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Notch and strain rate sensitivity of non-crimp fabric composites

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Abstract

The notch and strain rate sensitivity of non-crimp glass fibre/vinyl-ester laminates subjected to uniaxial tensile loads has been investigated experimentally. Two sets of notch configurations were tested; one where circular holes were drilled and another where fragment simulating projectiles were fired through the plate creating a notch. Experiments were conducted for strain rates ranging from $10^{-4}/s$ to $10^2/s$ using servo hydraulic machines. A significant increase in strength with increasing strain rate was observed for both notched and un-notched specimens. High speed photography revealed changes in failure mode, for certain laminate configurations, as the strain rate increased. The tested laminate configurations showed fairly small notch sensitivity for the whole range of strain rates.

Keywords: A. Glass fibres; B. Strength; B. Impact behaviour; Notch sensitivity

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1. Introduction

Due to the increasing use of fibre reinforced plastics in the construction of naval ship hulls the ballistic 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 (figure 1); 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 notched laminates at high rate loading. 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.

A number of studies have investigated the notch sensitivity of graphite/epoxy woven fabrics and prepreg tapes at quasi-static strain rates. These were mostly done for quasi-isotropic laminates without a systematic variation of ply orientation. Typical examples include alternation of the stacking sequence (in the out-of-plane direction) [1, 2], the hole diameter [1, 2, 3], specimen width [3] etc. Lagace [2] showed that the notch sensitivity of fabric laminates is generally the same as for prepreg tapes of similar configuration. Shembekar and Naik [1] suggested that $\pm 45^\circ$ woven fabric laminates are least notch sensitive whereas the $0^\circ / 90^\circ$ woven fabrics have the highest notch sensitivity.

The strain rate dependence of un-notched composites has been investigated in several experimental studies [5-9]. For dynamic strain rates ($>10/s$) split Hopkinson bars are frequently used resulting in a very complex study of wave propagation since the

wave propagation effects are dominant in composite materials. This may lead to some uncertainties in the test results. Barre et al [4] conducted a review of the dynamic properties of composites where results from 31 papers are summarized. The results are frequently contradictory. For example, the ultimate tensile strength of glass fibre epoxy composites is assumed to increase with increasing strain rate according to Rotem and Lifshitz [6] whereas it is suggested to decrease with increasing strain rate according to Armenakas and Sciammarella [7].

In the present study the notch and strain rate sensitivity of composite laminates are studied as a coupled event. The outline of the work is as follows. The notch sensitivity of glass fibre reinforced vinyl-ester laminates subjected to a uniaxial tensile load is experimentally investigated. The notch sensitivity is studied as a function of laminate ply orientation at strain rates ranging from 10^{-4} /s to 10^2 /s. The experimental programme was conducted using drilled circular holes to simulate notches created from fragment impacts. However, in order to relate this type of damage to that created from real fragment impacts a number of experiments were conducted using specimens with notches created from a fragment simulating projectile impact.

2. Experimental protocol

2.1 Material and Specimen Configuration

In this work glass fibre non-crimp fabrics [10] and vinyl-ester resin [11] has been used exclusively. Five different laminate configurations (LC) with different amount of 0° plies (LC0-LC100%) were tested, the stacking sequences and fibre orientations are specified in table 1. All laminates were manufactured using vacuum infusion technique. The notches (in the shape of circular holes) were drilled using standard twist drill and backing plates to avoid delamination at the drill exit. For experiments in the strain rate

range $10^{-4}/s$ to $10^0/s$ the un-notched specimens were tabbed using 2 mm glass/epoxy sheets whereas the notched specimen were prepared according to ASTM D5766/D 5766M. For experiments at strain rate $10^1/s$ and $10^2/s$ all specimens were tabbed using 1 mm aluminium sheets. This has proven to be the most successful tabbing type for the high rate test fixture. The geometrical properties of the specimens are found in table 2. Each laminate and hole configuration was tested at least three times.

	Stacking sequence	Laminate thickness, t [mm]	Percentage fibre in each direction [0,45,-45] (excluding the stitching)
LC100	[0]	1.4	[100%, 0%, 0%]
LC68	[0,-45,45]s	2.2	[68%, 16%, 16%]
LC50	[0,-45,45]s	1.4	[50%, 25%, 25%]
LC33	[0,-45,45]s	1.2	[33%, 33%, 33%]
LC0	[-45,45]s	1.6	[0%, 50%, 50%]

Table 1: Laminate configurations for the five different lay-ups.

	Width, w [mm]	Gauge length [mm]	Tabbing	Hole diameter, d [mm]	Strain rate
Type 1	25	100	GRP	0	10^{-4} to 10^0
Type 2	30	100	No tabbing	5	10^{-4} to 10^0
Type 3	25	100	Alu	0	10^1 to 10^2
Type 4	30	100	Alu	5	10^1 to 10^2

Table 2: Specimen geometry. Two types of tabbing material were used, Glass/epoxy (GRP) and aluminium (Alu).

2.2 Fragment simulating projectile damages

A limited number of reference experiments were conducted to investigate the difference between drilled notches and notches created from fragment impacts. Fragment

simulating projectiles were fired at two different speeds, one close to the laminate ballistic limit and another substantially higher than the ballistic limit. The ballistic limit is defined as the lowest speed where a projectile perforates the laminate. The low speed experiments were conducted using an air gun and the high speed experiments with a powder gun. Each laminate was clamped between two metal plates with centred circular holes of diameter 15 cm. The fragment simulating projectile was then fired in the centre of this hole. Schematic figures of the fixture are shown in figure 2a (front view) and 2b (side view). The ballistic limit for each laminate configuration is specified in table 3. These were obtained experimentally by firing a projectile slow enough to prevent perforation and then the projectile speed was increased incrementally until the projectile completely perforated the laminate. The geometrical shape of a fragment simulating projectile is found in figure 2c.

	Ballistic limit
LC100	178 m/s
LC68	223 m/s
LC50	178 m/s
LC33	155 m/s
LC0	198 m/s

Table 3: Ballistic limit for the different laminate configurations

Subsequent to laminate perforation each specimen was carefully cut out in order to let the centre of the notch coincide with the centre line of the specimen. The same specimen geometry as for the drilled notch specimens was employed and tensile test were conducted at two strain rates, $10^{-4}/s$ and $10^0/s$. Post-perforation pictures for the five different laminate configurations are presented in figure 3 (front side of specimen) and figure 4 (back side of specimen).

