these tests for two reasons: one is that sandwich panels are of particular interest for naval applications since they provide very high flexural stiffness per unit weight. The other reason was to compare multi-layered composite panels with single layered metal panels from a ballistic protection point. However, in this study we are only concerned with the residual strength of the face sheets.

After being exposed to the fragmenting shells, the panels were cut up in their length direction so that the panel width was reduced from 800 mm to 400 mm in order to fit the tensile testing rig. The face sheets of the panels were removed from the foam core so that each laminate could be tested as a separate specimen. Tensile testing was performed on laminates of dimension 1200 mm by 400 mm in the direction of 0-degree fibres. The tests were performed in a MTS universal testing machine at a constant displacement rate of 0.1 mm/s, i.e. an approximate strain rate of 10^{-4} /s. During the testing the machine displacement and load was monitored. Surface strain measurements were performed using a digital image correlation system (GOM Aramis). The test set-up is shown in figure 9b.

The panel laminates were tested until fracture which in all cases was a net section fracture through some paths along the fragment holes. The failure load was normalised with the undamaged cross-section area (thickness*400 mm²) to calculate a nominal failure stress which was then normalised with the strength of undamaged laminates.

6.2 *Estimation of hole area for comparison with percolation theory model*

From photographs of the panels and also from the strain images from the DIC-measurements one can try to estimate the fraction of holes. Figures 10-14 shows photographs of panels with fragment holes. These panels represent a side with entry holes, i.e. this side was exposed to incoming fragments. The hole radii are still difficult to see clearly. The photographs were read into an imaging software (PAINT.NET), the holes were masked manually and then the photograph was turned into a black-and-white bitmap. The masking was performed using two different techniques, one where only the visible holes were masked (b) and one where the entire delaminated area around the holes were mapped (c). These two masking techniques would represent a lower and an upper bound of the actual hole area of the panels. Each bitmap was analysed with a MatLab-script and the relative area of the holes was calculated.

As can be observed in figures 10-14, there is a large scatter in the relative hole area depending on what masking techniques that has been used. It was found that the lower masking bounds typically fall in the regime of 8%-10% hole density whereas the upper masking bounds typically fall in the regime of 20% hole density.

7. **Comparison of results between small and large scale laminates**

Envisaging the design procedure for simulating a complicated loading scenario as the coupled ballistic and blast loading, this would be performed by first modelling the fragment scatter produced by a threat (e.g. artillery shell). The fragment scatters would give a statistical distribution of amount of holes, hole size and hole position for the loaded panel. This information would then be used to get the statistical bounds of the residual strength of the fragment damaged panel (using e.g. the percolation theory model developed herein).

In this work we are reverse engineering the hole patterns from actual full scale testing which results in an inherent scatter of the results correlated to how well the hole areas can be mapped as exemplified in section 6.2. The minimum and maximum bounds for the calculated hole area of each panel (panel 1-9) have been plotted in the strength versus hole density graph in figure 15. In most cases, the percolation theory predictions fall within the area bounds of the full scale experiment panels. There are, however, a number of observations to be made.

All panels have a span in area bound of approximately 10 percent except for panel 3. Looking at the hole patterns for panel 3 (figure 11a), it can be seen that there are a high number of small holes (approximately 40 holes) and around each hole a significant delamination area is observed. These delamination areas add up to a larger total area resulting in a high upper bound. In reality, the amount of holes in the panel is likely closer to the lower bound which is also in agreement with the analytical predictions.

The residual strength for two panels, P7 and P5, falls outside of the analytical predicted value. P7 has a somewhat higher residual strength than the analytical predictions and P5 has a somewhat lower residual strength than the analytical predictions.

Looking at panel 5 (figure 12a), a large damage zone can be observed over the mid-section of the panel. A crack like formation runs from left edge of the panel to the right edge. A concentrated damage zone like this can explain why the residual strength of the panel is low despite a small area of damage.

