Effect of milled notches on the strength of open hole, filled holes, single and double lap shear CFRP tension coupons

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Effect of artificial splitting on the static strength of CFRP tension coupons

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Abstract

Splitting is the presence of a long, thin matrix crack observed in laminates stacked with unidirectional plies. The importance of splitting has been highlighted several times in the literature to explain failure scenarios of open and, more rarely, filled hole CFRP coupon specimens. This failure mode also seems to play an important role in the increase of residual strength after fatigue that is sometimes observed in such specimens. In this study, a machining process is used to mill artificial splits at the boundary of holes for open and filled holes, and for single and double lap shear specimens. A significant increase of the quasi-static tensile strength (up to + 20%) is observed in open/ filled hole coupons and for double lap shear specimens. However, for single lap-shear specimens, the results are within the dispersion of the experimental results or lower.

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1. Introduction

When loaded, CFRP laminates made of unidirectional carbon plies have various, coupled failure modes and complex failure scenarios. These phenomena are particularly present during low speed/low energy impacts, which have been widely studied in the literature and are among the most difficult to model [1, 2]. These coupled modes are also present for other types of out-of-plane loading, such as bolt pull-through [3]. Complex failure scenarios also occur during compression or simple tensile tests on coupons [4]. For example, during simple tests in filled hole compression [5] the failure scenario is: delamination at a free edge, propagation of delamination, local buckling, and offset failure. In general, the simple failure modes are coupled and it is important to capture them well to represent the complex failure scenario. Because of this complexity, most academic research has been done under uniaxial tension and compression stresses at coupon scale because few models are able to represent these scenarios correctly, even though studies on technological specimens have recently started to be carried out with the discrete ply model “DPM” approach [6, 7].

Among the elementary modes, splitting has held the attention of researchers for a long time in static [8-12] or in fatigue [13-21] loading and this mode is shown in Fig. 1. In this figure, we have voluntarily chosen to show prolonged, extremely fine matrix cracks, which occur in many rupture scenarios but which have been more particularly studied in the case of center notched or open hole coupons. As shown in Figure 1, this type of splitting develops in the direction of the 0° plies and is initiated at the tip of the geometric singularity. If, as in many cases, the matrix cracking at the edge of the hole is more diffuse, this crack geometry favors the reduction of the local stress concentration at the edge of the singularity. This effect has been identified from an experimental point of view by many authors [8-21] and demonstrated by a test-calculation dialogue using different, mostly discrete, modeling strategies [22-29]. This explains the interest in this type of fatigue damage, which, in some cases, would allow an increase in residual resistance [13-21]. In addition, it has been shown [27] that, depending on the position of the plies in the thickness, this type of damage is favored and consequently the static resistance can be improved by about 10%. This type of damage is also important in explaining the scale effects observed on open hole specimens [29-31].

In this paper, we propose experiments that push the logic of splitting, by making artificial splits at the edge of the hole using a diamond cutter and observing their influence on the static tensile strength.

2. Materials and Methods

The specimens were stacked with IMA/M21E unidirectional plies. The two types of stacking used were:

- Oriented [-45/0/0/45/0/90/45/-45/90/0/45/0/0/-45] (average thickness 2.6 mm)
- Quasi-isotropic $[0/45/90/-45]_{2s}$ (average thickness 2.1 mm)

Several types of tensile specimens were used and were tested on an INSTRON 4206 electromechanical quasi-static testing machine with a of capacity ± 100 kN at a speed of 1 mm.min-1. The 6 types of test specimens were the following:

Open-Hole and Filled-hole:

These specimens were 25 mm wide and had a 4.2 mm diameter hole in their center (see Fig 2 (a)). The quality of machining was ensured by the use of a dedicated carbide tool and by placing sacrificed plates on either side of the laminate in order to limit the damage generated at the entrance and exit of the hole (particularly delamination at the end of the drill) [32]. The drilling process was validated by checking that X-ray images of the holes revealed no delamination or cracking at the edge of the hole. For filled hole specimens, the bolt (see Fig 2 (b)) was installed according to the following parameters: screws and nuts following aeronautic standards (Imperial size fasteners: IVD (ion vapor deposited) coated quenched and tempered Titanium bolts and frangible cadmium plated steel nuts) low clearance; tightening torque imposed by the fuse nut ≈ 2.3 N.m

Open and Filled-hole with Artificial Splitting:

Four notches were machined tangent to the hole, two on either side of the laminate () (Fig. 3). The notches were oriented parallel to the loading direction. The cutting tool was a diamond disc with a diameter of 20 mm and a thickness of 0.6 mm. The notches were characterized by their length, width and depth. Several geometries (depth and length) were tested and will be specified later.

Single-lap shear and double-lap-shear reference specimens:

The specimens are shown Fig.4. It comprises:

- 4 Bolts and nuts following aeronautic standards installed without sealant and no treatment applied to the surfaces, low clearance.
- Two specimen widths: 25 mm and 16 mm for two different failure modes (combined bearing / pull-through and net tension failure, respectively, see Fig. 4).

Notched single-lap and double lap-shear:

The overall geometry of these specimens was identical to that of "single-lap shear" ones. The machining process was modified in order to achieve unidirectional notches and thus avoid weakening the bearing resistance of the holes. The process was then more complex and required the use of carbide milling cutters of very small diameter (1 mm) to generate the notches tangent to the hole. The cutting parameters were: cutting speed 84 $m.min^{-1}$ and feed per tooth 260 $mm.min^{-1}$. Several configurations were tested for each width and for each lay-up (18 test pieces). The precise configurations tested (and the acronyms chosen to represent them) were the following:

- Notches on the outer face of each half-part of the specimen and only on one side of the hole (code SL-O).
    - ➢ All the holes concerned (code SL-O-A), (see Fig 5 (a) and (b)).

  - Only the one hole concerned (code SL-O-E) corresponding to the most loaded (external one)

- Notches on both sides of each half-specimen (ext. and int.) of the specimen (code SL-OI)
  - All the holes concerned (code SL-OI-A)
  - Notches as for open and filled hole, symmetrical with respect to the most loaded hole and made on both sides of each half-specimen (SL-OI-E-D), only for symmetrical layup 2 (see Fig 5 (c))
- For notched double-lap shear specimens (2 specimens only), the overall geometry of these specimens is identical to the unnotched specimens and the geometry and location of the notches is identical to single lap shear specimens SL-OI-E-D (see Fig 5 (c)). The code for these specimens is DL-NCS.

Matrix of tests.

The matrix of tests (incomplete for practical industrial reasons due to the exploratory nature of this study) is given in Table 1 with the number of specimens tested.

