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Tensile Strength of UD-Composite Laminates with Multiple Holes

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The residual strength of glass fibre reinforced vinyl-ester laminates with multiple holes was investigated through an experimental programme. Different types of structured hole patterns and hole densities were investigated and analysed using digital image correlation strain measuring technique. Three different failure modes could be observed when the hole patterns and the hole densities were altered. These three failure modes were used as the foundation for a simple yet effective analytical model in order to predict the residual strength of damaged composite specimens. Finally, a number of laminates with randomly distributed holes were tested experimentally. The analytical model can predict the failure mode and failure strength of the experiments with sufficiently good fidelity.

Keywords: Glass fibres; Strength; Notch; Multiple holes

1 Introduction

The use of fibre reinforced plastic composites has been increasing substantially during the past decade, this mainly due to their good weight specific strength and stiffness properties. However, there are still many areas concerning the behaviour of composites that are not completely understood, examples of such are the high strain rate behaviour, progressive damage, sensitivity to damages, impact damages etc. As a consequence, several advanced material models have emerged which enables the use of finite element methods to predict the strength and progressive failure of composite structures. Early models were developed by Matzenmiller [1] and Hashin [2]. These models are based on four different ply failure criteria and use the fracture energy release rate of each failure mode to model progressive damage. The models have been extended and refined by Miami et al. [3] and also implemented into

commercial FE-codes [4]. There have also been efforts in using the aforementioned failure models to predict the strength of damaged composite laminates and laminates with single and multiple holes. Lapczyk and Hurtado [4] used these failure models to predict the strength of a fibre metal laminate with a centrally aligned circular hole. By calibrating the fracture energy release rates and viscous damping constants they found good agreement with experimental results for specimens with single hole configuration. However, no further analysis was made on specimens with multiple holes. Ghezzi et al. [5] studied the behaviour of composite laminates with two holes, and in particular how they interact with each other when the distance, hole size and position is altered. They used FE to see how the stress and strain concentration around the holes changes and found good agreement with their experimental results.

Within this work, the tensile strength of laminates with multiple drilled holes is studied as a first way of assessing the tensile strength of laminates multiple fragment impact damages. Previous study [6] has shown that the tensile strength of laminates with drilled circular holes is similar to that with impact damage from fragment simulating projectiles of the same size. Thus, drilled circular holes are used to simplify the manufacturing process of the composite laminates. Fragment impact damages on composites cause damages that are difficult to define and the damage boundaries are not always clear as is shown in figure 1. The problems in defining the damage boundaries causes large uncertainties in the modelling which is why using highly accurate modelling methods, such as FE, to predict the residual strength of the structure is not always feasible. Another fundamental problem in using finite element models to predict the strength of plates with multiple damages is the need of mesh refinement around the holes. The models need to have a substantial number of elements with a high computing cost as a result, especially if an advanced damage model is used (which can be the case with composite materials). Further, existing material models do not include all the different failure modes observed for composite laminates, example of such are splitting and delamination failure. Fragment impact damages are also stochastic by nature, which means that numerous numbers of different damage patterns and damage densities needs to be evaluated in order to get a good picture of a potential threat.

For metal structures, percolation theory has been used to create fast and simple semi-empirical statistical analytical tools to predict the residual strength of aluminium plates with randomly distributed perforations [7, 8]. For composite structures, however, a statistical approach is not as obvious since the inhomogeneity of the material give rise to several different failure modes, all of which can have different statistical distribution. Xu et al. [9–11] used complex potential method and conformal mapping theory to predict the stress distribution around holes in composite panels with multiple holes. The model was verified to experimental data for laminates with one single centred hole with reasonable accuracy, however no comparisons were made with experimental data for laminates with multiple holes. There is thus a lack of a simple, fast and verified modelling tool to predict the strength of composite laminates with multiple holes.