Specimens subjected to fragment impacts close to the ballistic limit have a larger and a more severe delamination area, in most cases wider than the specimen width. On the contrary, the high speed impacts make a cleaner notch i.e. removes more area from the specimen (similar to the plugging failure mode often seen for high speed impacts on metals). Compared to the drilled notches, the ballistic notches have a larger area with delamination and matrix failure. However, the amount of 0 degree fibres that are cut-off is the same or less than for the drilled specimens.

2.3 Tensile experiment apparatus

All tensile experiments were conducted in servo hydraulic machines. At low (10^{-4} /s) to intermediate (10^0 /s) strain rates a MTS50 machine with a maximum actuator speed of 0.15 m/s and 50 kN loadcell was used. At dynamic strain rates (10^1 /s and 10^2 /s) an Instron VHS 80/20 High Rate Test Machine with a maximum actuator speed of 20 m/s with and 100 kN loadcell was used. A detailed description of the Instron VHS 80/20 machine is given by Wang et al [8]. A nominal strain rate, $\dot{\epsilon}$, was assumed as the ratio of actuator speed to the specimen gauge length. The true strain rate varies over the entire specimen and especially in the vicinity of the notch. However, these effects were not taken into account for in the present study.

3. Summary of experimental findings

Composites tend to exhibit a number of failure modes, often in competition with each other. Examples of such are delamination, fibre tensile rupture, matrix compressive failure, splitting, fibre pullout etc. As the ply orientation of the laminates and the rate of the loading changes different failure modes are observed. In this section,

the strength, strain rate sensitivity and notch sensitivity results for the different laminate configurations are discussed together with the macroscopic failure modes.

3.1 Strength of notched laminates

The strength of notched specimens is presented by means of net section strength, σ_{cr}^N . That is, the strength that considers the reduction in net area caused by the notch. In the case of drilled circular holes the net area loss can be measured with high accuracy using digital callipers. However, a well defined hole size is difficult to find for the specimens with notches created from fragment impacts, see figure 3 and figure 4. For this purpose, the fragment simulating projectile diameter was used as a measure of the notch size. The values of the mean strength and standard deviations are presented in table 4. All configurations show standard deviations typically within 10 %.

The notched strength of the five different laminate configurations as function of strain rate is presented in figure 5. Results from the high speed fragment impact damaged specimens are represented by black markers and the impacts close to the ballistic limit with filled markers. Both cases are tested at quasi-static and intermediate strain rates.

The strength of drilled notch specimens correlate very well with the fragment impact damaged ones for laminate configurations with at least 50 percent 0-degree fibres (LC50, LC68 and LC100) even though the fragment impact damage causes more delamination. For these laminates, the strength is primarily governed by the tensile strength of the 0-degree fibres which are little affected by matrix failure and delamination. The strength of the laminates with low amount of 0-degree fibres is, on contrary, mainly obtained from the matrix and the $\pm 45^\circ$ layers and thus the large delamination areas reduce the laminates ability to carry load. Thus, the difference in strength between drilled and impact damaged specimens are larger for laminates with

low amount of 0-degree fibres (LC33 and LC0), especially for impact damages close to the ballistic limit. However, for specimens with some amount of 0° plies subjected to loads at elevated rates a drilled hole is a good assumption for a fragment impact damage.

3.2 Notch and strain rate sensitivity indicators

In order to relate the notched to the un-notched strength of the specimen a simple notch sensitivity indicator is introduced. The notch sensitivity indicator, η , is defined as,

$$\eta = \frac{\sigma_{cr}^N}{\sigma_{cr}^{UN}}, \quad (1)$$

where σ_{cr}^N is the net section strength of the notched specimen and σ_{cr}^{UN} the strength of the un-notched. Both strength values are evaluated at the same strain rate. The notch sensitivity increases with decreasing value of η and is non-existent when η reaches unity.

A strain rate sensitivity indicator, R , is introduced to relate the dynamic critical strength, σ_{cr}^D , to the strength at a quasi-static ($10^{-4}/s$) strain rate, σ_{cr}^S , as,

$$\sigma_{cr}^D(\dot{\epsilon}) = R(\dot{\epsilon})\sigma_{cr}^S. \quad (2)$$

The strain rate sensitivity, R , denotes the ratio of the strength at an applied strain rate $\dot{\epsilon}$ to the strength at a reference strain rate $\dot{\epsilon}^R = 10^{-4}/s$. Thus a value of $R = 1$ indicates an absence of strain rate effects whereas $R < 1$ represents a decrease in strength with increasing strain rate and $R > 1$ represents an increase in strength with increasing strain rate. The R -values for the notched and un-notched specimens are presented as a function of the strain rate for all laminate configurations.

3.3 Strain rate sensitivity – results and discussion

3.3.1 Laminate configurations with predominant amount of 0° plies

An increasing trend of the strength reminiscent of that for 0° woven-fabrics [9] is observed for laminates with predominant amount of 0° plies, see figure 6 and figure 7. At the highest loading rate ($10^2/s$) notched LC100 specimens tended to fail through fibre pullout at the tabbing explaining the deviant trend of the strain rate sensitivity. Post-test photographs of LC100 are presented in figure 8.

Difficulties were found when testing LC68 at the dynamic strain rates ($>10/s$) due to the higher thickness of the laminate resulting in high failure loads. As an example, the stitching layer of the laminate tended to shear off preventing the specimen to fail in the anticipated failure mode, in this case fibre tensile and splitting failure, see figure 9.

3.3.2 Laminate configuration with 50% 0° plies

Unlike the notched laminates with predominate 0° plies, notched laminates with 50 percent 0° plies (LC50) show higher strain rate dependence than the un-notched ones, see figure 10. Distinct changes in failure mode were observed for LC50 as the rate of loading increased. For low strain rates failure always occurred in the vicinity of the notch whereas failure in the entire test gauge was observed at elevated strain rates, see figure 11. At dynamic rates of loading the notched specimens showed a severe splitting failure where the 0° plies completely detached from the $\pm 45^\circ$ plies. In order to reveal the sequence of the failure modes high speed photography was used aiming to capture the transition in failure mode from failure in the vicinity of the notch (figure 12a) at low strain rates to the splitting failure mode at elevated strain rates (figure 12b).

Photographs clearly show that splitting occurs prior to crack growth at elevated strain rates.