Measurement method:

The strain was measured using an INSTRON 2620-201 dynamic extensometer +/- 5mm. The extensometer was fixed directly to the surface of the test piece, according to the plane of the test piece and on either side of the hole (Fig. 7). The strain values were recorded by a dynamic acquisition system independent of the machine's electronic card.

3. Results for Oriented specimens

3.1 Open hole and filled hole

Three non-machined specimens were tested and the results showed low dispersion (average ultimate breaking: 1060 Mpa). Figure 7 shows the tensile test results of the 4 notched test pieces vs an open hole test and Table 2 gives the geometry of the 4 different notches, with the gains obtained. The failure patterns are not provided in this paper but they differed little according to whether notches were present or not and were similar to those presented in [27]. Tests showed that the process made it possible to obtain significant gains in tension. These gains were greatest when the notch was long and deep. The loss of modulus was practically constant and limited for all the notch geometries tested (from -8% to -10%). A particular behavior was observed when the "notched 15 * 0.9 mm" test piece was tested. Its initial modulus was identical to that of the other "notched" test specimens but it quickly became non-linear (≈ 40% σ_{max}) and a significant jump in the measured strain was observed. This specimen presented the largest notches and the failure scenario was affected early but the gain remained significant (+ 20%).

Figure 8 shows the test results for test specimens with or without 5 * 0.9 mm notches, filled or not. A drop can be observed in the static strength of the filled specimen. In order to understand how the insertion of the fixation caused the decrease in this behavior of the specimens, an additional test was carried out: a bolt was installed on a test piece but without a tightening nut (nut not accosted) in order to prevent any preloading of the screw during the test. The static behavior of the test piece then returned to that of an open hole specimen. At first glance, the reduction observed on the filled hole coupon appeared to come from the compression (σ_{33}) of the area located under the screw head or the nut. This result is in agreement with the results of [32], which show a decrease in splitting tangent to the hole when the applied preload increases. Note the excellent resistance of the "notched" test specimens compared to that of their counterparts that were simply drilled. It is likely that the machining compensated for the closure of the splitting due to tightening. It is interesting to note that, for the notched specimens, the modulus was almost identical whether the test piece was filled or not, whereas it was different without the notches.

3.2 Single lap shear specimens

After having carried out a series of tests on tensile test pieces, the objective here was to find out if the increase in strength with artificial splitting could be observed within bolted assemblies. It is recalled that two widths of test pieces were considered in order to vary the failure modes (W = 25 mm and W = 16 mm). With this layup we observed significant dispersion concerning the moduli and the overall monotonous behavior (Figs. 9 and 10). The net stress (in the section of the hole) at failure was close to 640 MPa when W = 25 mm and close to 910 MPa when W = 16 mm. Also, only the MIN-MAX behaviors observed were plotted in these two cases. The overall failure of the non-notched test pieces occurred according to the modes expected by the width pre-sizing and was similar to that of test pieces with notches (Fig 11). The two failure modes observed were as follows:

- Failure in net section of the last row of fasteners + shear-out for the W = 16 mm specimens. Failure occurred randomly in the fixed or mobile half-specimen. Regarding the shear-out, the 0° fiber bands were not tangent to the hole but approximately in the middle of the net section (Fig 11 right).
- Pull-through failure and bearing of the four fasteners for the specimen that was 25 mm wide (Fig 11 left).

The notch process did not work on this configuration with oriented stacking. This remark is valid for both widths considered. The least notched test pieces (SL-O-E & SL-O-A) showed no apparent variation in their mechanical characteristics (Figs. 9 and 10) (results within the dispersion of the test). In addition, the specimen having notches on each side of the half test pieces (SL-IO-A) underwent a strength decrease, its bearing ability being weaker. For this layup, the "double-notched" configuration was not tested.

4. Results for Quasi-Isotropic specimens

4.1 Notched open hole

The behavior of the open hole reference specimens was almost linear up to the maximum load, with little dispersion. A small plateau was observed before the final brutal rupture. The average value at breaking was 710 MPa. All the configurations of notches gave a significant gain (see Table 3). The results show that the traction gains were greater when the notch was deep (+ 21.8%). In this last case, the loss of modulus was only -7.5%.

4.2 Notched single lap-shear specimens

For the reference specimens, the dispersion appeared to be very low during these tests. The failure stress (in net section) was close to 655 MPa when W = 25 mm and close to 670 MPa when W = 16 mm. The MIN-MAX behaviors noted on the test specimens are plotted in Figs. 12 and 13. The test pieces failed in the net section of the last fastener in the row (section bearing the most stresses σ_{11}).

Unlike those with oriented stacking, the quasi-isotropic specimens showed no bearing or pull-through breakages. The failure started at the edge of the hole and propagated at ± 45°. In addition, significant and constant shear-out of the outer ply at 0° was observed, which stopped tangentially at the head of the screw or the nut (Fig. 14).

It was observed that the notch process did not work on this configuration with quasi-iso layups either. This remark is valid for the two widths considered. The least notched test pieces (SL-O-E & SL-O-A) showed no apparent variation in their mechanical characteristics (results within the dispersion of the test). In addition, the test piece having notches on each side of the half test pieces (SL-IO-A) underwent a strength decrease, its bearing ability being weaker.

In the study of this layup, we were able to test the "double-notched / SL-OI-E-D" configuration. The process did not work at all on test pieces of width W = 25 mm, the resistance to bearing / pull-through then being very low (Figs. 12 and 13). On the other hand, on the test pieces of width W = 16 mm, no variation in the tensile strength was observed (values within the dispersion of the test) (Figs. 12 and 13).

The overall failure of the assemblies occurred in the net section of the last hole (the most loaded section). For the notched specimens (SL-OE / SL-OA / SL-OI-A), no bearing or pull-through failure was observed and the failure began at the edge of the hole then propagated to the free edge with an angle of ± 45°. Shear-out of the ply at 0° occurred on the surface (Figure 14).

Concerning the "double notched" test pieces (SL-OI-E-D), failure occurred (Fig. 15):

- in net section, propagation at ± 45° from the edge of the hole with shear-out of the ply at 0° on the surface for specimens W = 16mm.
  in bearing with a sudden ejection of a fastener for specimens W = 25mm.

4.3 Notched double lap-shear specimens

For the reference specimens, the dispersion appeared to be very low during these tests. The failure stress (in net section) was close to 684 MPa when W = 25 mm and close to 661 MPa when W = 16 mm. The MIN-MAX behaviors noted on the test specimens are plotted in Figs. 16 and 17.

