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# ANALYSIS OF THE EFFECTS OF AUTOMATED FIBER PLACEMENT SINGULARITIES BY MULTI-INSTRUMENTATED TESTS ON PLANE AND OPEN-HOLE COUPONS UNDER COMPRESSION LOADING

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## Abstract

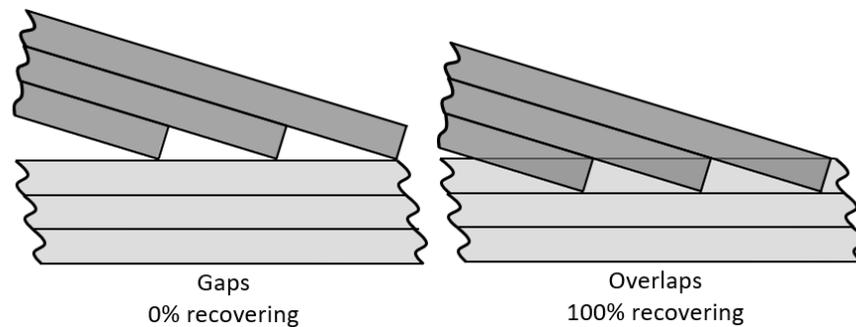
This study analyses the impact of singularities caused by the automated fiber placement manufacturing process on the compression behavior of composite coupons. Compression tests are performed on plain and open-hole coupons with standard aeronautical stacking layups, featuring various configurations of gaps and overlaps. A rich multi-instrumentation is used for monitoring and better understanding the effects of singularities on the damage and failure scenario. Micro-computed X-ray tomography (CT-scan) observations performed at different loading steps allow the monitoring of damage within the core of the coupons. The failure scenario is characterized using acoustic emissions sensors and computed tomography observations. The instrumentation helps to understand the effective local loading state at the coupon-scale and highlights the necessity of numerical simulations for better understanding the effect of singularities.

## 1. Introduction

The aeronautic industry is continuously striving to produce the lightest products while ensuring their robustness. To do so, an increasing diversity of parts and structures are made out of carbon fibre reinforced plastics (CFRP) due to their high specific properties. However, CFRP can be difficult to shape. The complexity of the aforementioned parts and structures keeps increasing. Thus, new industrial processes are required to ensure the production reliability, quality and rate. One of the industrial process that fulfill these constraints is the automated fiber placement (AFP).

Developed from the 1980's, AFP process consists of the deposition of thin tows composed of continuous carbon fibre pre impregnated with matrix (prepreg). This automatic and robotic process allows the manufacturers new parts design opportunities thanks to specific features such as (i) the ability to individually stop and restart the deposition of each tow, (ii) the ability to control the deposition speed of each tow and (iii) the modularity of the process enabling to lay down from 1 up to 32 tows in parallel. (The tows width spans from some millimeters up to tenths of millimeters [1]). This robotized and automatized process ensure to the aerospace industrials a consistent and controlled quality of the produced parts, thus increasing the productivity by reducing the rework time caused by quality control and reducing the material waste. However, AFP induces unavoidable features such as gaps and overlaps. Gaps are created because of an intentional or unintended lack of material while laying down a ply to

build a laminate. Overlaps are created when two prepreg tows, belonging to the same ply, are superimposed. These singularities are induced because of the part design itself or because of non avoidable manufacturing errors. Some composite structures feature non developable surfaces. Therefore, the deposition trajectories that are designed to intersect each others induce gaps or overlaps. Figure 1 presents two recovering strategies. On the left, the deposition of each tow is stopped as soon as it encounters another tow. That leads to a lack of material in a triangular region thus creates a gap. On the right, with a 100% recovering strategy, the tows are superimposed on each other in order to assure that no areas is left free of prepreg.