3.3.3 Laminate configurations with low amount of 0° plies

Laminate configurations with a low amount of 0° plies exhibited similar failure modes over the entire range of strain rates, see figure 13 and figure 14. However, an increase of the damage zone area was observed for LC33. For the pure $\pm 45^\circ$ laminates (LC0) the strain rate sensitivity of the notched specimens is substantially higher than the un-notched resulting in higher net section strength for the notched specimens compared to that of the un-notched ones. The reason for this behaviour is rather unclear and needs to be investigated further. Dynamic strain rate test results for un-notched LC0 could not be obtained since the failure loads of these specimens was lower than the test range of the VHS 80/20 machine.

3.4 Notch sensitivity – results and discussion

3.4.1 Laminate configurations with predominant amount of 0° plies

The unidirectional laminates showed constant and low notch sensitivity for all strain rates, see figure 17. The increase in notch sensitivity at the highest loading rate is a consequence of the unexpected failure mode described in section 3.3.1. The laminates with 68 percent 0° plies (LC68) showed similar notch sensitivity behaviour as the LC100, see figure 17.

3.4.2 Laminate configurations with 50% and lower amount of 0° plies

The notch sensitivity of LC50 is fairly constant for low and intermediate strain rates, see figure 17. For the dynamic strain rates the notch sensitivity decreases since the notched laminates show higher rate dependence than the un-notched.

Notched LC0 laminates show much higher rate dependence than the un-notched resulting in very low notch sensitivity.

4. Concluding remarks

Non-crimp fabric glass fibre/vinyl-ester composites exhibit small notch sensitiveness when subjected to uniaxial tensile loads at strain rates varying from 10^{-4} /s to 10^2 /s. The notched net section strength of these laminates is typically within 85 percent of the un-notched strength. Laminates with notches created from fragment simulating projectile impacts have similar net section strength as laminates with drilled circular holes. Hence, drilled circular holes can be used to simulate fragment impact damages. This should however be done with care since the difference in strength is larger at low strain rates than at intermediate strain rates, making the assumption more suitable for dynamic loading rates.

The notch sensitivity as function of strain rate is fairly constant for laminates with predominant amount of 0° plies whereas it decreases for laminates with 50 percent of 0° plies.

As the strain rate increases a change in failure mode is observed for several laminate configurations. At low strain rates fracture occurs in the vicinity of the notch whereas a splitting dominated failure occurs at elevated strain rates. Further, an increase in strain rate results in a higher strength for all the laminate configurations tested. The dynamic strength is typically 60 percent higher than the quasi-static strength.

Acknowledgements

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Figure 4: Specimen back side post-perforation pictures. High speed impacts (a)-(e) and impacts close to the ballistic limit (f)-(j).

Figure 5: Net section strength of notched laminates. Fragment simulating projectile results are represented by black markers (high speed) and filled markers (low speed) not connected by lines.

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Figure 7: Strain rate sensitivity of LC68, 68 percent 0-degree plies

Figure 8: Post-test photographs of LC100

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Figure 10: Strain rate sensitivity of LC50

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Figure 14: Post-test photographs of LC0

Figure 15: Strain rate sensitivity of LC33

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Figure 17: Notch sensitivity as function of strain rate for the different laminate configurations.