The notch process works very well on this configuration and very significant increase (+22.5 %) in the tensile strength for W = 16 mm and +4.5 % for W=25 mm are observed. The failure modes also vary slightly between the reference and "notched" test pieces (Fig. 18). The overall failure of the assembly occurs in net clean section of the last hole of the half-specimen in all cases. However, there is no shear-out of the 0 ° ply outside the central half-specimen of the "notched" test pieces. In addition, the failure of the "notched" specimens occurs clearly with a propagation at ± 45 ° from the edge of the hole while the failure of the reference specimen is more complex, with a failure pattern with "V" shape. The increase in strength observed in this case is clearly due to the absence of secondary bending and to pure bearing stresses.

5. Conclusions

An original and explorary study was carried out on the effect of artificial splitting with notches machined at the edge of the hole for 2 layups: oriented and quasi-isotropic, and 4 specimen geometries: open/filled holes and single/double lap shear specimen. A significant increase in static tensile strength was observed for open, filled hole and double lap shear specimens with notches (up to + 20%). This confirms the generally beneficial effect of splitting on the static resistance and it could be implemented either through stacking sequences that naturally favor it in fatigue or directly by means of the recommended machining, which has been patented by Airbus [34]. The methodology could be used to improve the resistance of a load-bearing structure loaded in a main direction, on which other substructures transmitting less stress could be fixed, or for secondary structures. The notch process was not effective in single lap shear tests with 4 fasteners despite the large number of machining variants tested. In some cases, it even decreased the strength of the assembly, which limits the scope of the innovation. Even if this first study must be confirmed by more extensive testing, this study is of scientific interest as it shows, once again, the very particular structural behavior of composites, even from coupon scale.

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Figures

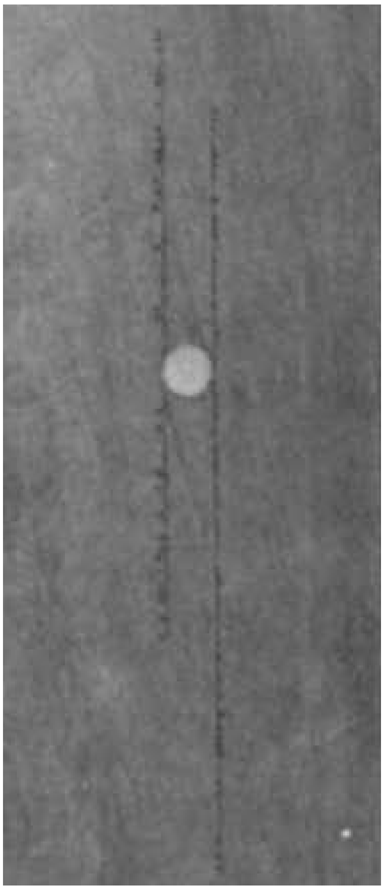
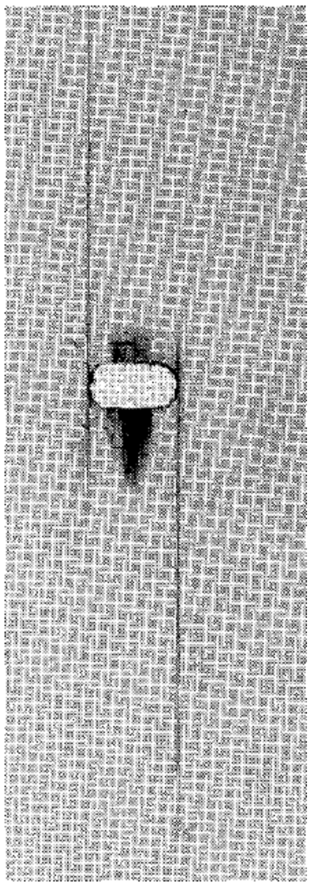
(a)  (b) 

Fig. 1: Example of splitting around open hole ((a) reproduced from [13]) or notch ((b) reproduced from [8]).

(a)  (b) 

Fig. 2: Open Hole specimen (a) and bolt and nuts used for Filled hole specimens (b).

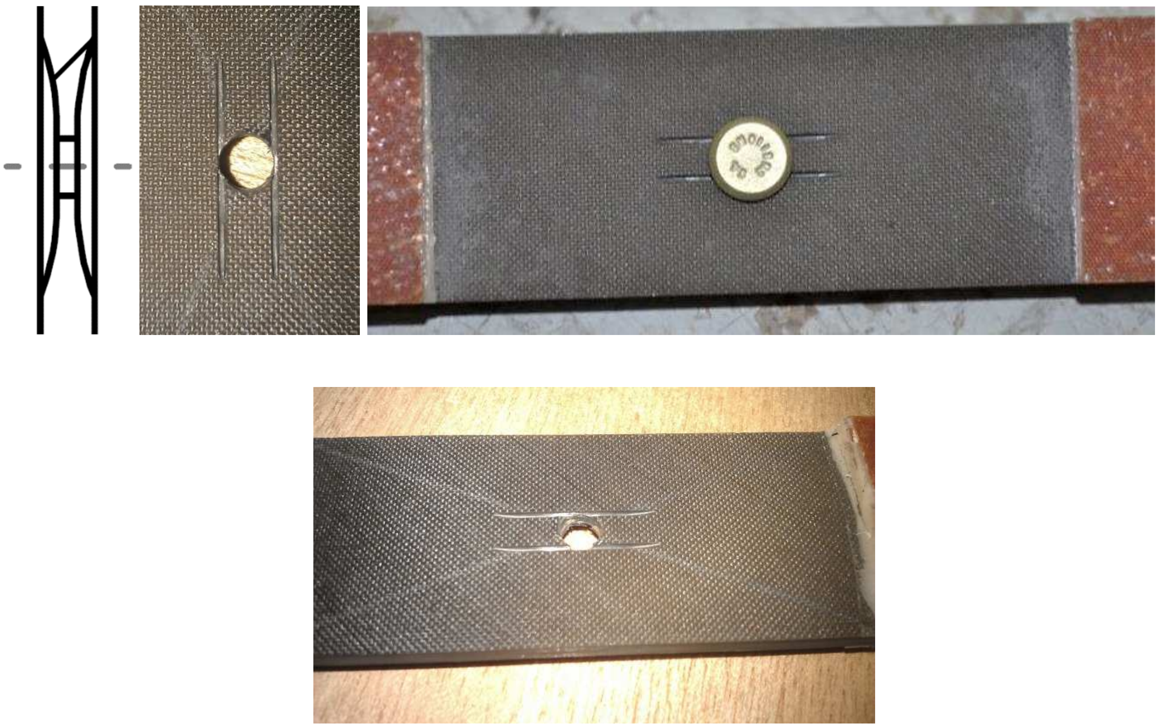


Fig. 3: Zoom on the artificial splitting.

