INVESTIGATION OF DAMAGE MECHANISMS IN 3D INTERLOCK TEXTILE COMPOSITES UNDER LOW VELOCITY SOFT IMPACT LOADING

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Abstract

Performances of a three-dimensional (3-D) woven composites subjected to impact loading are investigated in this study. Low velocity (lower than 10 m.s-1) impacts with largely deformable rubber impactors are adressed. Variability issues by performing repeated impact tests in the same conditions and the mass velocity effect on damage tolerance by varying the impact conditions are the main points of interest. Force-time and force-displacement curves and damage mechanisms observed on micrographies are particularly commented.

1 Introduction

Composite materials are increasingly being used for primary aircraft components because of their superior structural performance such as high strength, high stiffness, long fatigue life, and light weight. These structures are prone to impact loading during their service life. Conventional laminated composite have fibres only oriented in the plane of the laminate and are therefore vulnerable to delamination during impact. Three-dimensional (3-D) woven composites offer a better delamination resistance and damage tolerance because of through-the-thickness yarns. Therefore, interest for using 3-D woven composites for aircraft applications is growing. Several studies have already shown that 3-D woven composites have superior impact performance than 2-D laminates [1].

The current study focuses on a special kind of 3-D woven composite called 3-D interlock woven composite. Some authors have already studied interlock composites behaviour under high velocity ballistic impact [2]. However, impact can be of many different types. Impact can be caused for example by a bird or a runaway debris strike, a tool drop or by hail. Therefore, impact can be of low or high velocity and the impactor hard, soft or fragmentable. The impacted structure will behave differently dependently of the impact nature. In this work, the behaviour of a 3-D interlock woven composite under low velocity impacts (lower than 10 m.s-1) with largely deformable rubber impactors, also called soft impactors, will be studied. Such characteristics may correspond to a tire debris impact on an aircraft composite part for instance; it is complementary to high velocity impact of soft body such as birds [3-4]. Understanding of the damage mechanisms is the main purpose of this study. This work follows on an investigation performed within the research project VULCOMP on VULnerability of COMPosite Structures (2007-2010), which partly addressed the impact performance of different 3-D interlock carbon woven composites. The investigation which was both experimental and numerical [5-6] showed that the major damage mechanisms were yarn decohesion, matrix cracks and few yarn ruptures mainly located at the back side of the composite plate. The higher the ratio of through-the-thickness warp yarns to straight warp yarns is in the composite, the higher the impact resistance is. However, the lower the in-plane properties are. This work will focus on the impact behaviour of one single type of 3-D interlock carbon woven composites. Variability issues will be investigated by performing repeated impact tests in the same conditions and the mass velocity effect on damage tolerance will be studied by varying the impact conditions. First, the materials used for the impactor and the composite plate are described. Then, the experimental set-up is explained. Next, the variability study is presented and the results are analysed. Finally, the experimental results obtained for the mass velocity effect study are discussed. Force-time and force-displacement curves and damage mechanisms observed on micrographies are particularly commented.

2 Materials

2.1 Rubber impactor

The impactor is made from Styrene-Butadiene-Styrene (SBS) rubber which is a hard and durable rubber material typically used for aircraft tires or shoe soles. A SBS rubber impactor with a shore A hardness (SHA) [7] of SHA-60 was selected and especially manufactured for this study. As shown in Figure 1, the impactor was selected to have a simple regular and hemispherical shape in order to reduce the complexity of this study. The diameter of the impactor is Φ=70 mm. The hemispherical piece of rubber was bonded during the process to a steel cylinder. A steel screw part allows the fixation of an additional part including the force sensor. Finally, the impactor instrumented with the force sensor is fixed on a carriage to constitute the full mass.