**Figure 1.** Scheme of the 0% recovering strategy (on the left) and scheme of the 100% recovering strategy (on the right)

Sawicki and Minguet [2] tested plain coupons embodying gaps and overlaps under compression. The presence of gaps or overlaps reduces the compression failure stress. In addition, with a wider singularity the failure stress reduction gets more important until a width limit of 2.54 mm. Turoski *et al.* [3] studied open-hole and plain coupons featuring different gaps configurations under compression loading. The failure strength decreases for configurations with increasing number of gaps. Croft *et al.* [4] tested open-hole and plain coupons containing gaps and overlaps, as well as half gaps/ half overlaps placed in under compression loading. The effects of singularities is considered neglectable compared to the hole effects. In plain compression, the presence of gaps leads to the reduction of failure properties. The presence of overlaps leads to a slight increase of the failure properties which is in disagreement with the results of Sawicki and Minguet [2]. The authors concluded that the out-of-plane waviness induced by the presence of the singularities is one of the parameters that has the highest influence on the failure properties. Lan *et al.* [5], [6] studied the effect of out-of-plane waviness due to the presence of singularities through optical microscopy observation on the edge of specimens, which included various configurations of singularities in both number and type. Because of gaps, the thickness of the specimen is locally reduced and the empty area is filled by the adjacent plies leading to out-of-plane waviness. At the ply drop, the empty area left by the gap is filled with matrix creating matrix pockets. With the presence of overlaps, the thickness of the coupons is locally increased and the plies adjacent to the overlap are affected by out-of-plane waviness. Under loading, the thickness variation lead to stress concentration regions. The use of a caul plate during curing mitigates this effect. Due to the pressure applied by the caul plate, the matrix pockets are reduced. However, more severe out-of-plane waviness and ply thickness variation are observed within the specimen. In terms of mechanical properties, the caul plate mitigates the effects of singularities in coupons under tensile [5] and compression tests [6]. Del Rossi *et al.* tested configurations with multiple gaps and overlaps oriented along the length or the width of the specimens and located at different places along the length and the thickness of the laminate in [7]. Specimens are cured with a Caul plate and severe out-of-plane waviness is observed through optical microscopy.

It is clear that singularities affects the mechanical properties of AFP manufactured composites. However, it is not clear how the singularities affect the failure scenario. As the total failure of composite specimens under compressive load appear abruptly, Woigk *et al.* [8] observed the edge of specimens under compression loading with high speed optical cameras and are able to characterize similarities and differences in the total failure evolution of specimens including gaps and overlaps under compression loading. However, these observation are influenced by the frame rate of the camera that limite the image

definition. This also limits the observable damage types to delamination and to the total failure of the specimen due to fiber breakage. There is a lack of work in the literature studying the damage and failure scenario of coupons under compression loading with gaps and overlaps.

However, in tensile test, many different experimental means were applied to monitor the damage and failure scenario of coupons including singularities : acoustic emission in the work of Anay *et al.* [9], DIC in the work of Falco *et al.* [10], optical microscopy in the work of Nguyen *et al.* [11] and CT-scan observation in the work of Falco *et al.* [12]. Overall, the exploration of different experimental means separately seems to be insufficient for properly assessing the effects of singularities on the failure scenario of AFP manufactured coupons.

The objective of the present study is to characterize experimentally the influence of the singularities on the mechanical properties and on the failure scenario of plain and open-hole coupons under compression loading by combining different experimental means. The second section describes the experimental campaign including the design of the coupons embodying singularities and the multi-instrumented set-up used to monitor the failure scenario of the specimens under compression. The third section presents the experimental results and the effects of the singularities.

## 2. Material and methods

### 2.1 Specimen design

To test various singularities configurations, five different plates are manufactured using the AFP process. The plates are built with a 16 plies quasi-isotropic layup of prepreg. During curing, a caul plate is pressed to the plates to ensure a constant thickness of the laminate. 22 coupons are extracted from the plates. The specimens are 115 mm long and 25 mm wide with a nominal thickness of 2.944 mm. The open-holes specimens feature holes with a 4.8 mm in diameter.

