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 set 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.

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; 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, travelling at the speed of sound, will cause the ship hull panels to deform at an elevated strain rate (e.g. $10^{2}/s$). Hence, the high intensity pressure wave hits an already damaged structure motivating the study of notched laminates at high rate loading.

A number of studies have investigated the notch sensitivity of graphite/epoxy woven fabrics and prepreg tapes at quasi-static strain rates. These are 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 according to Rotem and Lifshitz [6] whereas it is suggested to decrease 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 fragment simulating projectile impacts.

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 (0-100%) where 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 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. The geometrical properties of the specimens are found in table 2.

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

	Stacking sequence	Laminate thickness, t [*mm*]	Percentage fibre in each direction [0,45,-45,90] (excluding the stitching)
LC100	[0]	1.6	[100%, 0%, 0%, 0%]
LC68	$[0,-45,45]_s$	2.2	[68%, 16%, 16%, 0%]
LC50	$[0,-45,45]_s$	1.6	[50%, 25%, 25%, 0%]
LC33	$[0,-45,45]_s$	1.2	[33%, 33%, 33%, 0%]
LC0	$[-45,45]_s$	1.8	[0%, 50%, 50%, 0%]

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

	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}

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. A powder gun was used to fire fragment simulating projectiles at a nominal speed of 550 *m/s*. This velocity is significantly higher than the ballistic limit of the laminates resulting in relatively clean notches. The diameter of the fragment simulating projectile was chosen close to the drilled hole diameter. The geometrical shape of the fragment simulating projectile is found in Fig. 1.

Fig. 1. Geometrical shape of fragment simulating projectile

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 Fig. 2 (front side of specimen) and Fig. 3 (back side of specimen).

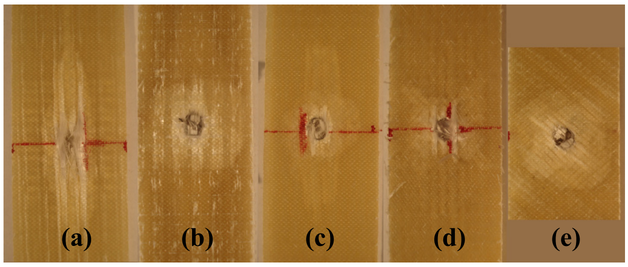

Fig. 2. Specimen front side post-perforation pictures for (a) LC100, (b) LC68, (c) LC50, (d) LC33 and (e) LC0.

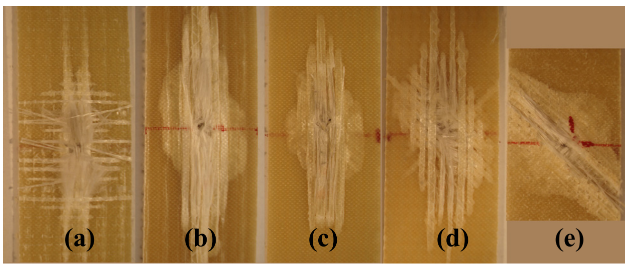

Fig. 3. Specimen back side post-perforation pictures for (a) LC100, (b) LC68, (c) LC50, (d) LC33 and (e) LC0.

2.3 Experimental 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. An Instron VHS 80/20 High Rate Test Machine with a maximum actuator speed of 20 m/s with a 100 kN loadcell was used for the experiments at strain rates $10^{1}/s$ and $10^{2}/s$. A detailed description of the Instron VHS 80/20 machine is given by Wang et al [8]. A nominal strain rate, $\dot{\varepsilon}$, 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

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 Fig. 2 and Fig. 3. For this purpose, the fragment simulating projectile diameter was used as a measure of the notch size. The notched strength of the five different laminate configurations as function of strain rate is presented in Fig. 4. Results from the fragment impact damaged specimens are represented by black markers at quasi-static and intermediate strain rates.

At intermediate strain rate the strength of drilled notch specimens correlate very well with the fragment impact damaged ones. The differences become larger at low strain rates but still within sufficient fidelity. For the pure ±45° laminates the delamination area on the backside of the specimen was wider than the specimen width, see Fig. 3e, explaining the larger deviations in strength compared to the other laminate configurations. 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. Worth elucidating is that the impact damages investigated here are at speeds significantly higher than the ballistic limit of the structure. For impacts close to the ballistic limit the damage becomes more severe. Whether drilled holes can be used as assumptions for these types of damages needs to be investigated more thoroughly.