The residual strength of plates with multiple impact damages is particularly

Figure 1: Composite panel that has been subjected to multiple fragment impacts caused by an explosion.

interesting for a number of practical applications. One is to estimate the flying safety of aircrafts and spacecrafts which have been subjected to multiple impacts from debris or ice. Another is to estimate the residual strength of military vehicle structures which have been subjected to ballistic impacts of any kind. This work primarily focuses on naval ship structures which are subjected to blast and ballistic loading. A typical scenario of a ship hull being exposed to hostile fire can be described as follows; shortly after detonation a scatter of fragments will travel at high speed creating patterns of penetration and perforation damages on the ship hull. Subsequent to these fragment damages a high intensity pressure wave will cause the ship hull panels to deform at an elevated strain rate. Hence, the high intensity pressure wave hits a structure with multiple randomly distributed damages due to fragment impacts. Due to the very high intensity of the pressure loading, the panel will most probably exhibit large deformations implying build up of membrane stresses so that tensile stresses will exceed compressive stresses. Thus, initially tensile loads will be studied.

Within the scope of this work, an extensive experimental programme has been conducted and a simple and fast semi-empirical analytical model has been developed to predict the residual strength of unidirectional composite structures with multiple randomly oriented fragment impacts. The lay-out of the paper is as follows. First the results from the experimental programme with different structured hole arrangements are presented. The experiments are designed in a "worst case scenario" way to trigger different failure mechanisms. Digital image correlation technique is used to find differences in strain fields between different hole configurations. Based on the experimental results a semi-empirical analytical model is then developed. Failure mechanism maps are created to explore the regimes of failure modes when the hole densities and hole configurations are changed. Finally, a limited number of plates with randomly distributed holes are tested experimentally and the analytical model is examined more thoroughly.

2 Experimental Protocol

Glass fibre non-crimp fabrics [12] and vinyl-ester resin [13] has been used exclusively and all laminates were manufactured using vacuum assisted resin transfer moulding. The material configuration is translucent which simplifies the visualization of crack growth, delamination and damage in the laminates. All laminates were unidirectional with the fibres aligned in the load direction (0° -fibres). The experiments were performed in a screw-driven Instron machine at a nominal displacement rate of 2 mm per minute. Each configuration was tested at least five times and all notches were in the shape of circular holes with diameter, $d = 5$ mm. Circular drilled holes have shown to be a good approximation of fragment simulating projectile impacts [6]. The experimental results for the different laminates are presented as strength normalized by the strength of an un-notched laminate of the same configuration. The strength is presented both as nominal strength, where the total cross-section area is used, and net-section strength, where the remaining net cross-section area is used. Laminates were tested without notches and with a single centred circular hole. Following these experiments a study with two circular holes, positioned in different configurations, was conducted to investigate the interaction between two holes. The aim was primarily to find a hole distance where the holes act independently of each other and the strength reaches that of a single hole laminate. This study has been illustrated in figure 2 and these hole configurations will be referred to as 2H (2 Holes) followed by the vertical distance between the hole, e.g. 2H0 (figure 2a) and 2H2 (figure 2c). A series of laminates with different patterns of

Figure 2: Laminates with different two-hole configurations, 2H0 (a), 2H1 (b), 2H2 (c), 2Hn (d).

multiple holes were tested subsequently. Here the aim was to investigate the strength and failure modes of the laminates when the net cross-section area decreases towards 0 %. Different type of hole patterns were tested in order to investigate the effects of hole position, examples of these are specified in figure 3. The laminates were named

with the number of holes followed by pattern configuration, e.g. 4C1 (figure 3a) and 6C2 (figure 3d). All laminates had the same specimen width of 45 mm which means that at least 9 holes were required to get 0 % remaining net section. The 10C specimens all have 0 % remaining net cross-section area and the holes have an overlap.

Figure 3: Examples of different hole configurations that were tested within the experimental programme.

3 Summary of Experimental Findings

3.1 Overview of the residual strength and post-failure photographs

A summary of the experimental results is presented in figure 4. For laminates with less than 6 holes, i.e. more than 33 % remaining net-section area, the normalized net-section strength equalled unity. This means that the laminates show little or no notch sensitivity. Different hole patterns showed the same strength (compare 6C1, 6C2 and 6C3) and the residual strength was only a function of the remaining net-section area.