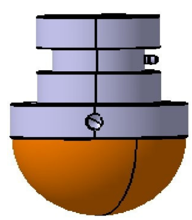


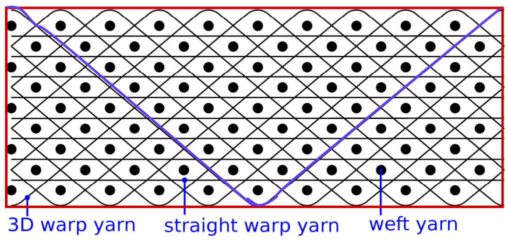
Figure 1. Hemispheric rubber impactor

It is known that the Mullins effect [8] may induce a change in the behaviour of newly manufactured rubber during the first tests. To prevent this effect from occurring, ten quasi-static compression cycles with a maximum load of 20 kN were performed on the rubber impactor. Besides, the hyper-elastic behaviour of the impactor was assessed in [6].

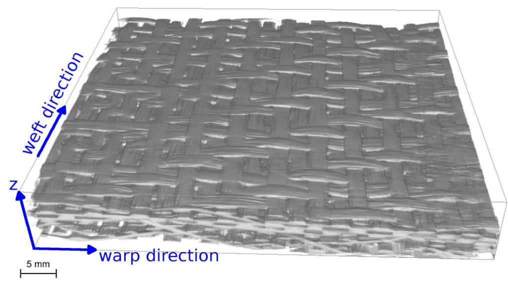
2.2 Interlock 3X woven composite target

Impact tests were performed on an interlock 3X woven composite plate. The fabric was composed of warp weaver (or 3D warp) yarns, stuffer (or straight warp) yarns and filler (or weft) yarns as depicted in Figure 2. The ratio of 3D (deviated) warp yarns to straight warp yarns was equal to 55%. Both the warp and the weft yarns were manufactured with carbon HR Tenax-E HTS40 F13 12K 10Z yarns. The areal density of interlock 3X is 2720 g/m^2.
The interlock 3X woven fabric was processed by Resin Transfer Moulding (RTM) using a RTM6 epoxy resin. The resin was injected at 120° C and the composite plate was cured at

160° C. The thickness of the interlock fabrics dryness is 10 mm thickness before injection whereas the final thickness of the plates is 2.7 mm. The useful dimensions of the plates issued from the RTM process are 500 mm x 500 mm. Figure 3 illustrates the cross section of the composite along the weft and the warp directions. The representative unit cell is represented by the rectangle. One can estimate that the unit cell has a thickness of 2.7 mm, a length of about 50 mm in the warp direction, and a width of about 10 mm in the weft direction.