Looking at panel 7 (figure 14a), the damages look quite the opposite. There are a large number of holes (resulting in large hole area) but the holes are well distributed with little damage between the holes. Portions of the panel have almost no damage (on contrary to

panel 5) and are able to carry and distribute the load between the holes resulting in higher residual strength.

8. Discussion and comparison between steel and GRP panels

The fragment protection properties of E-glass fibre composites is comparable to rolled homogeneous armour steel (RHA). Some data from the literature is collected in figure 16, which shows that the ballistic limit, v_{50} , for a 2.85 g fragment simulating projectile (FSP) is similar for steel and E-glass laminates with the same areal weight (kgm^{-2}). In figure 16 the baseline is provided by the class 2 RHA as defined by MIL-DTL-12560J where some of the data has been scaled using replica modelling. Class 2 is a relatively soft armour steel with an allowed hardness span of 262-302 HB and the steel is not optimised for fragment protection. Since the density of laminates is approximately one fourth of that of steel, a four times thicker laminate will have approximately the same ballistic performance as steel.

During the ballistic testing of the sandwich panels reported herein, also two kinds of steel panels were tested having almost the same areal weight as the composite sandwich panels. Two types of steel panels were used: SSAB Domex 240YPB with a yield strength of 262 MPa and an ultimate strength equal to 376 MPa, and SSAB Domex 355MCD with a yield strength of 372 MPa and an ultimate strength equal to 465 MPa. These panels were also tested in tension in same manner as the composite panels.

The steel panels had approximately the same number of holes as the composite panels when placed at the same stand-off distance. However, the holes were smaller. In figure 17 there is a photograph of a damaged steel panel and a similar hole masking as for the composite panels. The hole area was in the range of 2-5%, i.e. much less than for the

composite panels. Table 4 gives the average results of all panels tested including all materials and stand-off distances. The steel panels had a somewhat smaller strength reduction although the residual strength was similar for both materials. An important note is that the strain to failure was similar for both steel and composite panels, in the order of 1 to 2%.

If a particular design of a panel is performed on the basis of the same ballistic protection, a composite panel will be four times thicker than a steel panel. The weight will be the same however. The load carrying capacity of an undamaged composite panel will then be more than four times higher than for the steel panel. For a damaged panel, the composite panels will have a load carrying capacity outperforming the steel panels with a factor of 3-6, see Table 4. Actually, the load carrying capacity of a fragment damaged composite panel is almost the same, or higher, than an undamaged steel panel.

9. Concluding remarks

An extensive small- and large scale experimental programme has been performed in order to investigate the residual strength of glass fibre reinforced vinyl-ester panels subjected to fragment impacts. A finite element model which predicts the residual strength of fragment damaged panels with good accuracy has been developed and used to perform numerical experiments for a range of different randomly distributed hole configurations. Using percolation theory, an effective closed form analytical model has been developed which provides reasonably good residual strength predictions for a highly stochastic and complex problem. The analytical model only uses one input variable, the total surface hole area caused by fragment perforations, to predict the residual strength. Differences between experimentally measured residual strengths and analytical predictions are mainly caused by the difference in hole patterns which is not considered in the analytical model.

It is further concluded that glass fibre reinforced plastic panels that are designed for the same ballistic protection as corresponding steel panels (which approximately have the same areal mass) show considerable higher post-impact load carrying capacity than the steel counterpart.

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Ply direction →	45°	90°	-45°	0°	0°	45°	90°	-45°	Total
Areal weight fibre QUAD (g/m ²)	201	201	201	213	213	201	201	201	1632
Total thickness and calculated ply thickness (mm)	0.15	0.15	0.15	0.16	0.16	0.15	0.15	0.15	1.22
Areal weight fibre TRI (g/m ²)	192	0	192	213	213	192	0	192	1194
Total thickness and calculated ply thickness (mm)	0.14	0	0.14	0.16	0.16	0.14	0	0.14	0.88

Table 1: Laminate configuration and thickness

Configuration name	Number of holes	Area ratio of holes, P
5-1	5	0.0413
5-2	5	0.0412
5-3	5	0.0361
5-4	5	0.0436
5-5	5	0.0348
10-1	10	0.0757
10-2	10	0.0799
10-3	10	0.0862
10-4	10	0.0759
10-5	10	0.0822
20-1	20	0.142
20-2	20	0.160
20-3	20	0.153