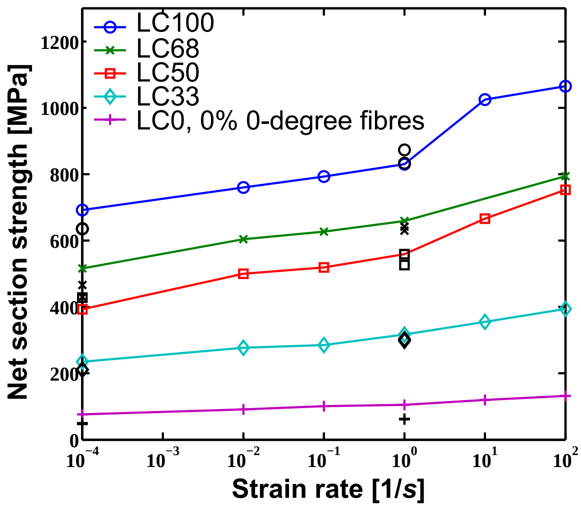

Fig. 4. Net section strength of notched laminates. Fragment simulating projectile results are represented by black markers not connected by lines

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,

$$\eta = \frac{\sigma_{cr}^{N}}{\sigma_{cr}^{UN}}, \tag{1}$$

where σ_{cr}^{N} is the net section strength of the notched specimen and σ_{cr}^{UN} the strength of the un-notched. 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,

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

The strain rate sensitivity, R, denotes the ratio of the strength at an applied strain rate $\dot{\varepsilon}$ to the strength at a reference strain rate $\dot{\varepsilon}^{R} = 10^{-4}/s$. Thus a value of R = 1 indicates an absence of strain rate effects whereas R < 1 represents a strain rate softening and R > 1 a strain rate hardening. 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 Notch and strain rate sensitivity – results and discussion

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

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 Fig. 5 and Fig. 7. For the unidirectional laminates (LC100) the strain rate sensitivity of the notched specimens is slightly lower than the un-notched ones. 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. The unidirectional laminates showed constant and low notch sensitivity for all strain rates, see Fig. 9. The increase in notch sensitivity at the highest loading rate is a consequence of the erroneous failure mode described earlier. Post-test photographs of LC100 are presented in Fig. 6.

The laminates with 68 percent 0° plies (LC68) showed similar notch sensitivity behaviour as the LC100.

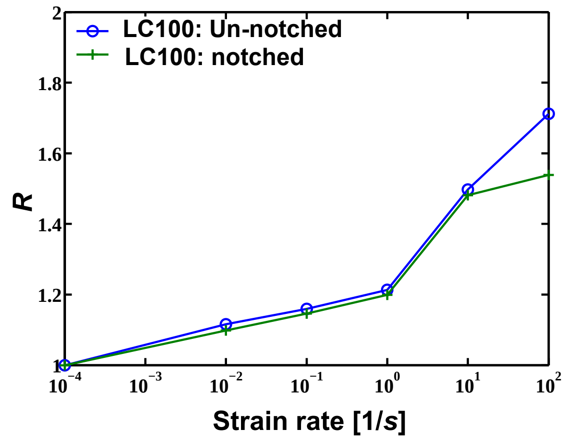

Fig. 5. Strain rate sensitivity of LC100, 100 percent unidirectional fibres.

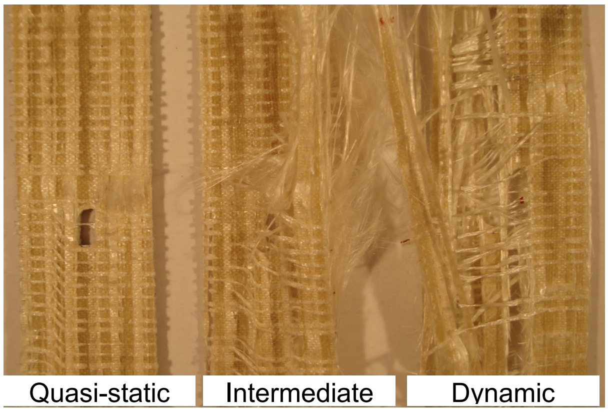

Fig. 6. Post-test photographs of LC100

Difficulties were found when testing LC68 at the dynamic strain rates (>10/s), this 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 correct failure mode, see Fig. 8.