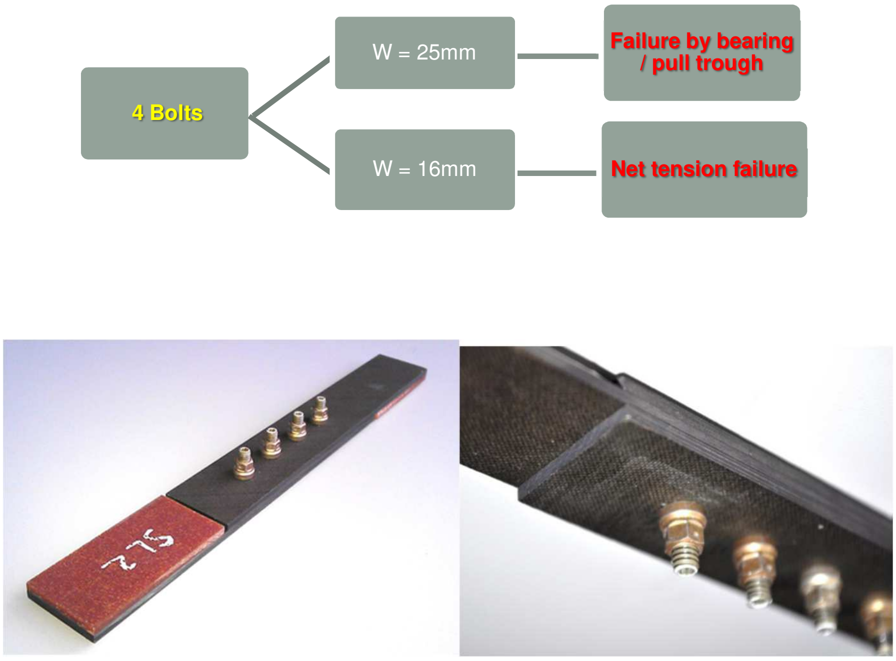


Fig. 4: Failure mode prediction and single-lap and double-lap shear specimen.

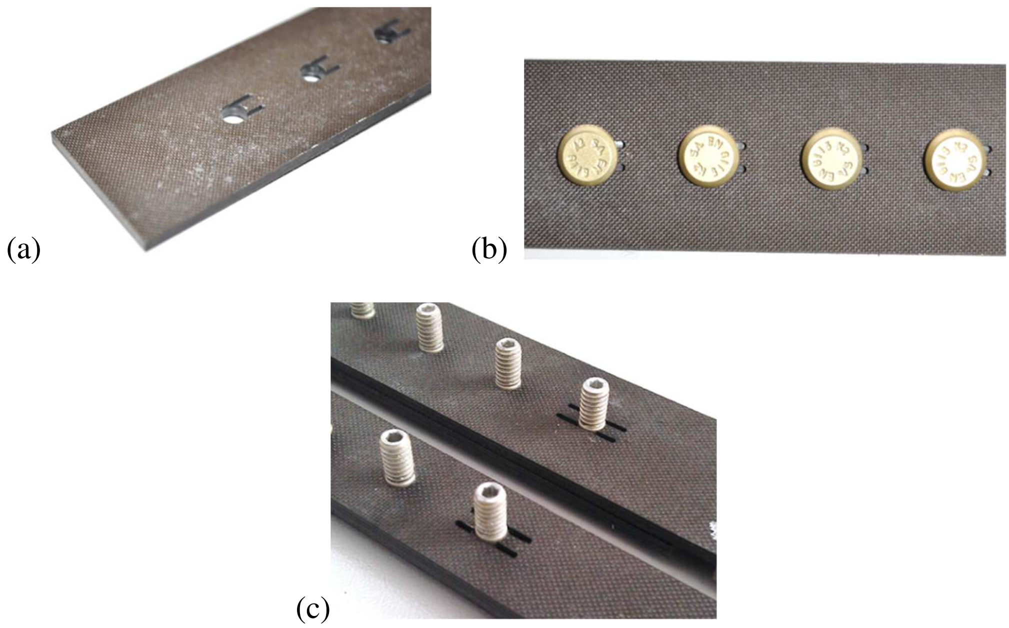


Fig. 5: Half specimen notched on one side (a) and (b) (Code SL-O-A); all holes concerned and symmetric notches on the most loaded hole (Code SL-OI-E-D).

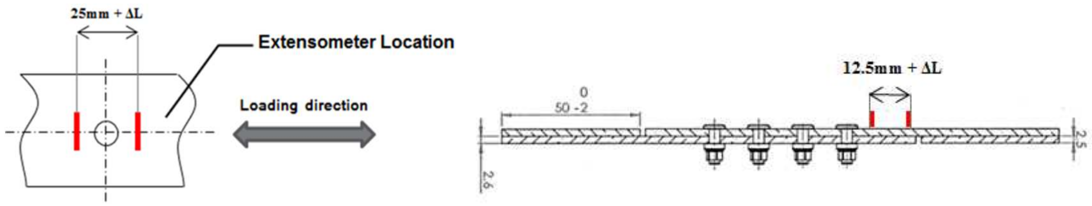


Fig. 6: Location of extensometer for coupons of single and double lap shear specimens.