Figure 2 presents the design of every specimen. Five designs for plain compression and six designs for open-hole compression. A scheme of singularities' positions within the coupons is indicated with a top view perspective and the layup of each configuration with the position of the singularities in the layup are presented. Plies with gaps are highlighted by stripped lines while overlaps are highlighted with a cross pattern. The rectangular gaps are made by the intentional omission of a tow during the AFP process while overlaps are fulfilled by the superposition of an extra two on top of the initial ply. The colors indicate the orientation of the plies that include singularities. To create design that are representative of industrial part designs, triangular gaps and overlaps are made by shifting tows during the deposition. These triangular gaps are placed at three different positions along the length of the specimens and are staggered along the thickness.

### 2.2 Test campaign

To achieve a better understanding of the effects of singularities on the failure scenario, observations at the inner core of the tested specimens are performed with a micro-computed X-ray tomograph (CT-scan). An initial CT-scan is performed before any loading to have an overview of the initial state of specimens. Then specimens are loaded until 90% of the failure load and scanned again. This load level is defined from a first batch of test until total failure of specimens and is the best compromise between a sufficient load level to able the observations of damage and a load level that does not lead to the total failure of specimen to ensure the ability to scan it again.

### 2.3 Experimental set-up

All the tests are carried out up to failure and are performed. The loading frame is a standard Zwick-Roell electromechanical testing machine with a capacity of 150 kN. Tests are equipped with a rich multi-instrumentation. The tests' set-up is presented in Figure 3. The multi-instrumentation consists of (i) two pairs of optical cameras used to establish two systems of stereo digital image correlation (SDIC) and (ii) two acoustic sensors mounted on the clamping jaws to record acoustic emissions. The optical cameras

are positioned following the scheme of Figure 4. The CT-scans were performed at Toulouse, France in IRT Saint-Exupéry facilities in an *EasyTom230* with a spatial resolution of 14  $\mu\text{m}$  voxel.

