Strength of GRP-laminates with multiple fragment damages

S. Kazemahvazi, J. Kiele, D. Zenkert
Kungliga Tekniska Högskolan, KTH
100 44 Stockholm, Sweden
sohrabk@kth.se

SUMMARY

The strength of glass fibre reinforced vinyl-ester laminates with multiple holes has been investigated experimentally. Different hole pattern configurations have been tested, primarily for unidirectional laminates. Unidirectional laminates have shown very low notch sensitivity and the laminate failure was governed by two competing failure modes; shear off failure and net section tensile failure.

Keywords: Notched laminates, fragment damages, glass fibre vinyl-ester, blast protection

INTRODUCTION

Due to the increasing use of fibre reinforced plastics in the construction of naval ship hulls the ballistic and blast performance of these materials has gained particular interest during the past decade.

A typical scenario of a composite 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 an already damaged structure motivating the study of laminates with multiple fragment damages. 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.

The notch sensitivity of fibre reinforced laminates with single holes has been investigated in several studies [1-5]. Studies were conducted for different multiaxial and unidirectional fibre lay-ups, different notch types and for different laminate thicknesses. Early models by Whitney and Nuismer [1] used the stress-failure model to predict the failure strength of laminates with one notch. They state that failure will occur when the stress at some characteristic length away from the notch tip reaches the un-notched strength of the laminate. These models are based on stress field predictions which tend to become very complicated in the case for laminates with multiple holes or damages. More recently several progressive damage models have evolved [6-8] and been implemented in commercial finite elements codes [9]. Hashin's failure initiation criteria [6] has been widely used in industry even though numerous studies have shown that the prediction is not accurate for several load cases. More importantly, these lamina based failure models do not consider delamination and fibre pull out failure modes which are quite common in notched composite laminates. Further, they do not consider the micro structural inhomogeneity of the material which affects crack growth directions and imposes different modes of failure.

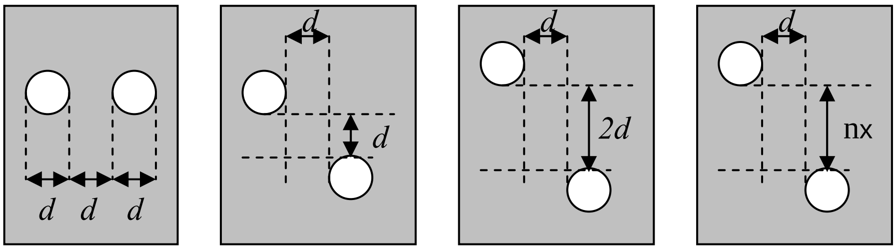
Within the scope of this study the notch sensitivity of laminates with multiple circular holes has been investigated through an extensive experimental programme. Primarily, the notched strength of unidirectional laminates, with the fibres aligned in the load direction, has been studied. Several hole configurations have been tested and different failure mechanisms were investigated using digital image correlation strain measurement. In order to understand the "in-situ effects", laminates with multiaxial fibre lay ups were tested and the effects of notch sensitivity of the load bearing ply with different neighbouring plies was investigated. The aim of the project is to understand the different failure mechanisms that occur for laminates with multiple notches and to provide experimental results for benchmarking of future and above mentioned failure models.

MATERIALS AND EXPERIMENTAL PROGRAMME

Glass fibre non-crimp fabrics [10] and vinyl-ester resin [11] 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. The experiments were performed in a screw-driven Instron machine at a nominal displacement rate of 2 mm per minute. Each laminate configuration was tested at least 5 times and all notches were in the shape of circular holes with diameter, d = 5 mm. Effects of hole size was hence not investigated but only the effect of hole density and hole configurations. 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. For the laminates with 0 % remaining net cross-section area, only the nominal strengths are presented.