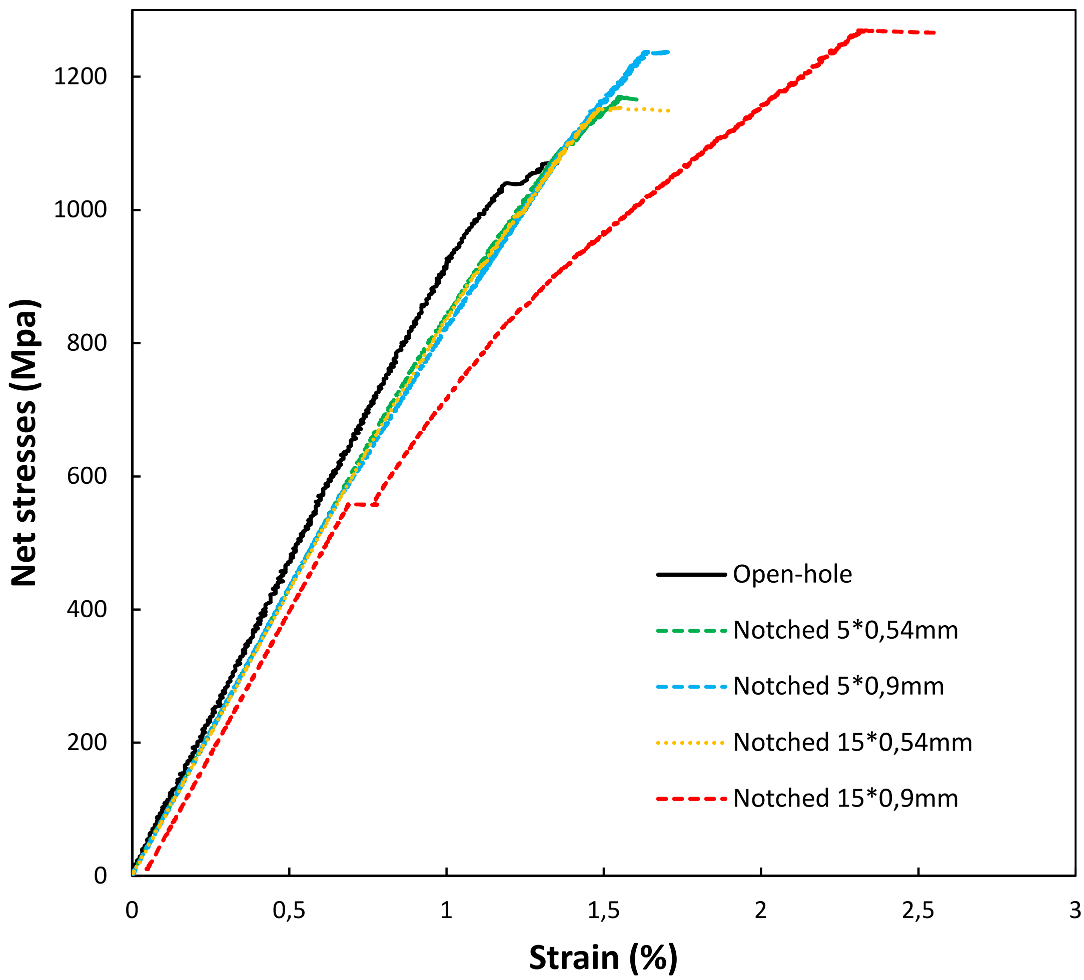


Fig. 7: Tension tests results for open hole specimen with and without different notches (oriented layup).

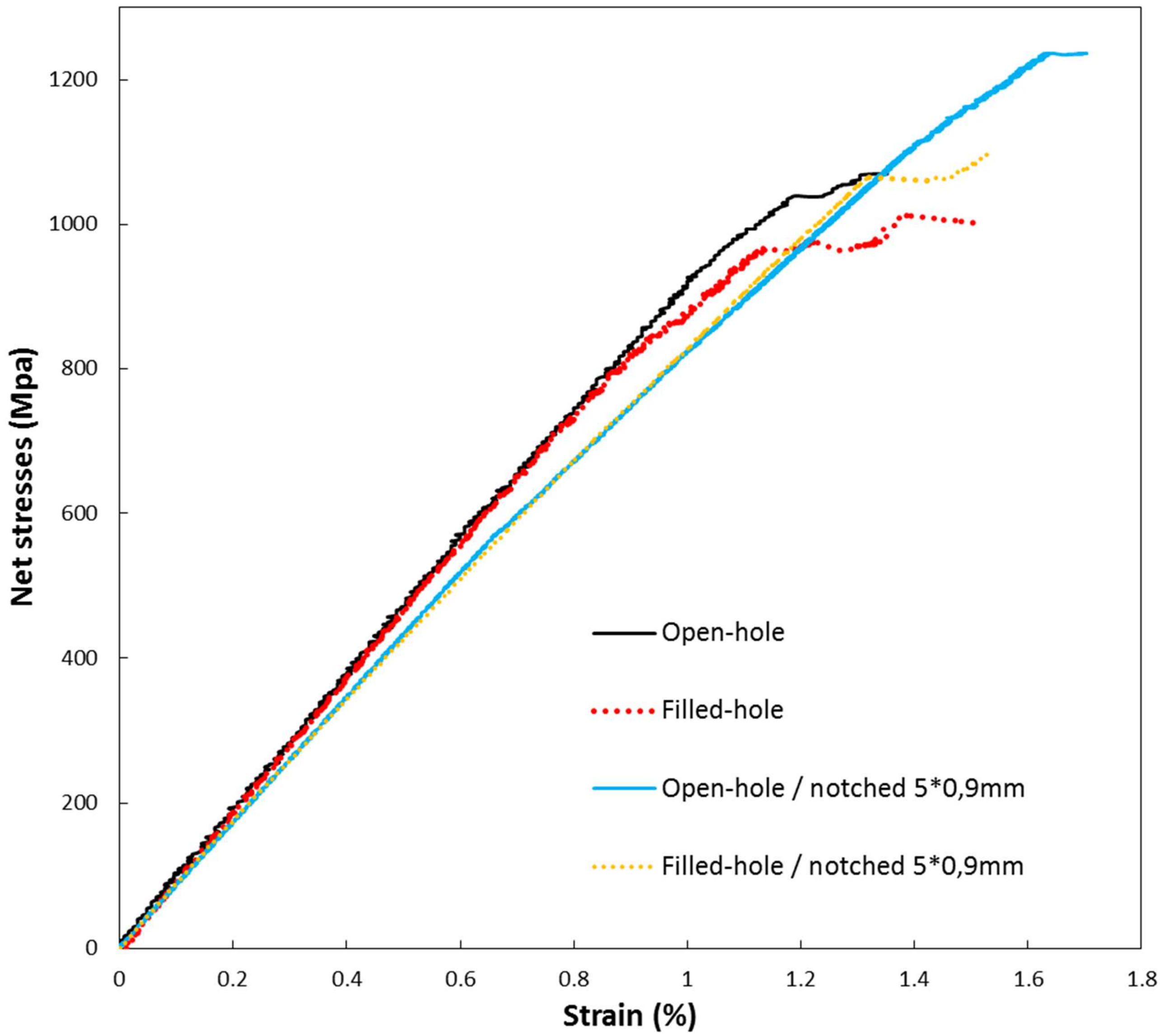


Fig. 8: Tension test results for open and filled hole specimens with and without notches 5*0.9 mm (oriented layup).