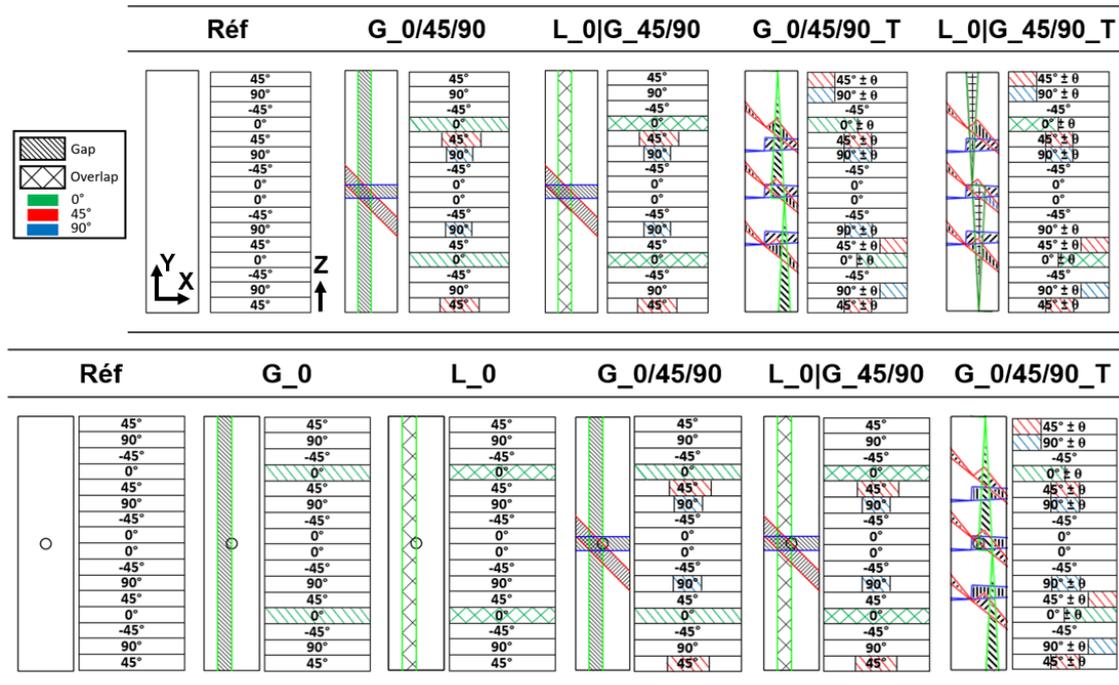


Figure 2. Design and layup of each type of specimen

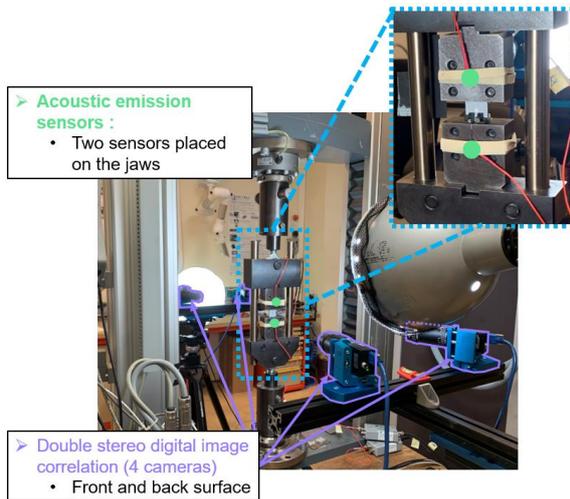


Figure 3. Experimental set-up

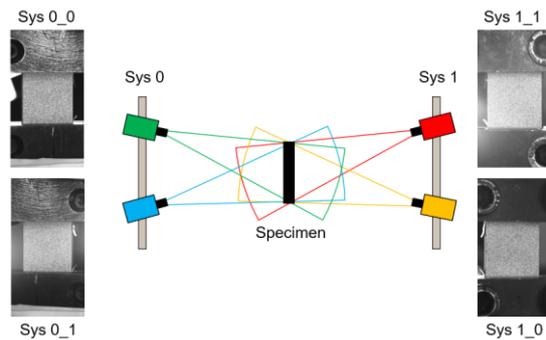


Figure 4. Scheme of the optical camera positions

### 3. Results

#### 3.1. Mechanical properties under compression

For each configuration, one specimen is tested until failure and another one is tested until 90% of the failure load defined from the first test until failure. Table 1 presents the change in mechanical properties of each configuration and the change in the nominal volume of prepreg material for each configuration with respect to the reference configuration. The change in the volume of prepreg material is calculated from the theoretical layup. The nominal tow dimensions (6.35 mm in width, 0.184 mm in thickness) is considered. The prepreg volume is calculated only for the region of interest, which consists on the area between the jaws. This area is 25 mm wide (width of the specimens) and 27 mm long (distance between the jaws).

In term of compression modulus, the presence of gaps in 0°, 45° and 90° soften the coupons up to 9.4% reduction for G\_0/45/90\_T. The softening effect of gaps is more important for the configuration with triangular gaps than for the one with rectangular gaps. This might be explained by the misalignment of the fibre that is needed to creat such shape of singularity. The presence of overlaps in 0° (L\_0|G\_45/90 and L\_0|G\_45/90) counterbalances the softening effects of gaps. From the table, it is clear that neither the change in compression modulus, the failure strain or the failure stress is correlated with any change in prepreg volume. As an exemple, the OHC design G\_0/45/90 present a reduction of 9.97% of the total material volume and a reduction of 12.36% of the material volume in the 0° plies while the reduction of compression modulus is of 3.9% and the reduction of failure strain and failure stress are of 15.1 and 14.6% respectively. In addition, an increase of the material volume in the 0° plies for L\_0 does not induce an increase of the compression modulus or of the failure properties.