TESTING OF UNIDIRECTIONAL LAMINATES

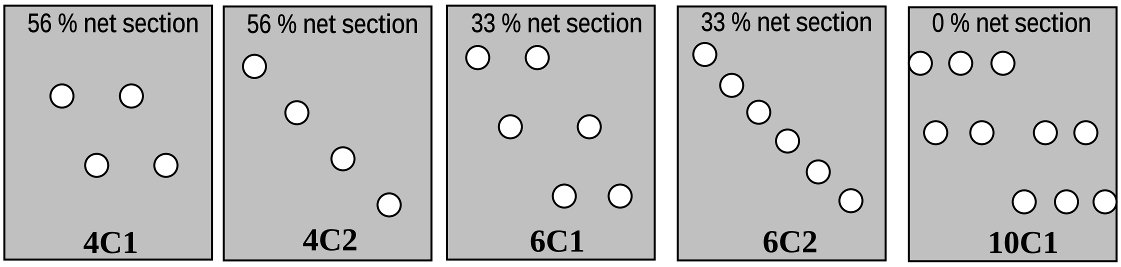
Firstly, unidirectional laminates (with the fibres aligned in the load direction, 0º) were tested without notches and with a single centred circular hole. Following these experiments a study with two circular holes, positioned in different configurations, was conducted to investigate the interaction 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 1 and these hole configurations will be referred to as 2H (2 Holes) followed by the vertical distance between the hole, e.g. 2H0 (figure 1a) and 2H2 (figure 1c).



(a) **(b)** **(c)** **(d)**

Figure 1: Laminates with different two-hole configurations, 2H0 (a), 2H1 (b), 2H2 (c), 2Hn (d).

A series of laminates with different patterns of 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 2. The laminates were named with the number of holes followed by pattern configuration, e.g. 4C1 (figure 2a) and 6C2 (figure 2d). All laminates had the same specimen width of 45 mm.



(a) **(b)** **(c)** **(d)** **(d)**

Figure 2: Four different hole configurations were tested.

Summary of experimental findings

A summary of the experimental results for the unidirectional laminates is presented in figure 3. As shown in figure 3, the unidirectional laminates show little or no notch sensitivity. Several hole configurations and patterns were tested and the net section strength proved to be a good estimation of the residual strength of the notched laminates with one exception. As the remaining net cross-section area decreased to below 30 % (7C1) a shift in failure mode was observed. 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 higher normalized net section strength.

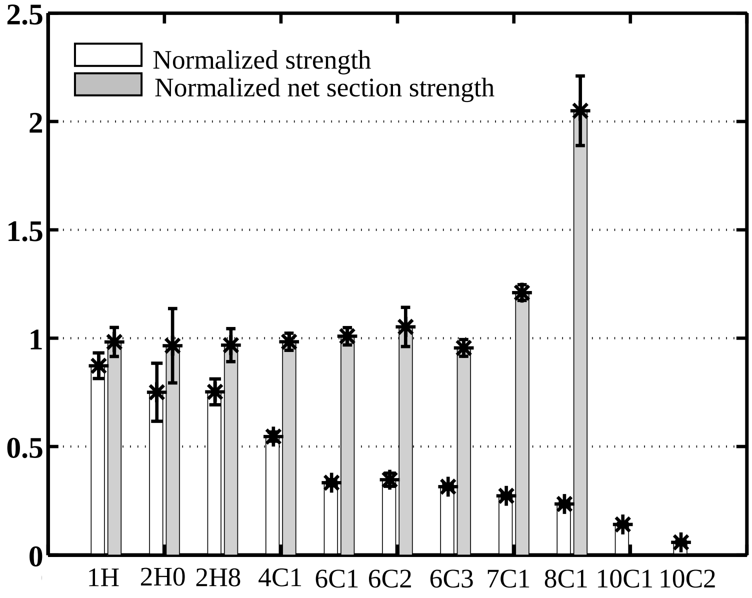


Figure 3: Normalized strength (white bars) and normalized net section strength (grey bars) for unidirectional 0º laminates with different hole configurations.

For laminates with shear-off dominated failure, large changes is observed for different hole patterns. In the shear-off failure region the laminate strength is coupled to the distance between the holes. The 10C1 and 10C2 have the same hole pattern but the holes are at different distances apart. In 10C1 the longitudinal distance between the holes is 2*hole diameter whereas the distance is 1*hole diameter for the 10C2. The two different failure modes are sketched schematically in figure 4; the net section tensile failure which is coupled to the net section area (figure 4a) and the shear-off failure which is coupled to a characteristic shear length between the holes (figure 4b). Figure 4c shows the shear forces that arise in the matrix, when the remaining cross-section area is small, and causes shear-off failure.