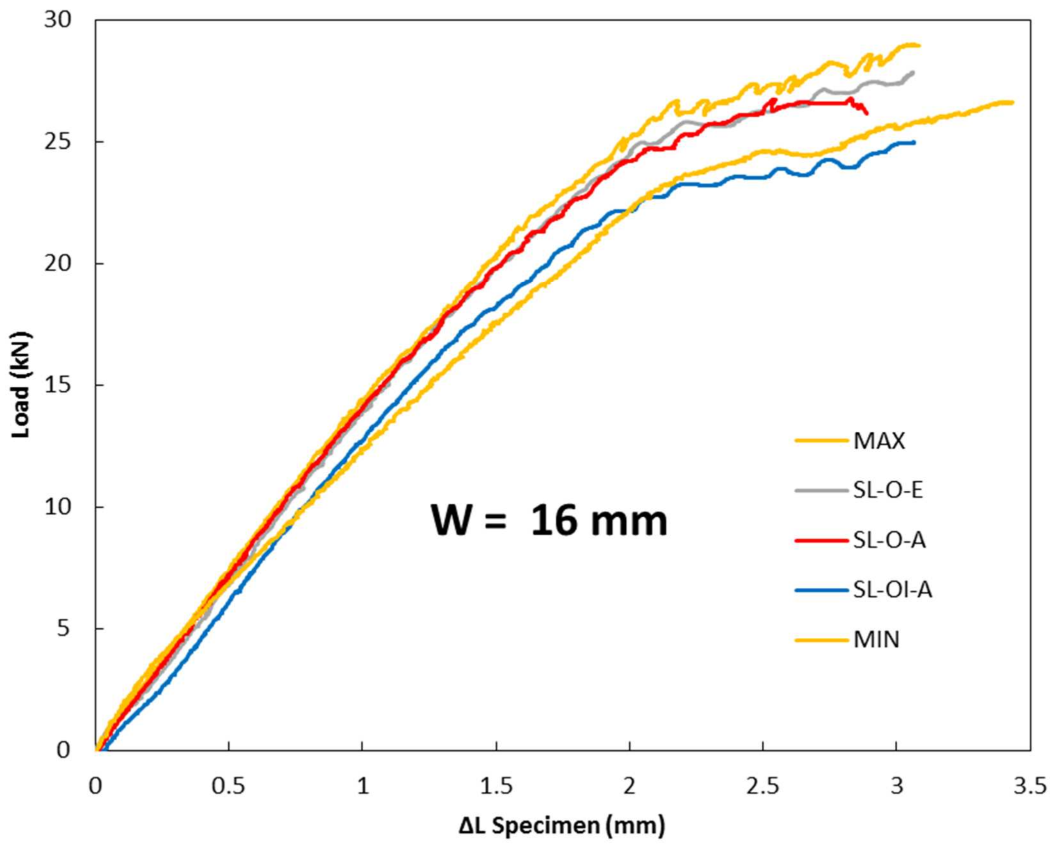


Fig. 9: Tension test results for single-lap shear specimens (W = 16 mm), (oriented layup).

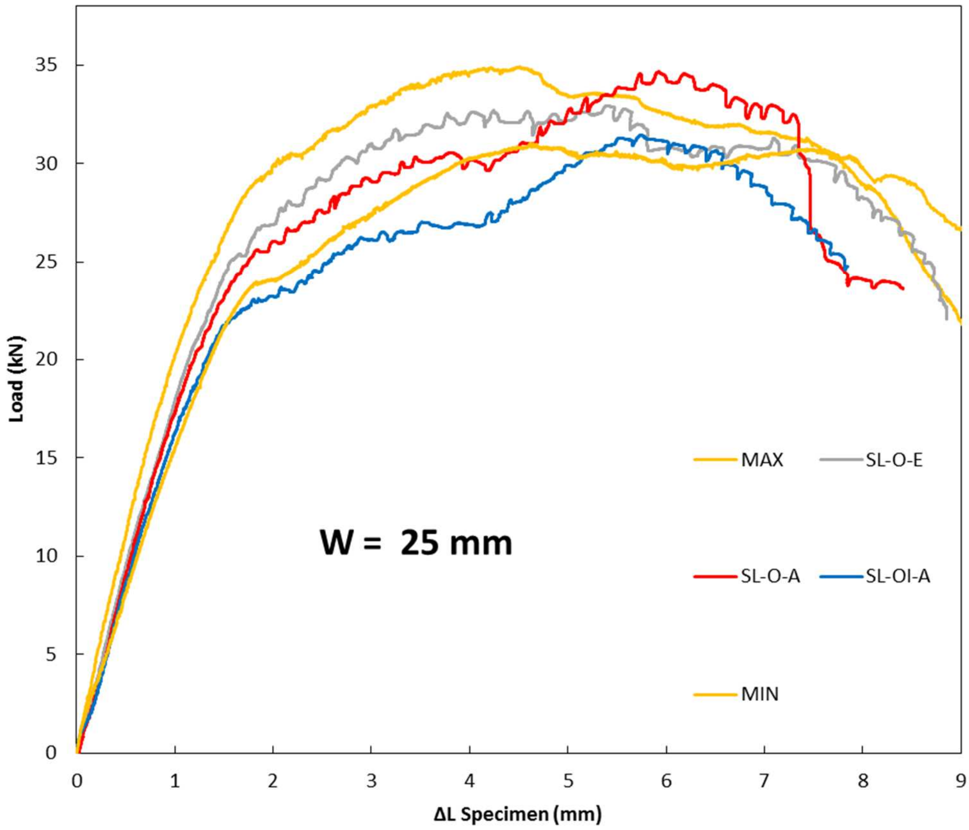


Fig. 10: Tension test results for single-lap shear specimens (W = 25 mm), (oriented layup).

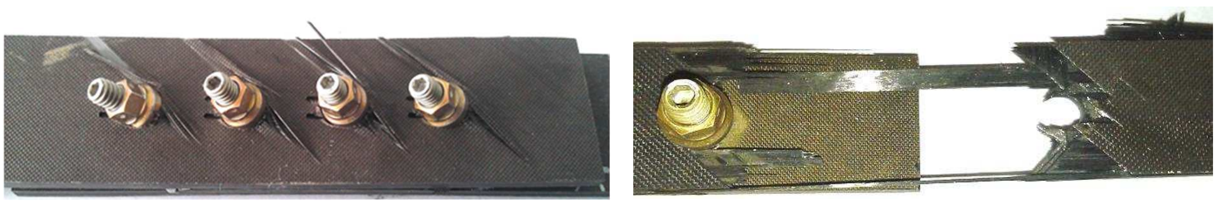


Fig. 11: Failure Patterns of “notched” single lap shear specimens. Left, W = 25; right W = 16 (oriented layup).