Table 2: Hole configurations that were tested in the experimental programme

E_1	E_2	G_{12}	$\hat{\sigma}_{1t}$	$\hat{\sigma}_{1c}$	$\hat{\sigma}_{2t}$	$\hat{\sigma}_{2c}$	$\hat{\tau}_{12}$
(GPa)	(GPa)	(GPa)	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)
41	9.8	2.8	1250	600	20	100	60

X_{1t} (N/mm)	X_{1c} (N/mm)	X_{2t} (N/mm)	X_{2c} (N/mm)	η
15	15	0.5	0.5	< 0.0005

Table 3: Material data properties used in the finite element model. The indexes 1 and 2 refer to the axes along and transverse the fibre direction respectively. The indexes t and c refer to tensile and compressive loading. E is the Young's modulus, G the shear modulus, $\hat{\sigma}$ the strength, X the energy release rate and η the viscosity coefficient.

	Steel thickness t	Composite thickness $4t$
Un-notched strength (MPa)	372-465	520
Notched strength (MPa)	167-201	99-199
Load carrying capacity, un-notched (N/mm)	372-465	2080
Load carrying capacity, notched (N/mm)	167-201	396-796

Table 4: Comparison between steel and composite panels with the same areal weight in terms of un-notched (undamaged) and notched (damaged) strength and load carrying capacity.

(a)

(b)

Figure 1: (a) Specimen geometry and (b) examples of manufactured specimens with different hole configurations.

Figure 2: Example of FE-model mesh for a simulation with 110 holes. Element size is approximately 0.2 mm in the vicinity of the holes.

Figure 3: Comparison between experimental and simulated load-deflection response for hole configuration 5-1. Contour graphs show the in-plane strain field in the loading direction slightly prior peak load.

Figure 4: Comparison between experimental and simulated load-deflection response for hole configuration 10-1. Contour graphs show the in-plane strain field in the loading direction slightly prior peak load.

Figure 5: Comparison between experimental and simulated load-deflection response for hole configuration 20-1. Contour graphs show the in-plane strain field in the loading direction slightly prior peak load.

Figure 6: Comparisons of experimentally measured failure loads and finite element model failure load predictions for (a) quadri-axial laminates and (b) triaxial laminates.

Figure 7: Summary of experimental and simulation results for quadriaxial and triaxial laminate configuration. Solid line shows predictions using percolation theory.

Figure 8: Summary of experimental and simulation results for triaxial laminate configuration. Solid line shows predictions using percolation theory for triaxial only.

Figure 9: (a) Set-up for creating fragmentation damages on large scale panels and (b) set-up for tensile testing of damaged large scale panels.

Figure 10: Graphs of Panel 1 (P1); (a) Pre tensile test photograph (b) Minimum masking around holes only (c) Maximum masking including all delamination (d) Digital Image Correlation graph at peak load.

Figure 11: Graphs of Panel 3 (P3); (a) Pre tensile test photograph (b) Minimum masking around holes only (c) Maximum masking including all delamination

Figure 12: Graphs of Panel 5 (P5); (a) Pre tensile test photograph (b) Minimum masking around holes only (c) Maximum masking including all delamination

Figure 13: Graphs of Panel 6 (P6); (a) Pre tensile test photograph (b) Minimum masking around holes only (c) Maximum masking including all delamination

Figure 14: Graphs of Panel 7 (P7); (a) Pre tensile test photograph (b) Minimum masking around holes only (c) Maximum masking including all delamination

Figure 15: Summary of laboratory experiments (squares), numerical predictions (diamonds) and large scale experiments (crosses).

Figure 16: Graph of ballistic data from open literature comparing E-glass fiber composites with steel armour, v50 for a 2.85 g FSP. Some of the data has been scaled using replica modeling.

Figure 17: Graphs of a steel panel; (a) Pre tensile test photograph (b) Masking around holes