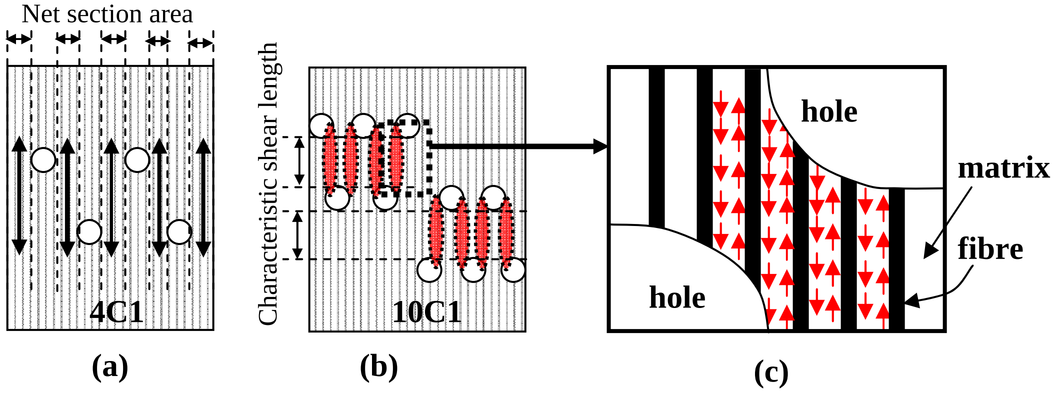


Figure 4: Schematics of different failure mechanisms for different hole densities, (a) fibres are still able to carry load and (b) the load has to been carried through shear forces between the holes. (c) Shear forces in the matrix in a unidirectional 0º laminate

In order to understand the effects of characteristic shear length on the residual strength of the laminates, digital image correlation technique [12] was used to measure the full strain field of the specimens. Several specimens with zero remaining net section area (10C) and different hole patterns were tested. Figure 5 shows strain fields in the longitudinal loading direction, ε_x, and shear strains, ε_{xy}, for two different hole configurations 10C1 and 10C4. The measurements are taken at the maximum load prior to ultimate failure. Both hole configurations have zero net section area but the 10C4 configuration have larger longitudinal distance between the holes, resulting in a higher characteristic shear length.

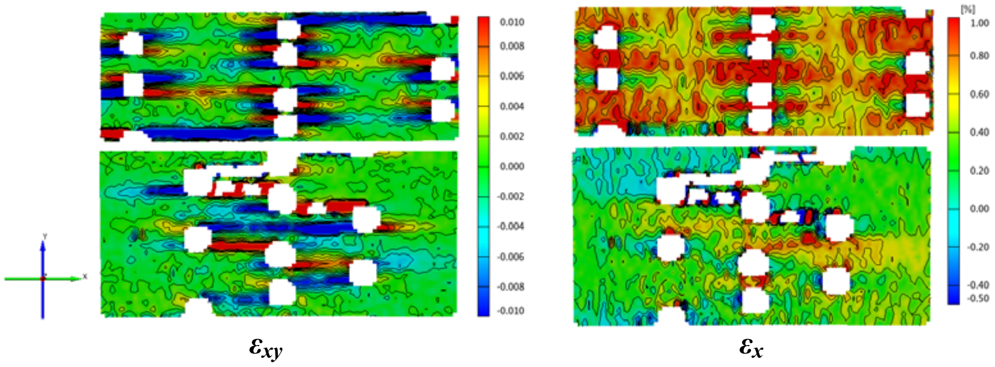


Figure 5: Full strain fields from digital image correlation experiments. All holes have 5 mm diameter and all specimen widths are 45 mm Top specimens are 10C4 configuration and bottoms specimen are 10C1 configuration.

The 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 10C4 specimen has large longitudinal distance between the holes and less hole interaction and smaller distances of large shear strain is observed. The longitudinal strains are significantly higher for the 10C4 specimen indicating that the fibres carry more load. Both specimens failed in a shear-off failure mode but the 10C4 specimen failed at 2.2 times higher load.

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.