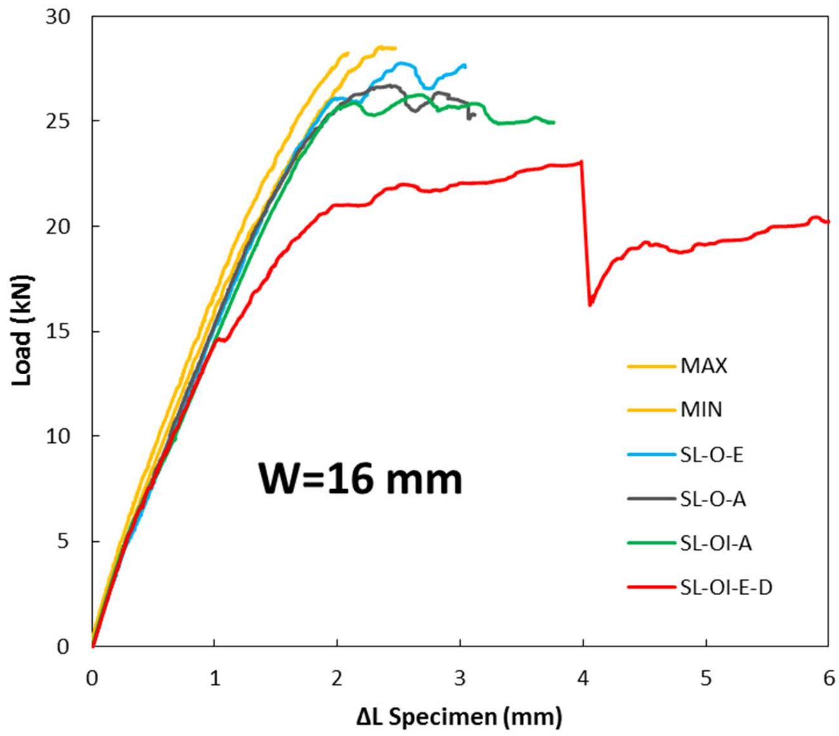


Fig. 12: Tension test results for single-lap shear specimens (W = 16 mm), quasi-isotropic layup.

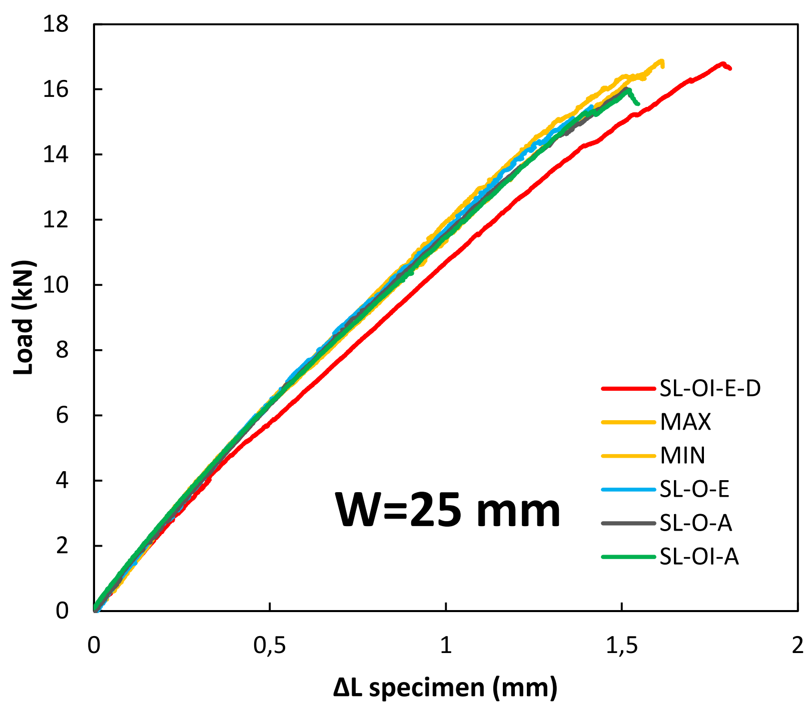
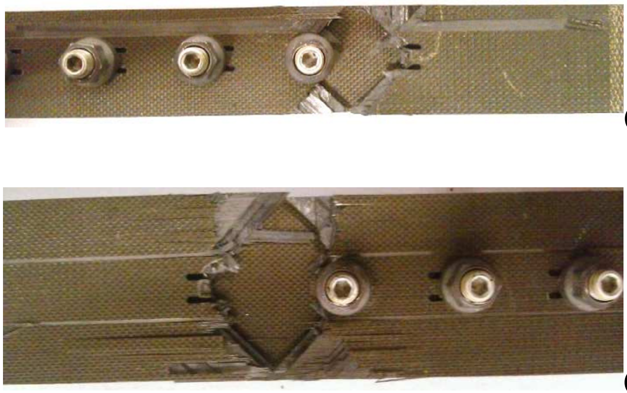


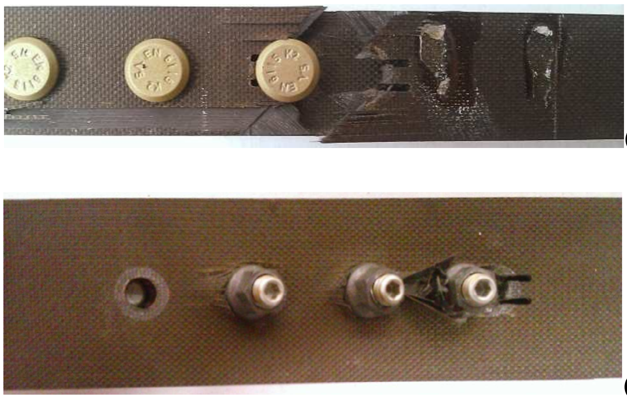
Fig. 13: Tension tests results for single-lap shear specimens (W = 25 mm), quasi-isotropic layup.



(a)

(b)

Figure 14. Failure modes of SL-O-A specimens W=16 mm (a) and W=25 mm (b), quasi-isotropic layup.



(a)

(b)

Figure 15. Failure pattern of SL-OI-E-D specimens W = 16 mm (a) and W = 25 mm (b), quasi-isotropic layup.