Laminates with seven holes or more, i.e. < 22 % remaining net-section, had a normalized net-section strength larger than unity. The net-section strength of the laminates is thus larger than the strength of an un-notched specimen indicating that another failure mode than net-section fibre failure is present. The failure was dominated by matrix shear-off as opposed to fibre tensile failure which was the dominating failure mode for laminates with more than 30 % remaining net cross-section area. Two competing failure modes were thus observed, shear-off failure and net section tensile failure. The stress redistribution of the shear-off failure is

reminiscent of a shear lag problem. As the cross-section area decreases, the 0-degree fibres can not carry any load directly and the load has to be transferred through shear forces between the holes. For unidirectional laminates this load is mainly carried by the matrix. Due to the shear lag effect, laminates with little net-section area still carry a significant amount of load resulting in normalized net-section strength higher than unity. For laminates with shear-off dominated failure, large

Figure 4: Normalized strength (white bars) and normalized net section strength (grey bars) for unidirectional 0° laminates with different hole configurations.

changes is observed for different hole patterns. In the shear-off failure region the laminate strength showed strong coupling to the distance between the holes. In figure 4, results from two 10C1 specimens are presented. Both specimens have the same hole pattern but one of them has twice as large distance between the holes which results in twice as high strength.

The two observed failure modes are sketched schematically in figure 5; the net section tensile failure which is coupled to the net section area (figure 5a) and the shear-off failure which is coupled to a characteristic shear length between the holes (figure 5b). Figure 5c shows the shear forces that arise in the matrix, when the remaining cross-section area is small, and causes shear-off failure. Post-test photographs of laminates with different amount of remaining cross-section area are shown in figure 6. Fibre tensile failure is always observed for laminates with 33 % (6C) or more remaining cross-section area. For the laminates with less than 33 % remaining cross-section area, it can be clearly seen that the damage is shear

failure in the matrix. As the net section area decreases, the damage zone tends to concentrate around and between the holes. In the case of zero net section area, virtually no damage is observed in the regions outside the holes.

Figure 5: Schematics of different failure mechanisms for different hole densities, (a) fibres are still able to carry load and (b) the load has to be carried through shear forces between the holes. (c) Shear forces in the matrix in a unidirectional 0° laminate.

3.2 Zero Percent Net-Section Laminates

In order to understand the effects of characteristic shear length on the residual strength of the laminates, digital image correlation technique [14] was used to measure the full strain field of the specimens. Several specimens with zero remaining net-section area and different hole patterns were tested. Figure 7 shows strain fields in the longitudinal loading direction, ε_x , and shear strains, ε_{xy} , for the two 10C1 hole configurations. The measurements are taken at the maximum load prior to ultimate failure. Both hole configurations have the same hole pattern but the configuration at the top have larger longitudinal distance between the holes, resulting in a higher characteristic shear length. The bottom 10C1 specimen has large shear strains between the holes while the longitudinal strain is fairly small and evenly distributed. This indicates that the matrix is subjected to large shear strains but the fibres do not carry any significant load. The top 10C1 specimen has large longitudinal distance between the holes and less hole interaction and smaller zones of large shear strain is observed. The longitudinal strains are significantly higher for the top 10C1 specimen indicating that the fibres carry more load. Both specimens failed in a shear-off failure mode but the top specimen failed at 2.2 times higher load. In order to address this behaviour more thoroughly two different hole patterns were chosen and a number of experiments for different shear lengths (different distance between the holes) were performed. A summary of these experiments are presented in figure 8. It can be seen that for the same shear length both hole patterns have the same failure load. The strength of the specimen increases as the shear length

Figure 6: Post-test photographs of five unidirectional laminates with different hole patterns. All holes have 5 mm diameter and all specimen widths are 45 mm. The remaining net cross-section area varies from 55 % to 0 %.

increases until a plateau level is reached. This plateau level is given by the local net-section strength of the laminate (marked by dashed lines in figure 8). Since the 10C2 specimen has smaller minimum local net section than the 10C1 specimen (five holes instead of four holes) it fails at a lower local net-section load. There are thus two competing local failure modes; shear failure and local net-section failure.

Figure 7: Full strain fields from digital image correlation experiments. All holes have 5 mm diameter and all specimen widths are 45 mm. The hole patterns are the same but the top specimen has twice as large longitudinal distance between the holes than the bottom one.