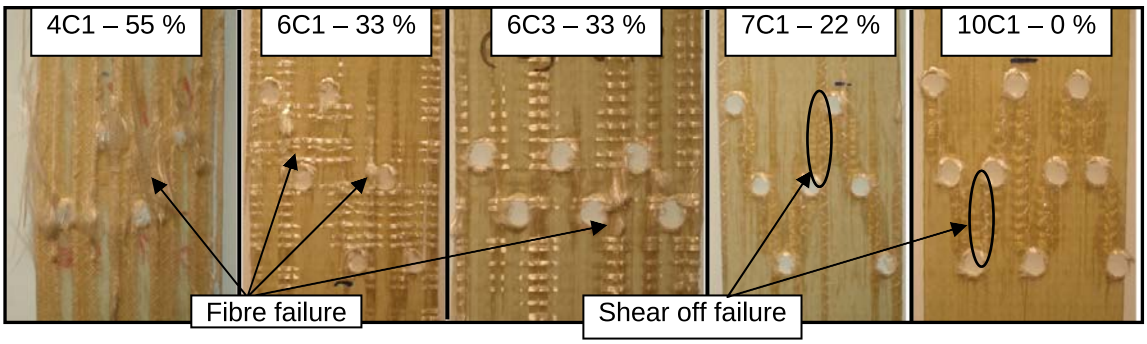


Figure 6: Post-test photographs of five unidirectional laminates with different hole patterns. All holes have 5 mm diameter and all specimen widths are 45 mm. The remaining net cross-section area varies from 55 % to 0 %.

For the laminates with less than 33 % remaining cross-section area, the dominating failure mode is matrix shear off. 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.

TESTING OF MULTIAXIAL LAMINATES

A number of multiaxial laminates were tested using the same method as for the unidirectional laminates. The different laminate configurations are specified in table 1.

Table 1: Configurations of multiaxial laminates

Name (amount 0º fibres)	Fibre weight 0º (g/m^2)	Fibre weight -45º (g/m^2)	Fibre weight 45º (g/m^2)	Fibre weight 90º (g/m^2)	Fibre weight Total (g/m^2)
DB (0%)	2	802	802	0	1606
DBL (51%)	828	396	396	18	1638
LT (51%)	856	0	0	826	1682

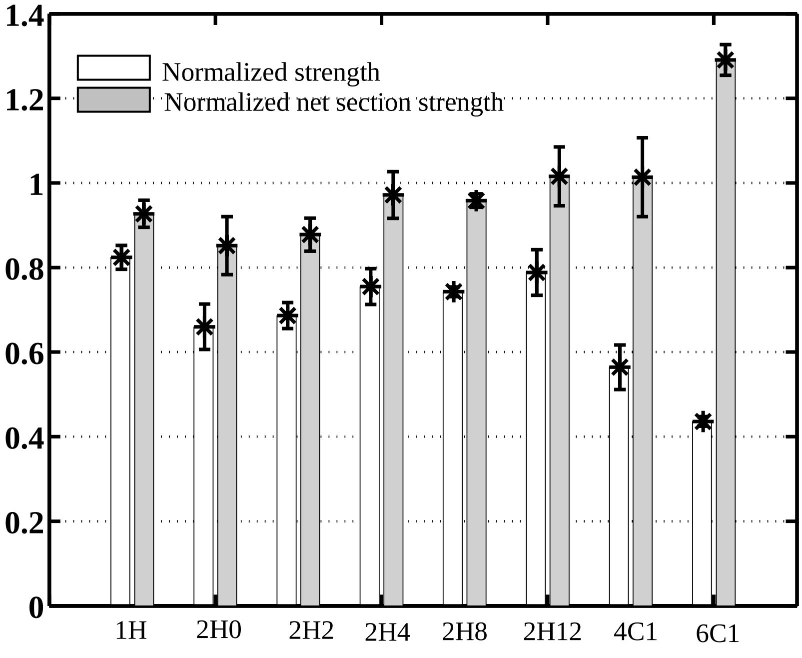


Figure 7: Normalized strength (white bars) and normalized net section strength (grey bars) for LT laminates with different hole configurations.