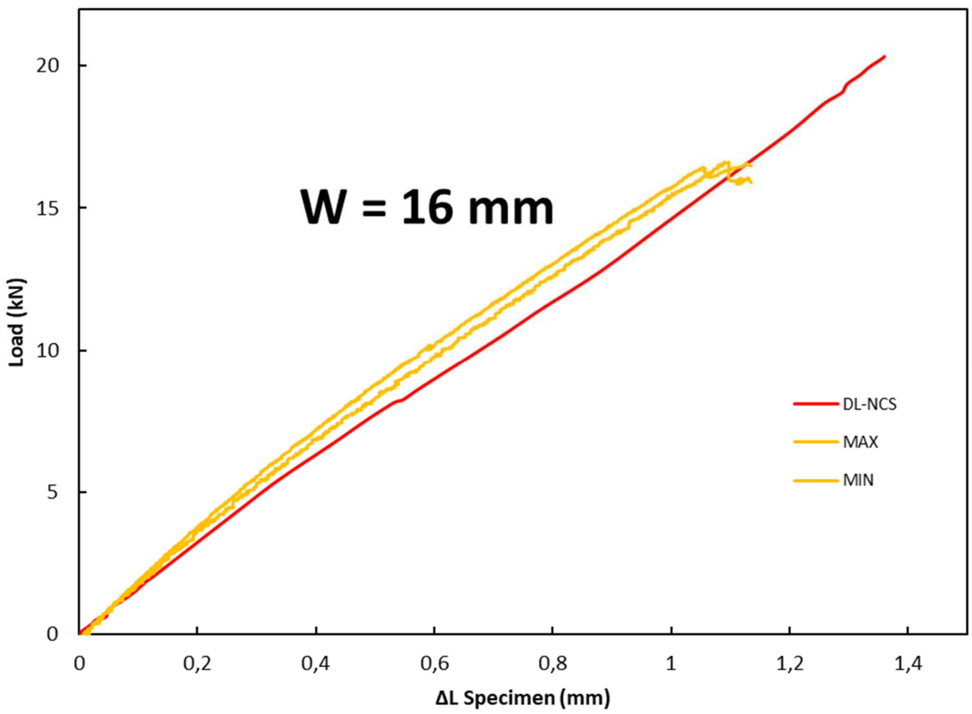


Fig. 16: Tension test results for double-lap shear specimens (W = 16 mm), quasi-isotropic layup.

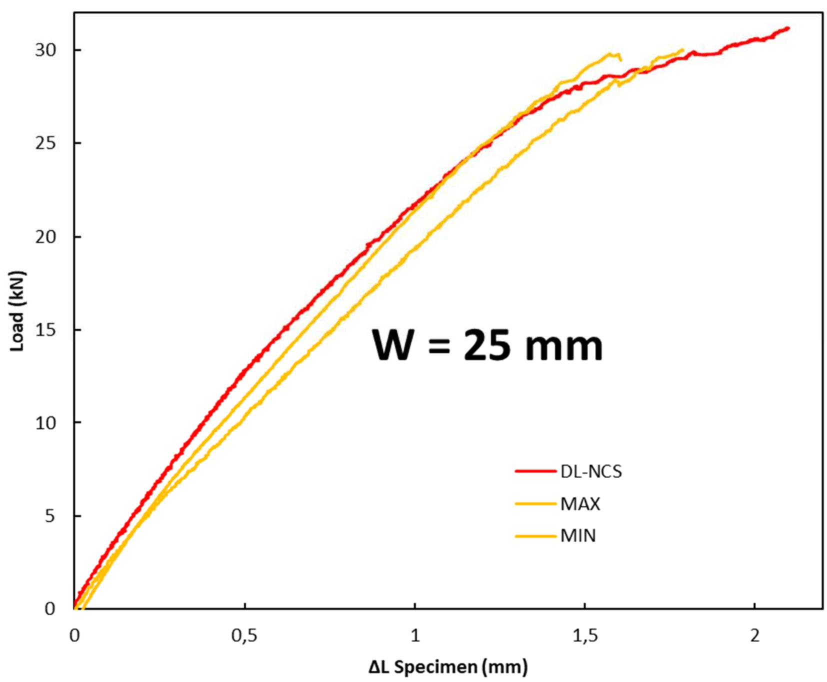
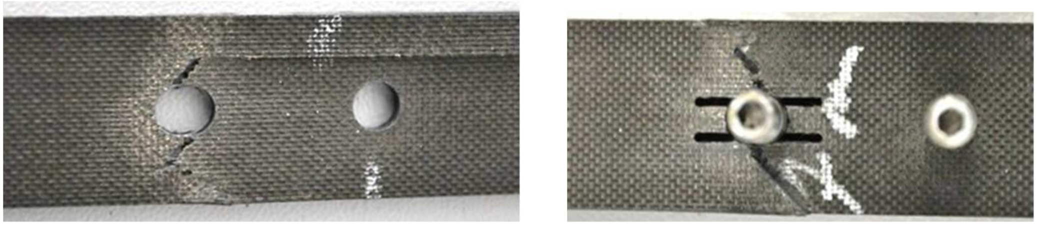
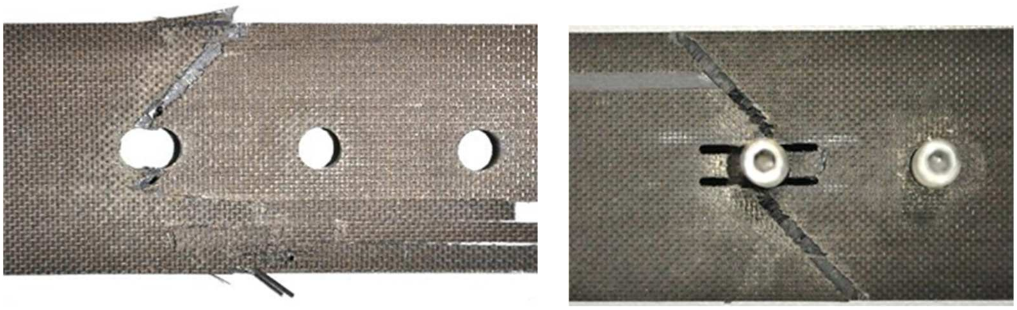


Fig. 17: Tension tests results for double-lap shear specimens (W = 25 mm), quasi-isotropic layup.



W= 16 mm



W = 25 mm

Figure 18. Failure mode patterns for double lap shear specimens: reference specimens (left) and notched specimens (right); W=16mm (upper) & W=25mm (lower)

Tables

	Oriented	Quasi-Isotropic
Reference Open Hole	3	3
Reference Filled Hole	3	3
Notched Open Hole	4	3
Notched Filled Hole	1	0
Reference Single Lap Shear	3	3
Notched Single Lap Shear	6	6
Reference Double Lap Shear	0	6
Notched Double Lap Shear	0	2

Table 1: Matrix of tests.

Notch length	5		15	
Notch depth	0.54	0.9	0.54	0.9
Max Stress	1169	1237	1153	1270
Gain (%)	**10**	**17**	**9**	**20**

Table 2: Geometry of notches and static gains.

Notched specimens

Length (mm)		5	
Depth (mm)	0.65	0.65	1
Net max stress (Mpa)	781.4	745.6	863.7
Gain (%)(/open-hole)	+10.1	+5.1	+21.8
Longitudinal modulus (Gpa)	511	506	498
Variation in modulus (%) (/open-hole)	-5	-6	-7.5

Table 3: Results for Notched open-hole specimen, Quasi-iso stacking.