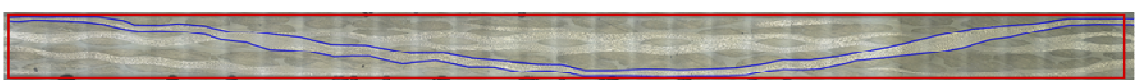


a) Diagram of the cross section unit cell

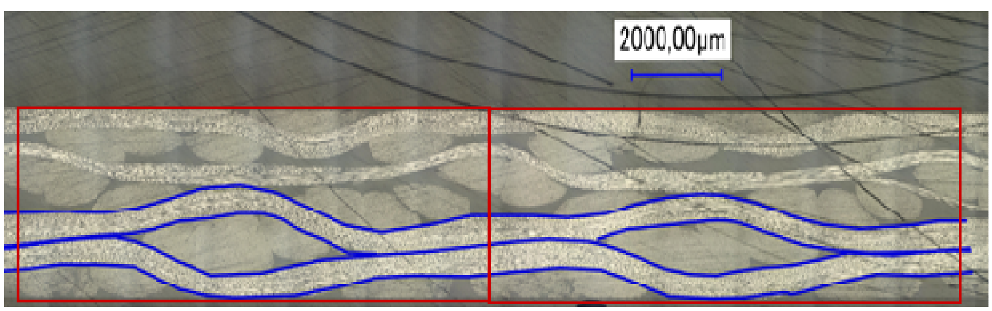


b) Micro-CT scan

Figure 2 3D interlock 3X 55% woven composite



a) Along the warp direction



b) Along the weft direction

Figure 3 Micrographs of the 3D interlock 3X 55% woven composite cross section

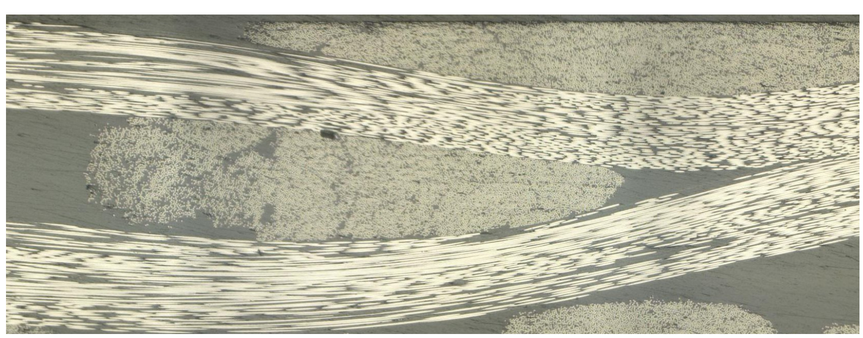


Figure 4 Details of the interlock 3X 55% woven composite microstructure

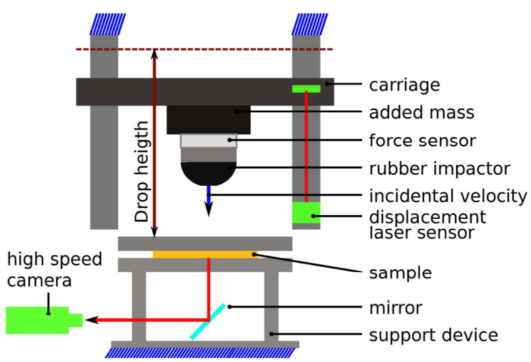
Figure 4 shows a close-up of the interlaced weft and warp yarns. One can see that the fiber distribution within a yarn is uneven probably caused by compaction during the RTM process. Some resin rich areas are clearly visible and can take the form of paths within the yarn.

3 Experimental set-up

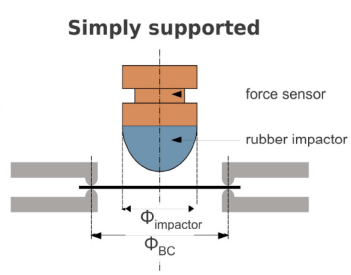
The impact tests were performed on the home made drop tower illustrated in Figure 5a. The composite specimen was simply supported along a circular perimeter of diameter Φ_{BC} = 154 mm as shown in Figure 5b. The ratio $\Phi_{BC}/\Phi_{impactor}$ = 2.2 was adopted to avoid boundary effects.

The composite specimens were square with a side length equal to 180 mm. On the top surface, a piece of paper was stuck to obtain during testing a print of the impactor. On the other side a speckle pattern was sprayed to allow measurement of the displacements and strains using a digital image correlation (DIC) system. The plate was then placed on the bottom support and the top part was assembled with four bolts tightened with a torque of 80 mN. The contact force history between the elastomer and the composite specimen was measured by a piezoelectric sensor KISTLER 9061A.

The displacement history of the carriage was measured by a laser sensor so that the velocity of the falling mass can easily be assessed. Maximum contact area was determined from the print on the paper of the impactor that was beforehand covered with blue chalk. Moreover, one high speed camera (PHOTRON APX RS) was used to record images of the back of the specimen during impact. The acquisition speed was 8400 image/s to get a good resolution. Due to a lack of available space between the specimen and the ground, a set of two mirrors assembled with hinges inclined at a 45∘ angle relative to the ground was placed under the composite plate. The two mirrors provided two images of the back side of the specimen that could be recorded by only one camera.



a) Home made drop test tower



b) Rubber impactor and interlock target

Figure 5 Experimental set-up

4 Variability study

4.1 Testing procedure

Impact tests were performed at incident energy of 272 J using a mass impactor of 17.9 kg that was dropped at a 1.55 m height. That level of energy was selected because previous tests performed during the VULCOMP project at that energy level showed some discrepancies in the damage tolerance of the composite. A more thorough study was needed to investigate this issue. Four specimens were then cut from the same composite plate and tested under the same impact test conditions one after the other. It was unfortunately not possible to perform more tests due to a lack of availability of the composite material.