Figure 8: Strength as function of characteristic shear length, C_l , for two different hole patterns, 10C1 and 10C2. The dashed lines show the local net-section strength of the laminates.

4 Semi-Analytical Failure Model

4.1 Definition of failure modes

The experimental programme revealed three different competing failure modes for unidirectional laminates with multiple holes; global net-section failure, local net-section failure and shear failure. The failure modes, as depicted in figure 9, were used as a foundation for a simple and fast analytical model to predict the residual strength of the laminates. Each failure mode is coupled to a geometric quantity that relates the un-notched strength of the laminate to the notched strength. The global net-section area, A^{global} , is defined as the remaining projected cross-section area, $1 - A_{holes}/A_{total}$, where A_{holes} is given by projecting the area of all holes/damages on a single cross-section, i.e. the amount of cut off 0-degree fibres. A_{total} is the total cross-section area of the laminate. When A^{global} equals one, no holes or damages are present in the laminate and when A^{global} equals zero, all fibres are cut off somewhere in the laminate. The local net-section area, A^{local} , is defined as the minimum remaining cross-section in the laminate, $1 - A_{holes}^{max}/A_{total}$, where A_{holes}^{max} is the minimum remaining local area on a single cross-section. The shear length, C_l , is defined as the minimum total length of material that needs to be sheared off for the specimen to separate completely.

Figure 9: Three observed failure modes. Global net-section failure, local net-section failure and shear failure.

Global Net-Section Failure

The global net-section failure mode is active when the global net-section area, A^{global} , is larger than 0.3 (30 %) as observed in section 3.1. This is, however, only true if the local net-section area, A^{local} , is large enough to avoid local net-section failure. The global net-section strength, $\hat{\sigma}^N$, is defined as in equation 1 where $\hat{\sigma}^{UN}$ is the un-notched strength of the laminate.

$$\hat{\sigma}^N = \hat{\sigma}^{UN} A^{global} \quad (1)$$

Local Net-Section Failure

Two hole patterns with the same global net-section area can have different local net-section area, depending on how the holes are arranged with respect to each other. The local net-section strength of a laminate is calculated according to equation 2. Local net-section failure typically occurs for hole configurations with large shear length and small local net-section area.

$$\hat{\sigma}^N = \hat{\sigma}^{UN} A^{local} \quad (2)$$

Shear Failure

Assuming that the shear failure strength of a laminate is only dependent on the characteristic shear length and not the shape of hole arrangements an expression for the strength could be derived. As shown in figure 8 laminates with different hole patterns show the same strength behaviour as function of characteristic shear length. An exponential curve fitting was made to these results to find the material

constants a , b and c in the expression in equation 3. The expression in equation 3 is defined so that the strength of the laminate equals zero when the shear length, C_l , equals zero.

$$\hat{\sigma}^N = a(e^{bC_l} - e^{dC_l}) \quad (3)$$

4.2 Failure Mechanism Maps

In order to explore the failure regimes and validate the analytical model failure mechanics maps were created. The failure maps were created as functions of the three geometrical quantities; global net-section area, local net-section area and characteristic shear length with contours of nominal strength. Figure 10 shows a failure map with varying global net-section area and characteristic shear length. The different areas of the map can roughly be interpreted as follows. In the top left corner, $A^{global} = 1$ and $C_l = 0$, which means that we have an undamaged specimen (full cross-section area). In the region to the left in the map (along the y-axis) specimens have small C_l , which means that the holes are aligned close to each other, and varying A^{global} which means that the amount of hole changes. In the bottom line of the map (along the x-axis), on the contrary, A^{global} is small which means that there are a lot of holes and the C_l varies which means that the distance between the holes changes. Two failure regions are plotted, global net-section failure and local failure. The local failure includes local net-section failure and shear failure. Experimental data are included as free crosses together with their nominal failure strength values. For specimens with A^{global} smaller than 0.05, local failure mode is predicted for all shear lengths. As A^{global} increases, larger shear lengths are required in order to trigger local failure modes. For specimens with small amount of holes ($A^{global} > 0.6$) no local failure was observed. The failure strength is predicted with fairly good accuracy (predominantly within 10 % of the observed mean value) and the failure mode predictions were accurate for all the experiments performed within the scope of this work. For each point of local failure in figure 10, both local net-section failure and shear failure can occur depending on the value of the local net-section area, A^{local} . In figure 11 specimens with the same global net-section area ($A^{global} = 0$) are plotted for different values of A^{local} and C_l . Experimental results are presented for two different hole patterns, 10C1 and 10C2, with $A^{local} = 0.56$ and $A^{local} = 0.44$ respectively. For small shear lengths, which means that the holes are close to each other, shear failure dominates. As the shear length increases a switch in failure mode is observed and specimens fail in local net-section fibre failure. The analytical model predicts the experimental observations with sufficient fidelity and a clear transition in failure mode, from shear failure to local net-section fibre failure, could be observed. In figure 11, regions dominated by local net-section failure and shear failure has been marked. Experiments on the boundaries of the two failure modes showed mixed failure where both fibre- and shear failure was observed.