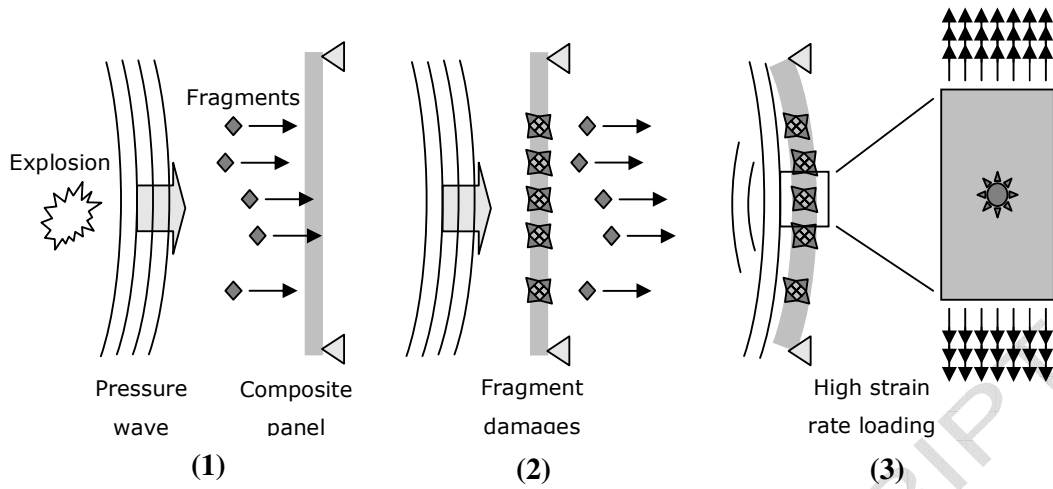


Figure 1

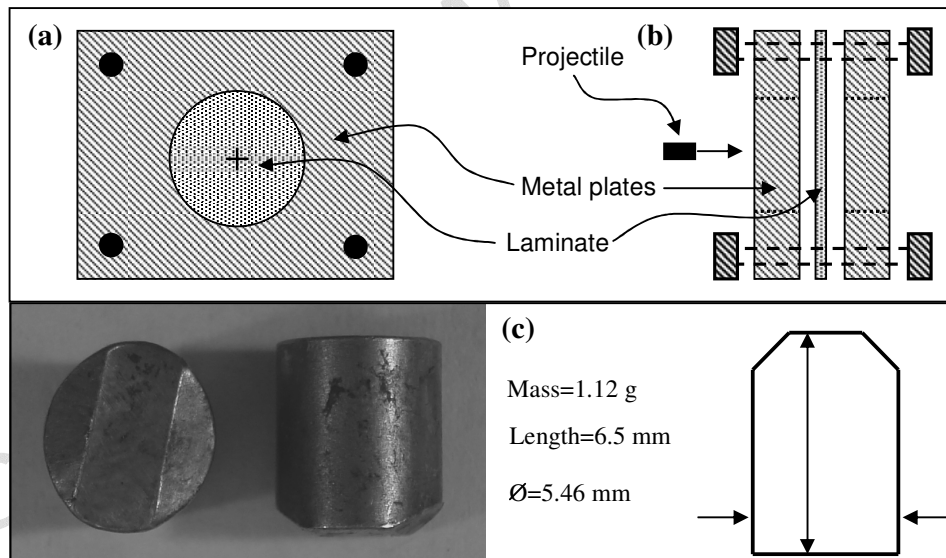


Figure 2

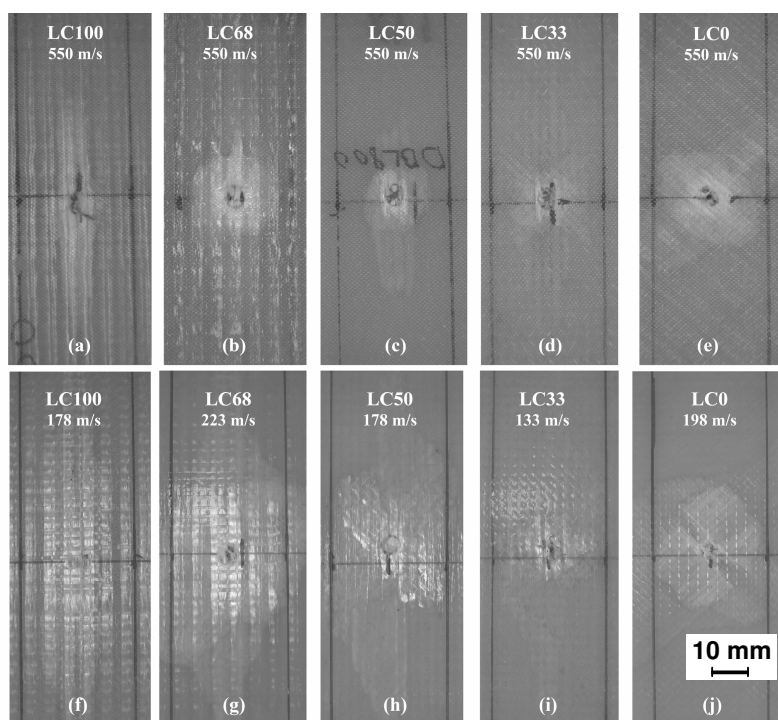


Figure 3

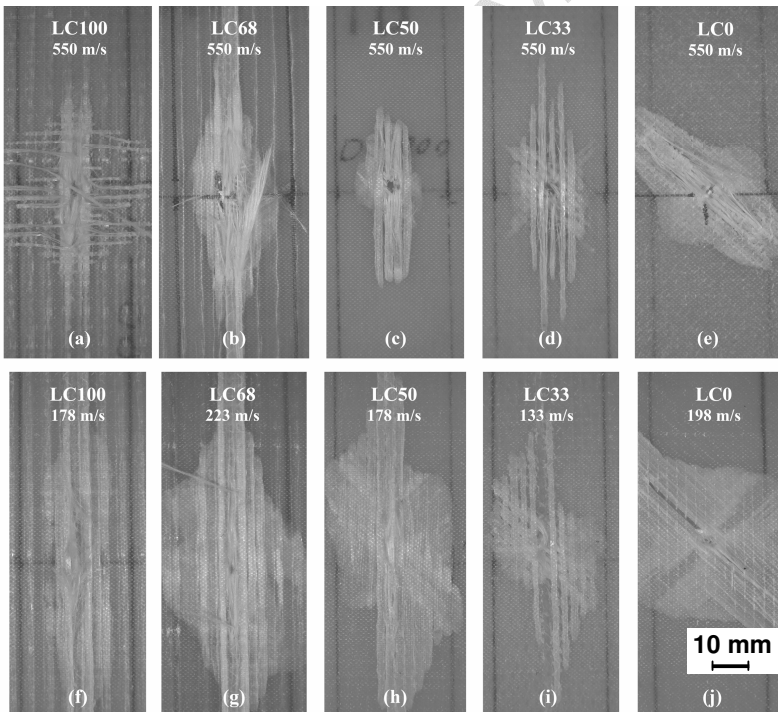


Figure 4

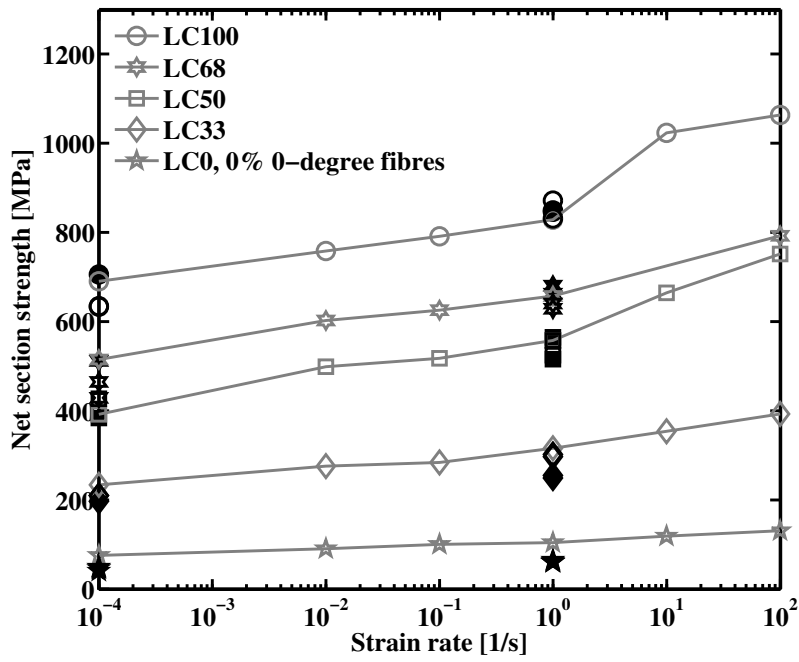


Figure 5

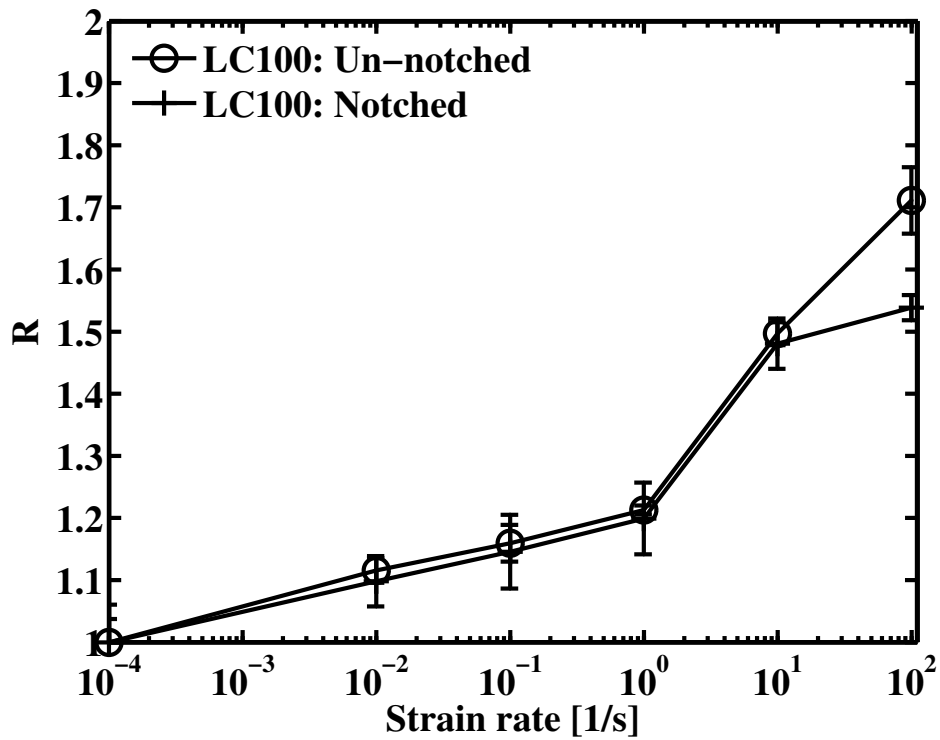


Figure 6

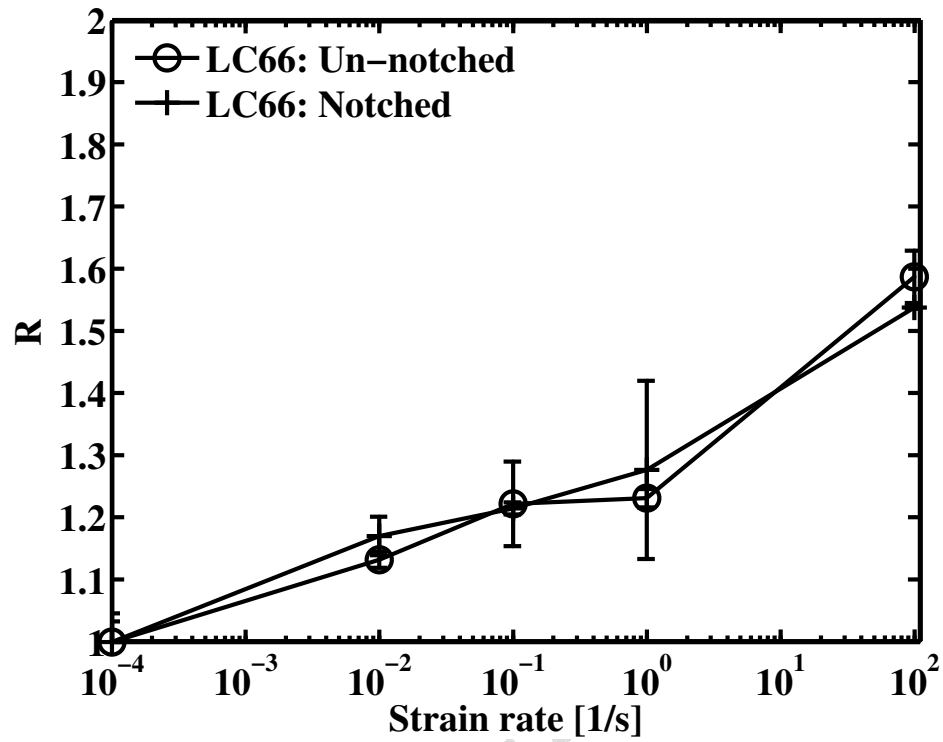


Figure 7

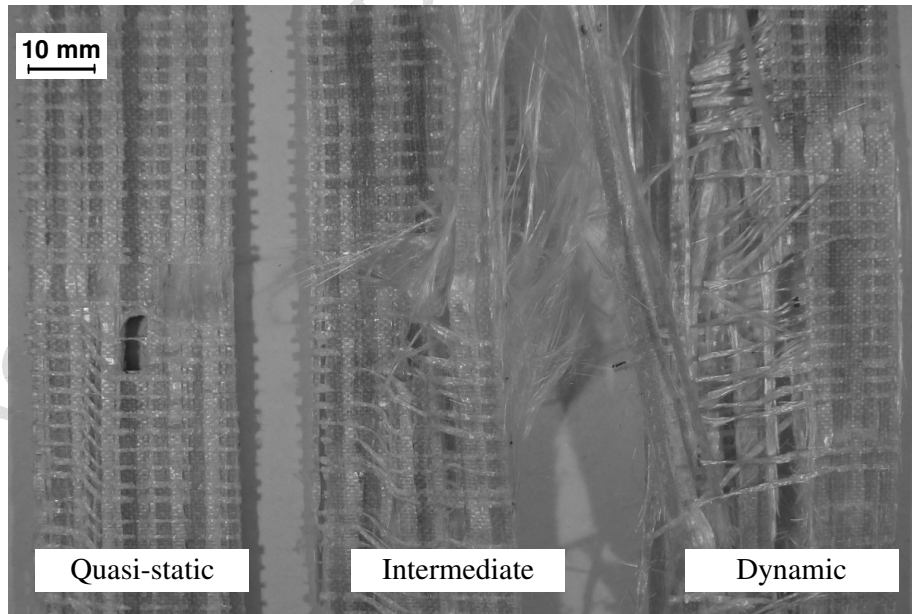


Figure 8

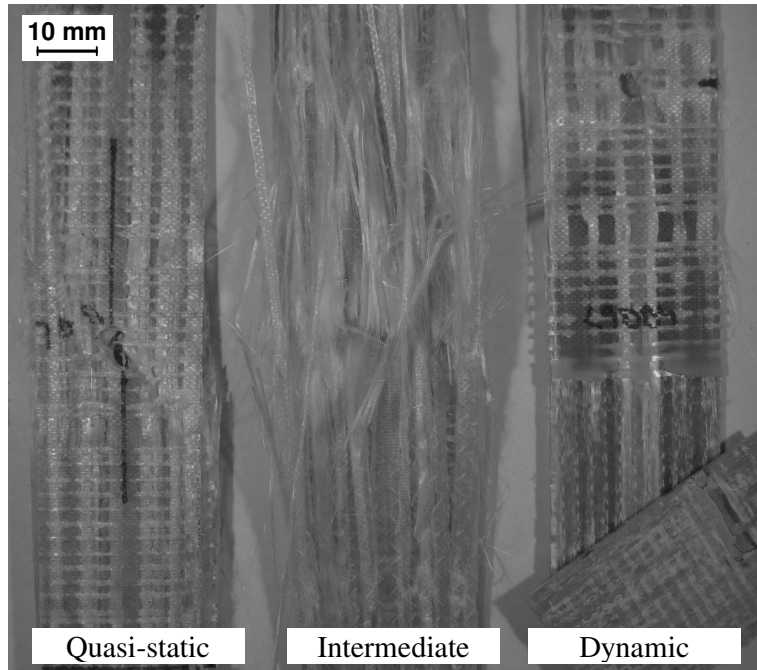


Figure 9