4.2 Results

The force-time curves obtained for the four tests are presented in Figure 6. The curves for tests 1 and 2 have a rather smooth bell shape which indicates that a low level of damage occurred. The first part of the curves for tests 3 and 4 are smooth but after the peak oscillations reveal that severe damage has occurred. Note that the slopes of the curves are identical before the peak for tests 1, 2 and 4. The different slope observed for test 3 is not yet explained. Pictures of the back side of the plates are shown in the figure. Plate of test 1 has no external visible damage whereas plate of test 2 is clearly damaged on the back side. However, the force-time curves are identical for the two plates. Plates of tests 3 and 4 have been so severely damaged that they have perforated.

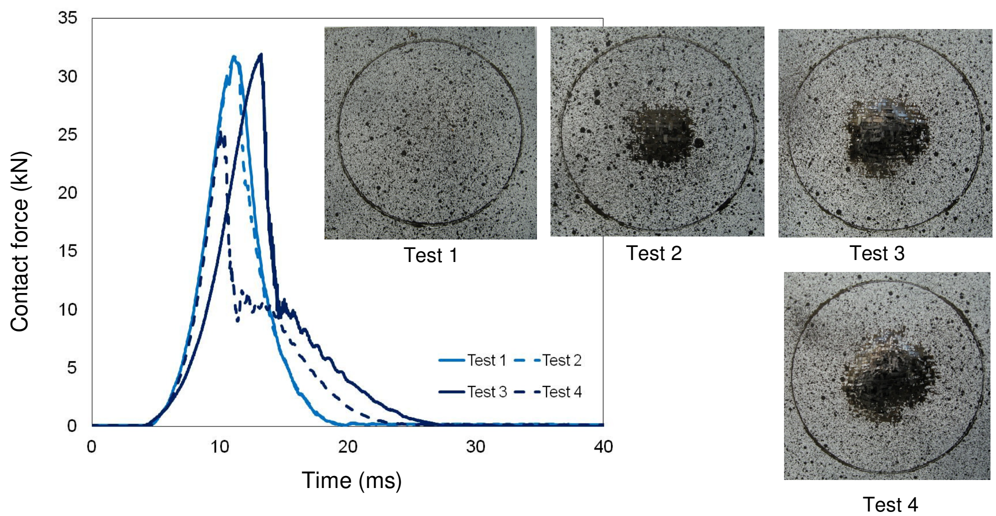


Figure 6. Contact force versus time at 272 J (Interlock 3X 55% woven composite)

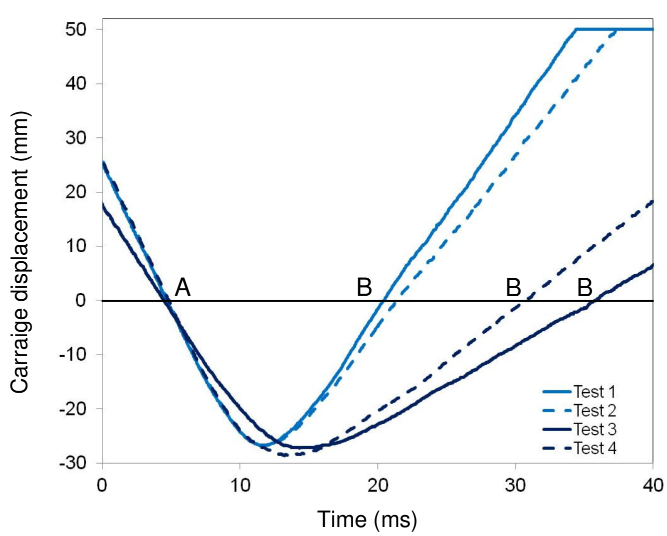


Figure 7. Carriage displacement versus time at 272 J (Interlock 3X 55% woven composite)

The carriage displacement as a function of time obtained for the four tests is presented in Figure 7. The displacement decreases with time and reaches zero as the impactor hits the specimen (point A). It is interesting to note that the slopes are identical for tests 1, 2, and 4. This means that the impactor hits the specimen at the same speed estimated equal to 5.5 m/s from the experimental data. This value is the same as the theoretical one. However, for test 3, the slope is much lower and corresponds to a speed equal to 3.98 m/s at point A. Reason for this deviation is unknown. It explains that the force-time curve for test 3 does not follow the same trend as for the other tests. Results for this test are therefore not considered for further discussion. Looking at the carriage displacement curve for the three other tests, one can note that the carriage rebounds from the specimen at different speeds. The more the plate is damaged, the lower the speed of the carriage is and the longer the contact time between the impactor and the plate is. In addition, note that the maximum carriage displacement is nearly the same for every test.