Figure 10: Failure mechanism maps with contours of nominal strength as function of global net-section area and characteristic shear length. Free crosses show experimental values.

5 Randomly Distributed Hole Patterns

A number of specimens with randomly distributed hole patterns were tested in order to validate the analytical model. The hole patterns were created using an in-house code that randomly, and with a uniform distribution, mapped out a certain number of points on the test gage of the specimen. The points were used as the centre point of each circular hole. Different specimens with amounts of holes ranging from nine to twenty holes (R9 to R20) were tested. Figure 12 shows the hole patterns that were mapped out with the code together with photographs of the final specimen hole patterns that were tested experimentally subsequently. The code also calculates a theoretical value for the global net-section area, A^{global} . The global net-section area, together with the manually measured shear length, was used as input data for the analytical strength predictions. For some specimen configuration no shear length were calculated since there was a lack of an obvious shear path between the holes (see R20-2 and R10-1). The experimental and predicted failure loads for each random hole configuration is presented in figure 13 together with their respective failure modes. Small discrepancy was found between the failure strength predictions and the experimentally measured failure strength. The difference in failure strength typically lies within the deviation of the experimental results. All specimen configurations failed in a global net-section failure mode accept for the R20-1 configuration which failed in shear-off failure mode. The different failure modes can be observed in the post-test photographs depicted in figure 14. The characteristic shear failure mode, as for specimen R20-1, is recognised by the damage

Figure 11: Failure mechanism maps with contours of nominal strength as function of local net-section area and characteristic shear length. The global net-section area is constant and equal to zero. Free crosses show experimental values.

Figure 12: The different experimentally tested random hole patterns and their geometrical properties.

zone which is concentrated between the holes and virtually no damage is observed outside the hole region.

Figure 13: Experimental and predicted failure loads, with its respective failure mode, for specimens with randomly distributed holes.

Figure 14: Post-failure photographs of specimens with randomly distributed holes.

6 Concluding Remarks

An extensive experimental study has been conducted on unidirectional glass fibre reinforced vinyl-ester laminates with multiple circular holes. The quasi-static tensile

strength of the laminates was investigated for different amount of holes and different hole arrangements (hole patterns). The following major observations were made in the experimental programme:

1. Three different failure modes were found; global net-section failure, shear-off failure and local net-section failure
2. The failure modes changed with changing hole pattern and hole density
3. Each failure mode was coupled to a geometrical quantity
4. Specimens with large amount of holes typically fail in shear failure mode while specimens with smaller amount of holes fail in global net-section failure
5. The failure strength of specimens with net-section failure mode is independent of the hole pattern but strongly dependent of the amount of holes
6. The failure strength of specimens with shear-off failure mode is dependent on a characteristic shear length which can change with hole pattern and the amount of holes

The results from the experimental programme were used to create a simple and fast analytical model to predict the residual strength of unidirectional laminates with multiple holes. Good agreement was found between the analytical predictions and the experimental results. Further, a number of specimens with randomly distributed hole patterns were tested and their failure strength could be modelled with sufficient fidelity.

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