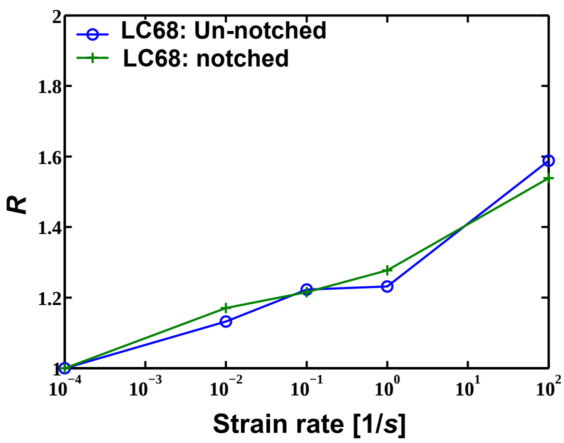

Fig. 7. Strain rate sensitivity of LC68

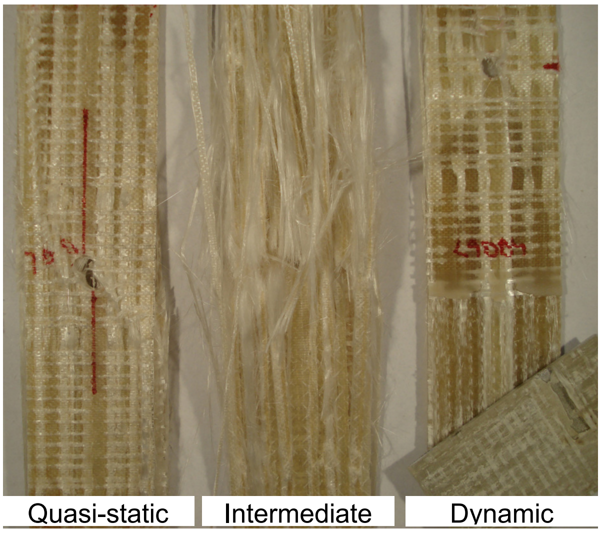

Fig. 8. Post-test photographs of LC68

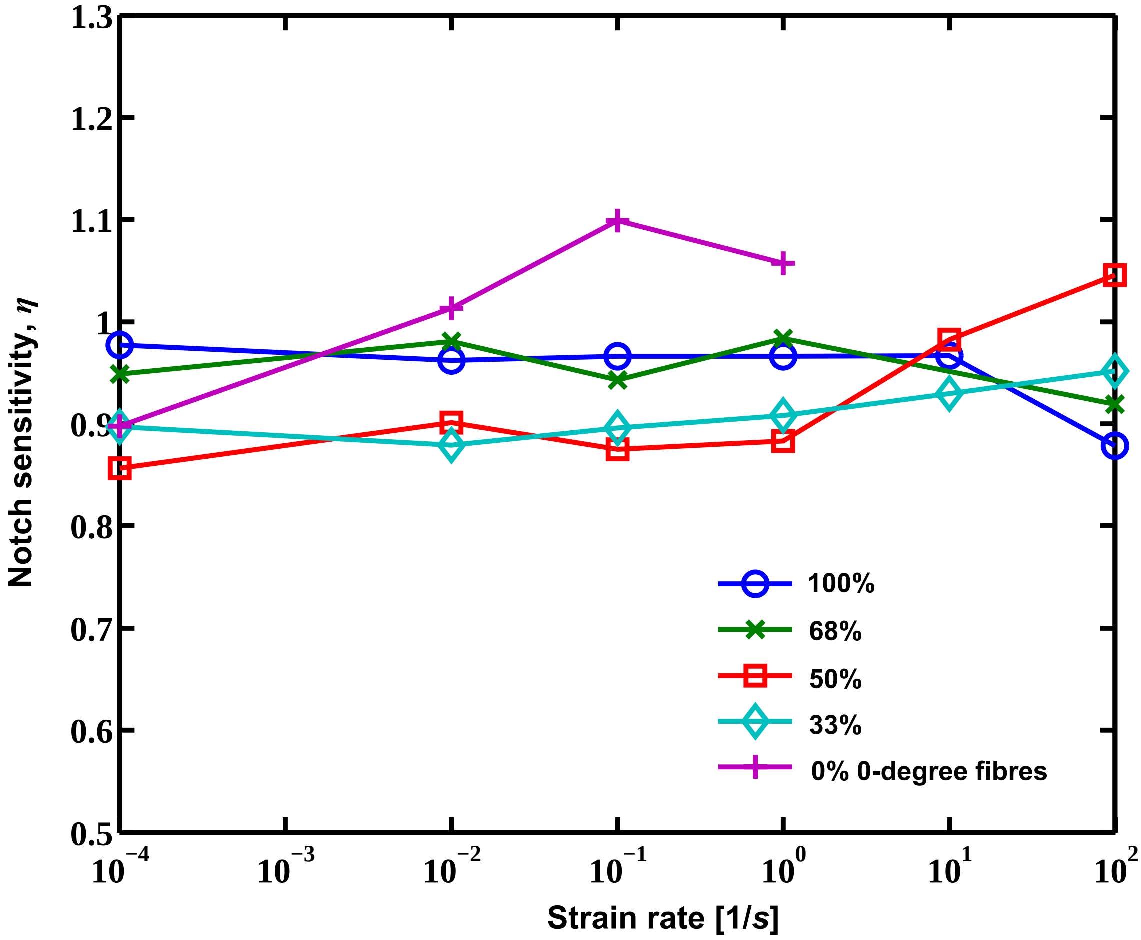

Fig. 9. Notch sensitivity as function of strain rate for the different laminate configurations