4.3. Conclusions and remarks

This study showed that damage extend due to impact can vary even though the test conditions are identical. Reasons for this deviation can come from different sources. First, it has been established by previous measurements that the carriage velocity can undergo variation up to 5% which means that a nominal velocity of 5.5 m/s can range from 5.22 m/s to 5.77 m/s. This translates into an incident energy that may range from 244 J to 298 J. Next, the rubber impactor may not have exactly the same mechanical behavior from one test to the other. Finally, as observed in section 2.2, the interlock 3X woven composite is a material which is heterogeneous on a large scale. The matrix is not evenly distributed which leads to resin-rich areas. The textile pattern is not perfectly repeated and uniform due to the RTM process. These factors influence greatly the mechanical properties of the composite. Moreover, the representative unit cell (10 mm x 50 mm) is very large compared to the impactor size (70 mm in diameter). The position of the unit cells on the contact zone under the impactor may be an important factor that can influence the response of the specimen.

5 Mass-velocity effect study

4.1 Testing procedure

Tests were performed with three incident energies: 202 J, 239 J and 272 J. The incident energy of the impactor was imposed by the couple mass/incident velocity of the impactor. For each energy level, three different mass/incident velocity couples were used. The incident velocity was adjusted for each mass by changing the drop height to obtain the desired incident energy as summarized in Table 1.

	9.9 kg	13.9 kg	17.9 kg
202 J	h = 2.08 m v =6.38 m/s	h = 1.48 m v = 5.39 m/s	h = 1.15 m v = 4.75 m/s
237 J	h = 2.46 m v = 6.94 m/s	h = 1.75 m v = 5.86 m/s	h = 1.35 m v = 5.14 m/s
272J	h = 2.8 m v = 7.41 m/s	h = 2 m v = 6.26 m/s	h = 1.55 m v = 5.51 m/s

Table 1. Mass/incident velocity couples used for the impact tests

After impact, microscopic observations were done on interlock samples cut from the tested plates in order to analyse induced damages. The samples were cut along the weft and warp directions at the center of the plates as depicted in Figure 8. Specimen S_{wa} reveals damage in the warp direction whereas specimens S^1_{we} and S^2_{we} are used to observe damage in the weft direction.

4.2 Results

The force-time curves and the carriage displacement-time curves obtained for 202 J are presented in Figure 9. The force-time curves have a rather smooth bell shape which indicates that not too much severe damage has occurred. As the mass is increased, the contact force increases from 21 kN to 24 kN and the contact between the impactor and the plate lasts longer. As expected, the impactor speed decreases with increasing mass which translates into a lower slope for the force-time and the displacement-time curves as the impactor hits the plate.