The experimental results for the biaxial LT laminate configuration is presented in figure 7. The majority of the hole configurations for this laminate show low notch sensitivity similar to that of unidirectional laminates. A small drop in normalized strength is observed for the 2H0 configuration but as the distance between two holes increases the normalized strength tends to that of a single hole laminate (2H12). The normalized net section strength was higher than unity for specimen with more than 6 holes. For these specimens (6C1) little or no fibre tensile breakage was observed, the failure mode was predominantly shear off failure, see figure 8. For the four hole configuration (4C1), both fibre tensile failure and matrix shear-off was observed.

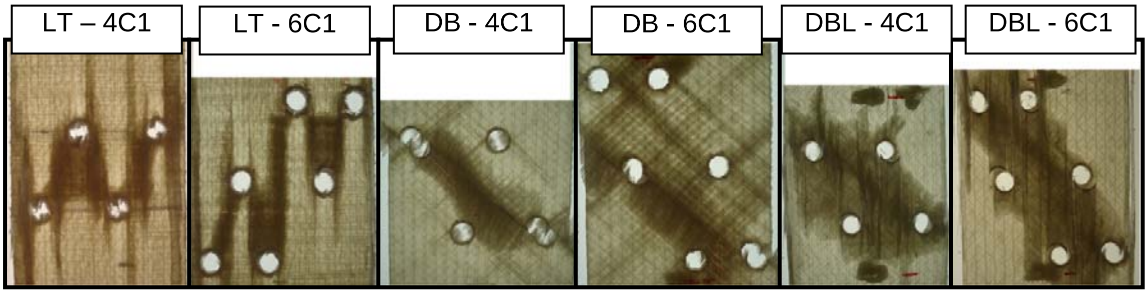


Figure 8: Post-test photographs of multiaxial laminates with different hole patterns. All holes have 5 mm diameter and all specimen widths are 45 mm.

For laminates with only ±45° fibres (DB) a shear-off dominated failure point is difficult to determine. Essentially, a DB laminate with a single hole is dominated by shear-off failure which is why the normalized net section strength is always higher than unity. This can be seen in figure 9 where all normalized net section values are larger than unity. The failure of the DB laminates always occurred parallel to the fibres and on a line between one or more holes, see figure 8.

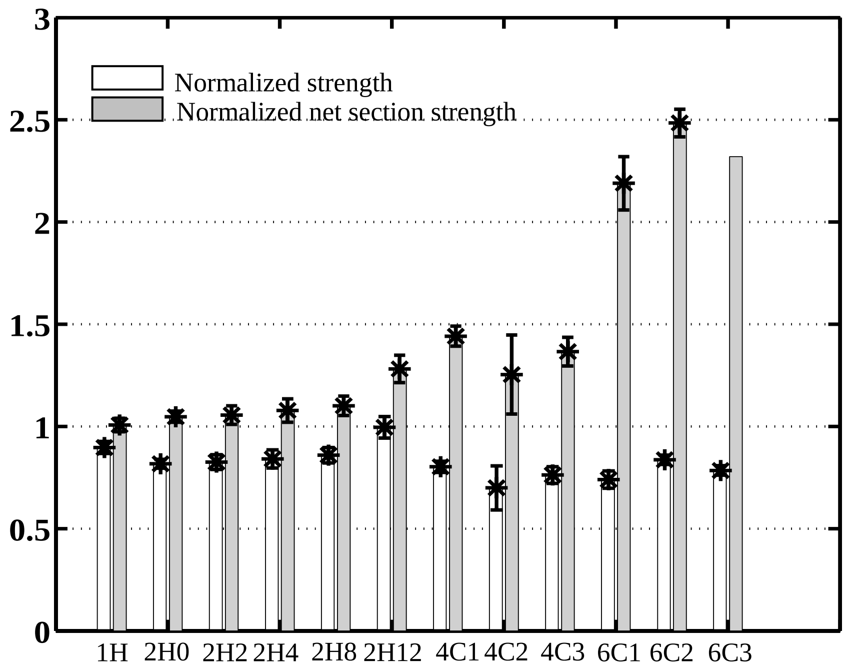


Figure 9: Normalized strength (white bars) and normalized net section strength (grey bars) for DB laminates with different hole configurations.