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 Fig. 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 Fig. 11. At dynamic rates of loading the notched specimens showed a severe splitting failure where the 0° plies completely detached from the ±45° 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 (Fig. 12a) at low strain rates to the splitting failure mode at elevated strain rates (Fig. 12b). Photographs clearly show that splitting occurs prior to crack growth at elevated strain rates.

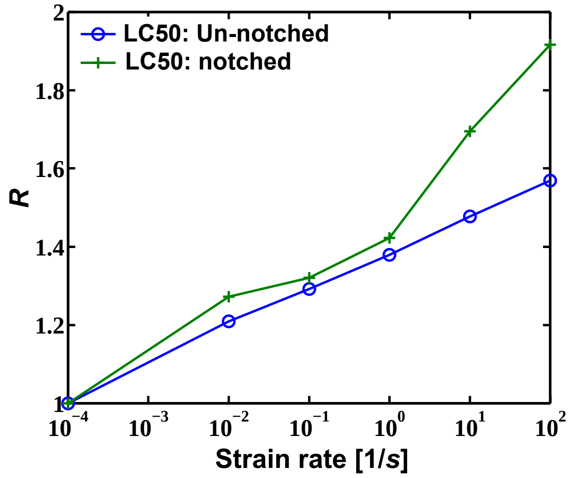

Fig. 10. Strain rate sensitivity of LC50

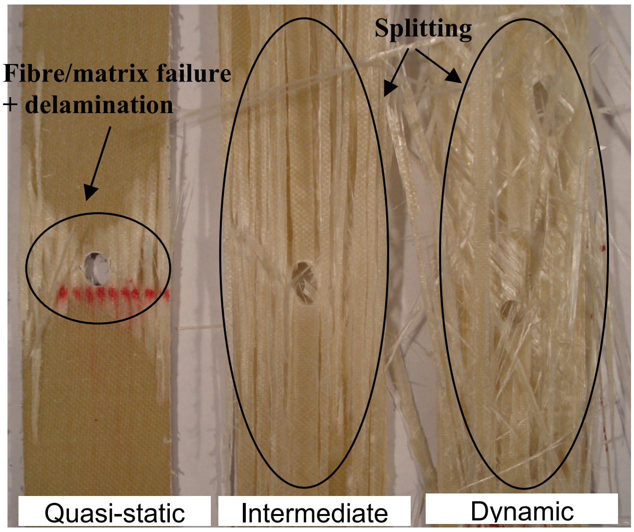

Fig. 11. Post-test photographs of LC50

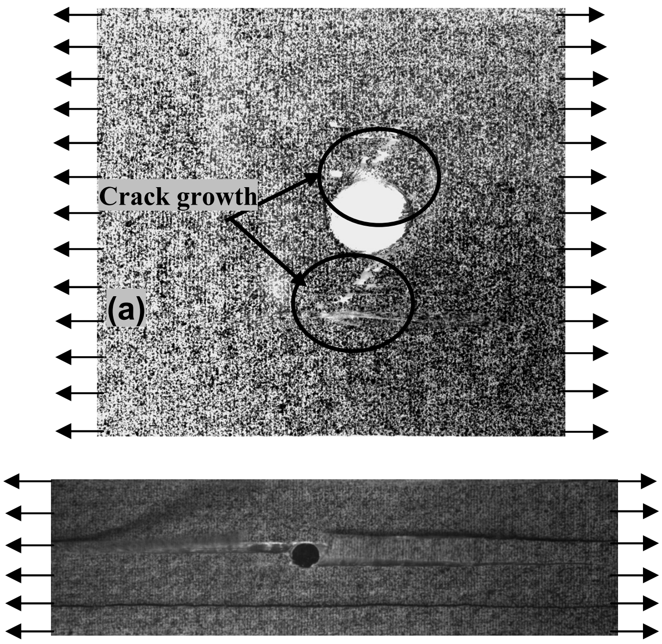

Fig. 12. High speed photography of LC50 showing initiation of failure at different loading rates, (a) quasi-static and (b) intermediate.