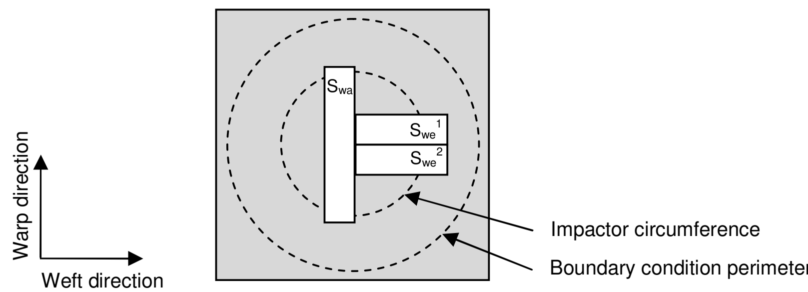


Figure 8. Cut sections for microscopic observations

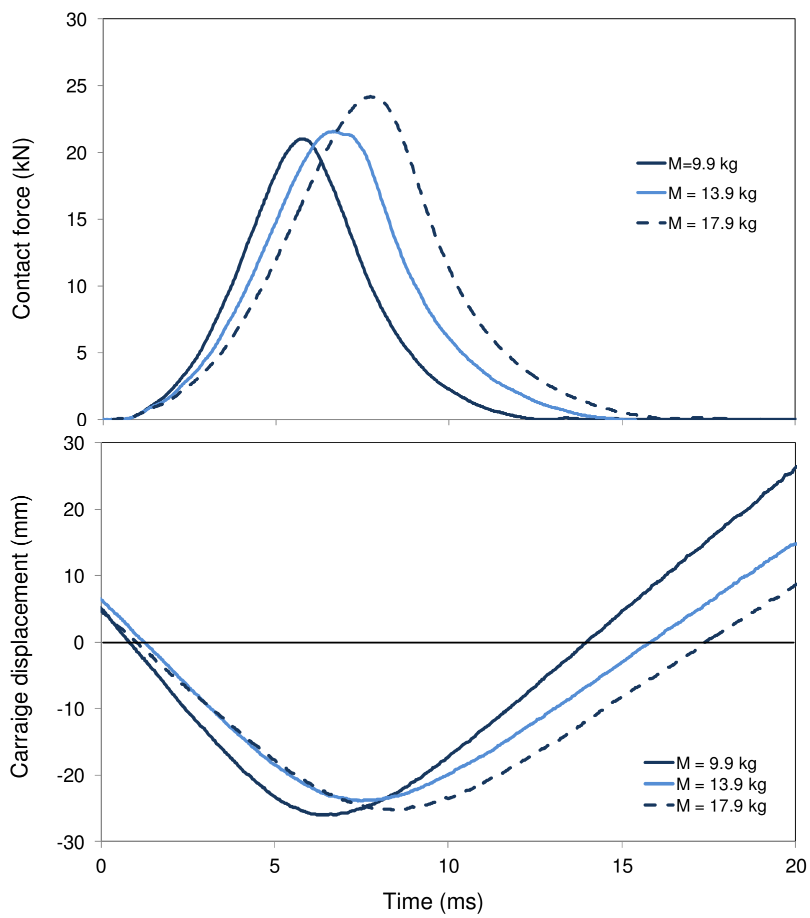


Figure 9. Mass/velocity effect at 202 J: contact force and carriage displacement versus time

Figure 10 presents microscopic observations of damages that occurred along the weft direction. The impactor radius (R) is indicated. Different damage modes can be seen, in particular transverse cracks in the matrix and in the yarns, longitudinal cracks in the upper warp yarns, and matrix-yarns debonding. As the mass increases, fewer cracks in the matrix and yarns are present and more yarn debonding is observed near the surface opposed to the impacted one.