The DB laminates showed small sensitivity to different hole patterns. The two hole patterns showed small changes in normalized strength with increasing distance between the holes. For two holes at 12 diameter distance (2H12) the normalized strength was the same as for specimens with one hole indicating a small or no interaction between the holes. Configurations with multiple holes (4C and 6C) showed small differences in strength when the hole patterns were changed. The normalized strength of the 4C configurations were the same as for 6C configurations (accounting for the deviation in the data) which shows the good load transfer ability of the DB laminates.

Laminates with both ±45º and 0º (DBL) fibres show higher notch sensitivity which results in lower net section strength for laminates with few holes, see figure 10. When the two holes are 12 diameters apart (2H12) the normalized strength is still considerably lower than for a single hole specimen. In terms of notch sensitivity, the combination of ±45º and 0º fibres thus perform worse than each fibre configuration independently. However, as the numbers of holes increases the normalized net section strength increases rapidly. This effect arises since the ±45º fibres are able to carry the shear loads and distribute the load, between the holes to the 0º fibres. For the DBL laminates a combination of fibre tensile failure and matrix shear off was observed for both four and six hole configurations, see figure 8.

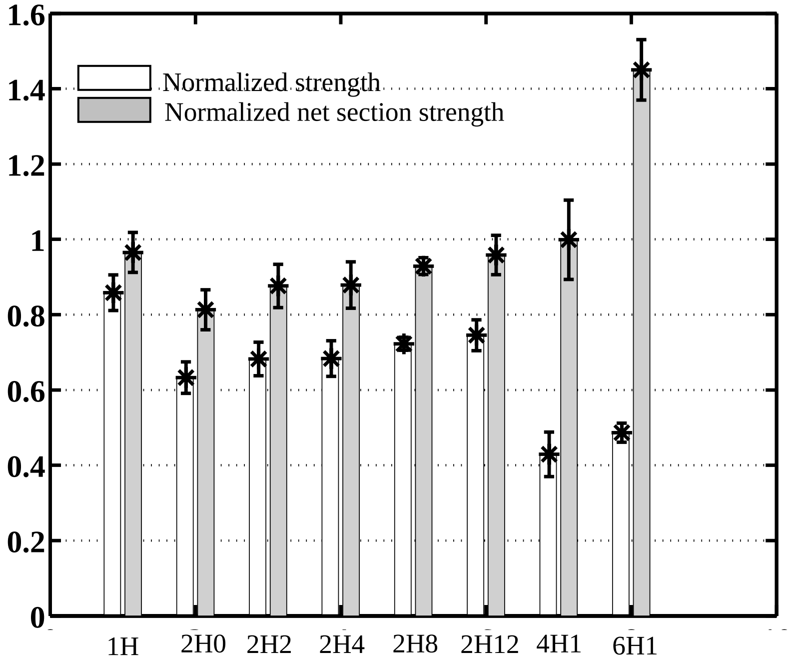


Figure 10: Normalized strength (white bars) and normalized net section strength (grey bars) for triaxial DBL laminates with different hole configurations.

CONCLUDING REMARKS

Glass fibre reinforced vinyl-ester laminates with numerous different hole patterns have been tested in uniaxial tension. The unidirectional laminates showed very small notch sensitivity and the residual strength of the notched laminates could be estimated with the net section strength (the strength considering the loss in cross-section area due to holes). However, when the remaining net cross-section area decreased to less than 30 %, the laminate failure was governed by matrix shear failure as opposed to fibre tensile fracture leading to a significant change in net section strength. The residual strength of a unidirectional laminate is governed by two competing failure modes; net section tensile failure which is coupled to the net section area and the shear-off failure which is coupled to a characteristic shear length. No significant change in strength as function of hole patterns was observed for unidirectional laminates with more than 30 % remaining cross-section area. For laminates with less than 30 % remaining cross-section area, changes in hole pattern gave higher changes in failure strength. This is an effect of the change in characteristic shear length between the holes.

Laminate configurations with good ability to distribute shear loads, such as ±45º or multiaxial laminates, showed a combination of shear-off failure and fibre tensile failure for laminates with more than 30 % remaining cross-section area.

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