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 Fig. 13 and Fig. 14. However, an increase of the damage zone area was observed for LC33. As for LC50, notched laminates with low amount of 0° plies showed higher strain rate sensitivity than the un-notched ones, see Fig. 15 and Fig. 16. For the pure ±45° 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.

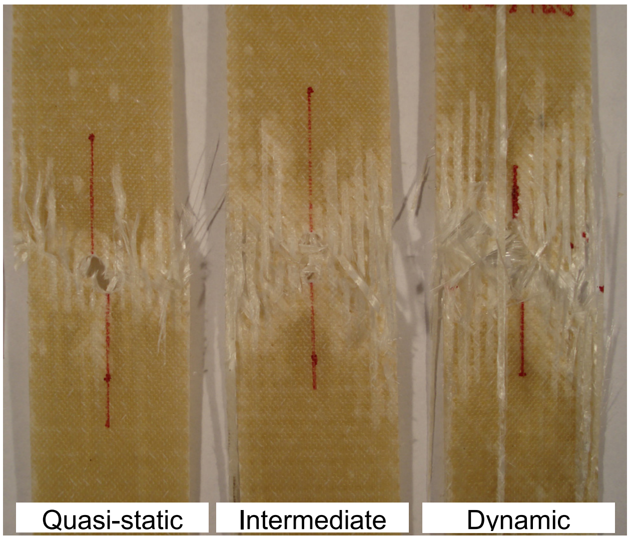

Fig. 13. Post-test photographs of LC33

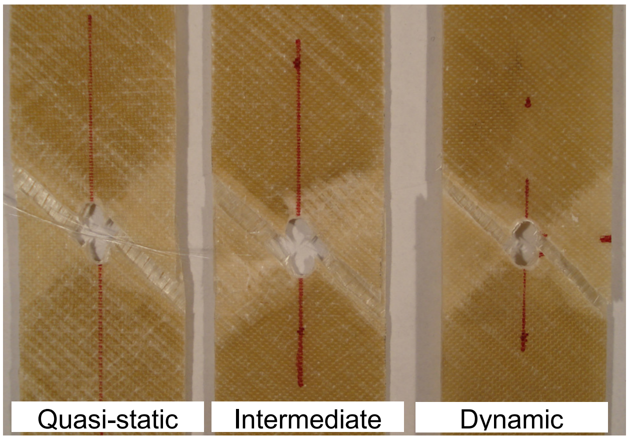

Fig. 14. Post-test photographs of LC0

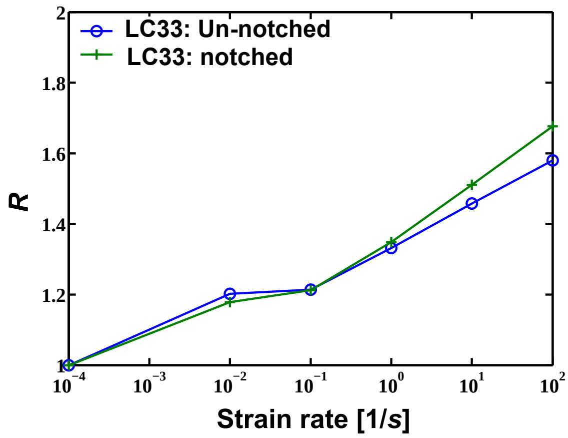

Fig. 15: Strain rate sensitivity of LC33

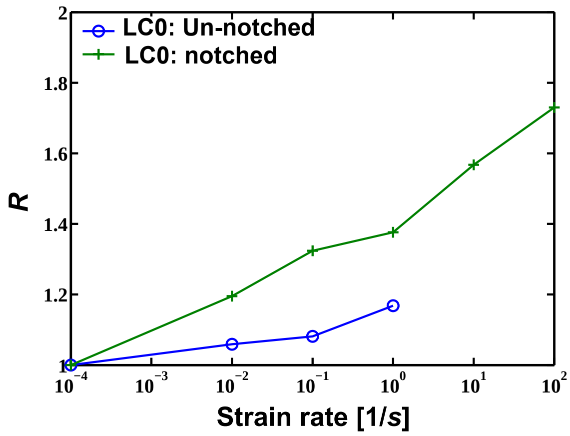

Fig. 16: Strain rate sensitivity of LC0

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 90 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 sensitiveness as function of strain rate is fairly constant for laminates with predominant amount of 0° plies whereas it decreases for laminates with low amounts 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.

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