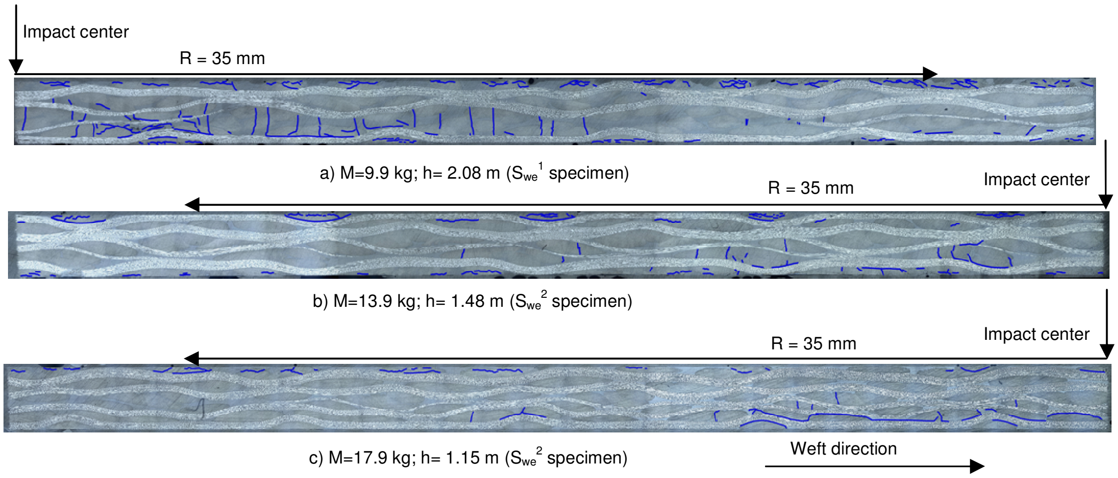


Figure 10. Damages observed along the weft direction

Figure 11 presents microscopic observations of damages that occurred along the warp direction. The impactor diameter (D) is indicated. Transverse matrix and yarn cracks are present for the three cases. As the mass increases, fewer longitudinal cracks in the upper weft yarns are present. Warp yarn decohesions are visible for the three mass/velocity couples but the location changes. For M= 9.9 kg, yarn decohesion are localized under the impact close to the lower surface. As mass increases, yarn decohesions are still close to the lower surface but are spread over a wider zone away from the impact center.

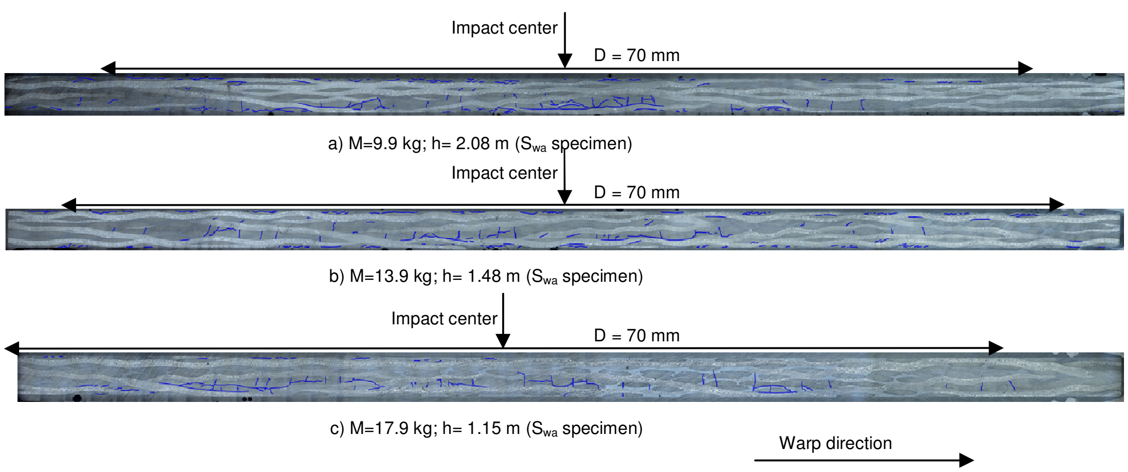


Figure 11. Damages observed along the warp direction

6 Conclusions

The performance of a three-dimensional (3-D) woven composite subjected to impact loading with largely deformable rubber impactors was investigated in this study. Several impact tests were performed at energy levels varying from 202 J to 272 J obtained with different mass/incident velocity couples. First of all, variability issues due to different sources were highlighted. Variations up to 5% on the velocity mesurements, the evolution of the rubber impactor behavior, the textile pattern not perfectly repeated and uniform due to the RTM process but also the very large representative unit cell compared to the impactor size influence greatly the performance of the textile under soft impact loading. Moreover, the analysis of the force-time and the carriage displacement-time curves and the mass-velocity effect study confirmed expected tendencies. It could be noticed that even though the force-time curve has a rather smooth bell shape, quite significant damage can occur as observed with test 2. Finally, microscopic observations of damages along both the weft and warp directions showed transverse cracks in the matrix and in the yarns, longitudinal cracks in the upper warp yarns, and matrix-yarns debonding. They also revealed that the damage mechanisms were influenced by the mass/velocity couples. Parallel to this present work, numerical investigations have been carried out and will be presented in a forthcoming paper.

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