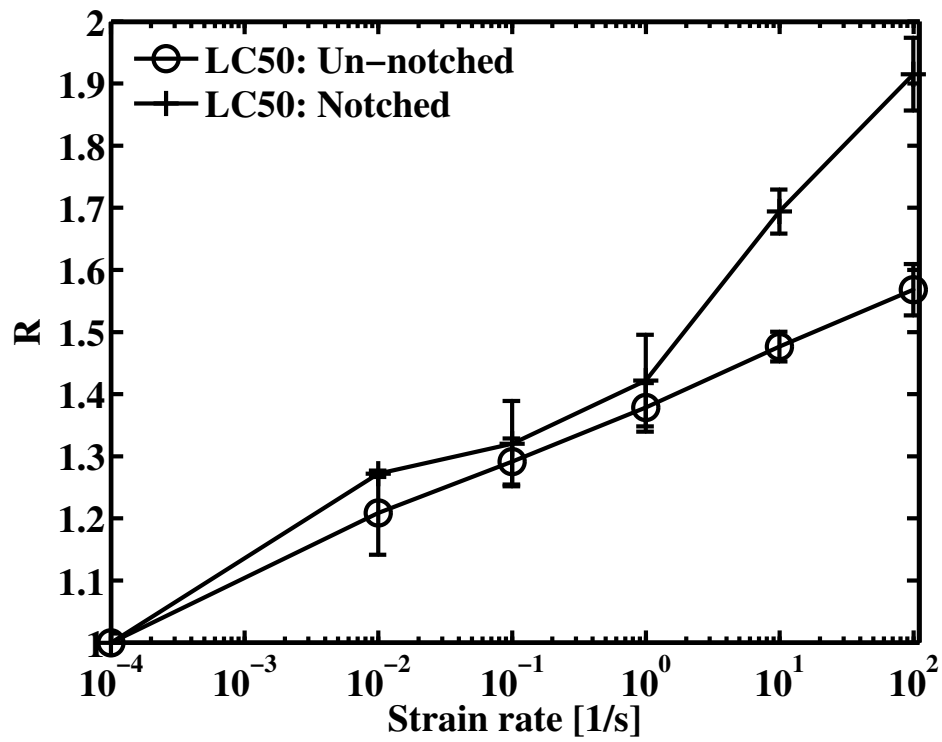


Figure 10

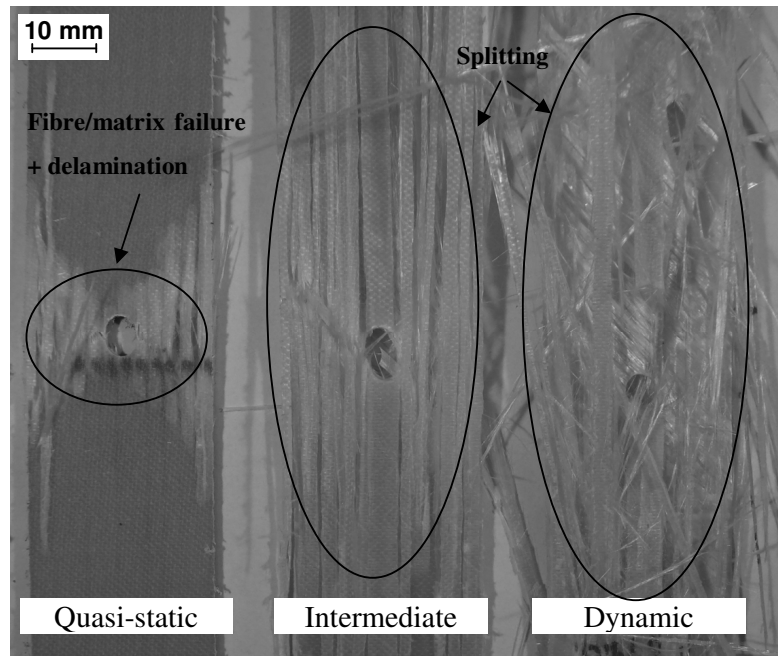


Figure 11

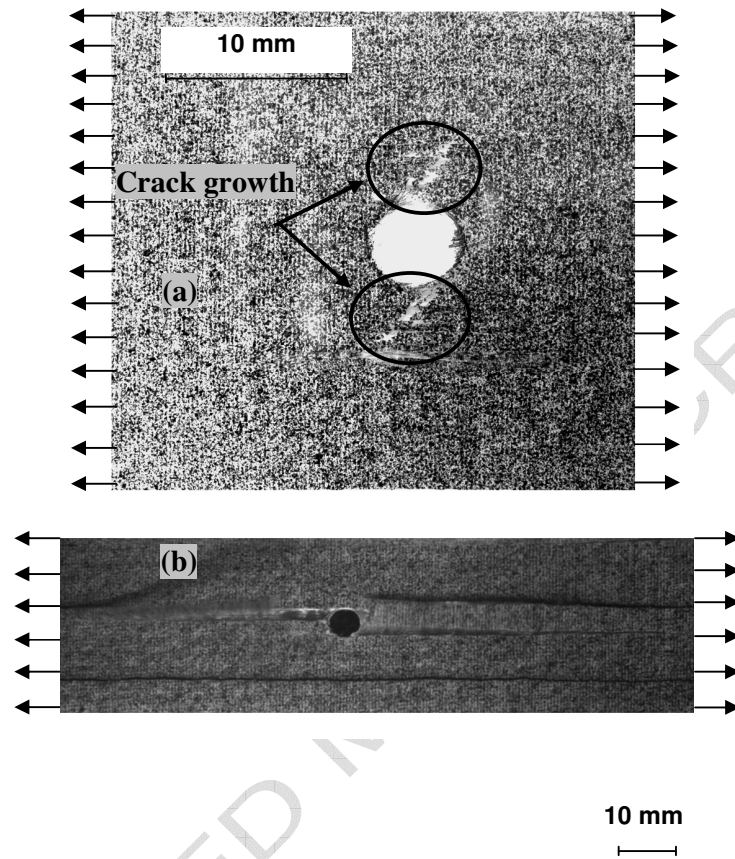


Figure 12

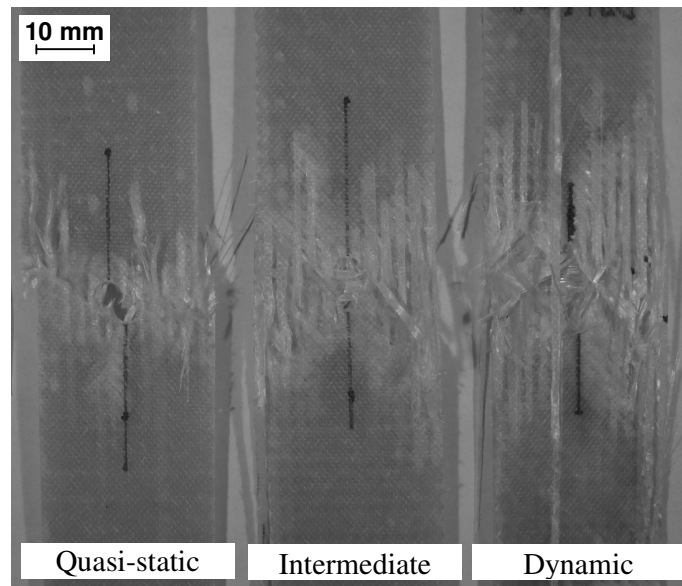


Figure 13

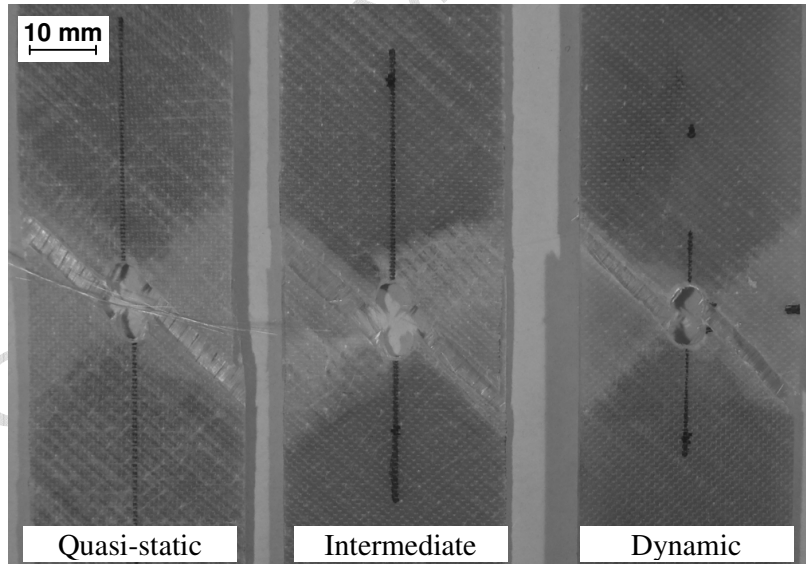


Figure 14

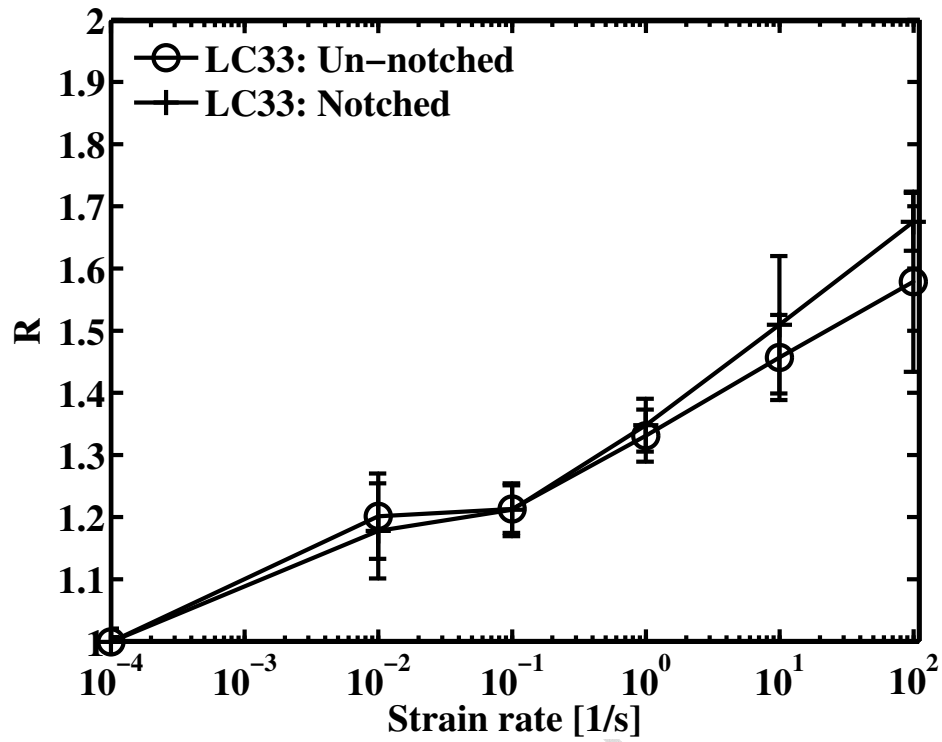


Figure 15

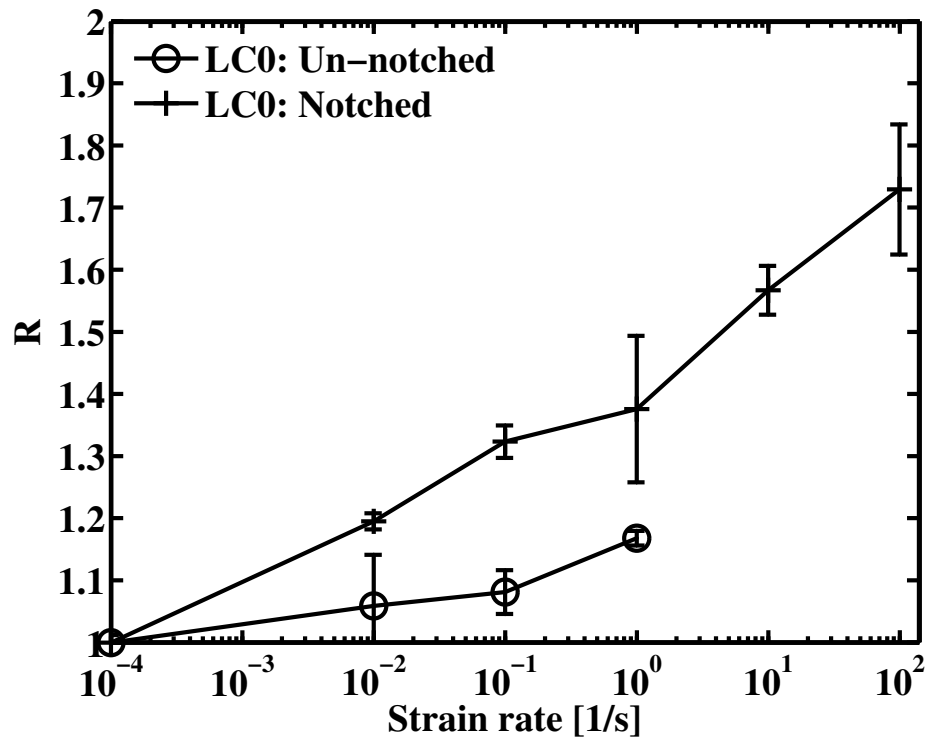


Figure 16

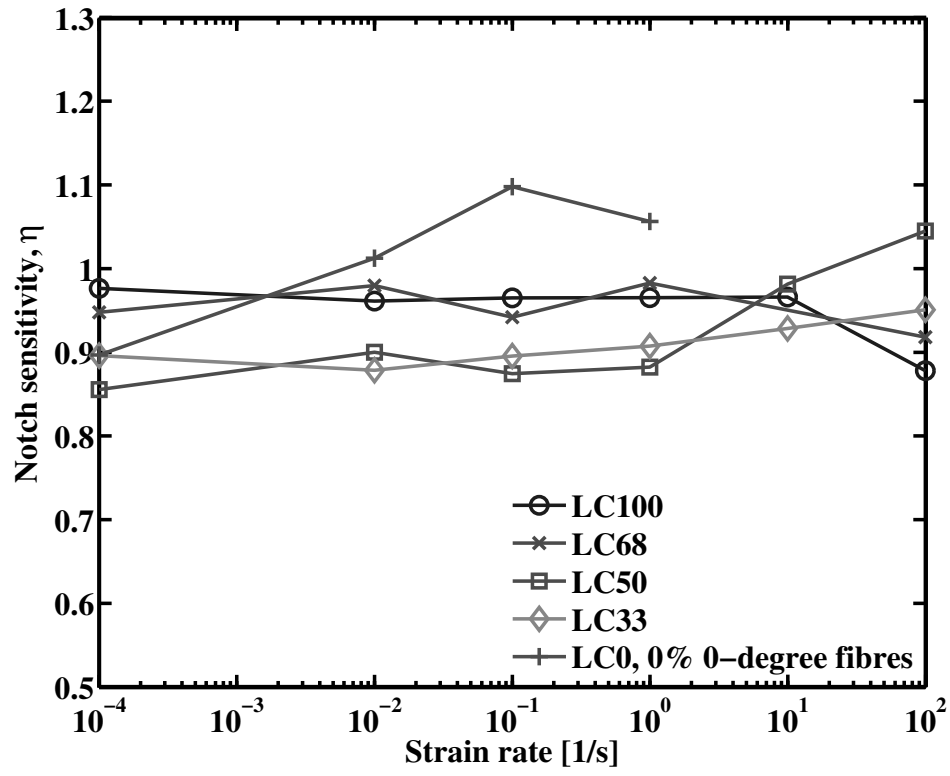


FIG.17

Laminate configuration	Notch configuration	Strength (MPa) $\dot{\epsilon} = 10^{-4}$ (1/s)	Strength (MPa) 10^{-2} (1/s)	Strength (MPa) 10^{-1} (1/s)	Strength (MPa) 10^0 (1/s)	Strength (MPa) 10^1 (1/s)	Strength (MPa) 10^2 (1/s)
LC0	<i>no hole</i>	85±1	84,5±7	91.9±3	99,3±0,5	-	-
LC0	<i>5 mm circular hole</i>	76,3±1	91,2±1	101±2	98.0±9	119.6±3	132±8
LC0	<i>FSP</i>	47 & 50	-	-	63 & 61	-	-
LC0	<i>FSP - ballistic limit</i>	41	-	-	66 & 61	-	-
LC33	<i>no hole</i>	262±2	315±18	318±10	349±11	382±18	416±38
LC33	<i>5 mm circular hole</i>	235±5	277±18	285±10	317±10	355±26	394±11
LC33	<i>FSP</i>	211 & 211	-	-	298 & 303	-	-
LC33	<i>FSP - ballistic limit</i>	198	-	-	250 & 256	-	-
LC50	<i>no hole</i>	459±7	555±31	593±17	633±18	678±11	720±19
LC50	<i>5 mm circular hole</i>	393 ±6	500 ±2	519 ±27	559 ±29	666 ±14	753 ±23
LC50	<i>FSP</i>	428	-	-	526 & 559	-	-
LC50	<i>FSP - ballistic limit</i>	385	-	-	566 & 517	-	-
LC66	<i>no hole</i>	544±26	616±7	665±37	670±8	-	864±23
LC66	<i>5 mm circular hole</i>	516±17	604±16	627±5	659±74	-	794±1
LC66	<i>FSP</i>	430 & 466	-	-	642 & 630	-	-
LC66	<i>FSP - ballistic limit</i>	513	-	-	682 & 664	-	-
LC100	<i>no hole</i>	708±43	790±14	821±21	859±5	1060±13	1212±38
LC100	<i>5 mm circular hole</i>	692±26	760±28	793±41	830±40	1025±28	1065±14
LC100	<i>FSP</i>	635 & 636	-	-	873 & 833	-	-
LC100	<i>FSP - ballistic limit</i>	707	-	-	848 & 851	-	-

Table 4: Mean value strengths and standard deviations of the tested laminate and notch configurations. All values are given in MPa at five different strain rates.