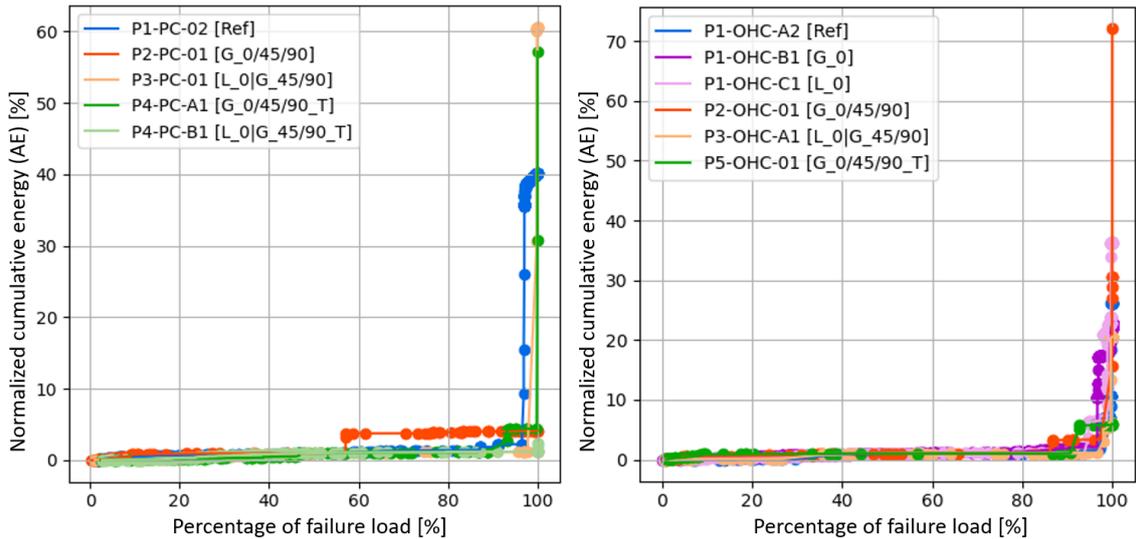
In open hole compression, the trends obtained in terms of failure properties change depending on the configuration follows those found in literature. The configuration with the greatest amount of gaps presents the lowest failure properites while the presence of overlaps reduces the gap effects. The effects of singularities is less important in plain compression than in open-hole compression. That may be explained by the hole effect that is more important than the effect of singularities. The presence of overlaps limits the softening effects of singulairites or increase the stiffness, as for the coupon L\_0|G\_45/90. The specimens with the most gaps present the lowest failure properties with a strain reduction of 15.1% and a failure stress reduction of 14.6% for the G\_0/45/90 configuration. The reduction effect of triangular singularities on the failure properties is less severe than the rectangular singularities.

**Table 1.** Results of the compression test campaign and change in volume of material compared to reference coupons

Coupon type	Change in compression modulus [%]	Change in Erupture [%]	Change in $\sigma_{max}$ [%]	Change in prepreg volume at 0° [%]	Change in prepreg volume at 45° [%]	Change in prepreg volume at 90° [%]	Change in total prepreg volume [%]
(PC) Ref	/	/	/	/	/	/	/
(PC) G_0/45/90	-8,3	29,3	18,5	-12,7	-16,47	-11,76	-10,90
(PC) L_0 G_45/90	-0,003	15,2	16,9	12,7	-16,47	-11,76	-4,55
(PC) G_0/45/90_T	-9,4	28,3	15,1	-7,22	-7,16	-6,52	-5,89
(PC) L_0 G_45/90_T	0,8	7,6	7,5	7,22	-7,16	-6,52	-2,28
(OHC) Ref	/	/	/	/	/	/	/
(OHC) G_0	-2,6	-3,5	-5,2	-12,36	/	/	-3,09
(OHC) L_0	-2	-2,3	-1,7	5,84	/	/	1,46
(OHC) G_0/45/90	-3,9	-15,1	-14,6	-12,36	-16,80	-10,71	-9,97
(OHC) L_0 G_45/90	4,2	-8,1	-3,1	12,36	-16,80	-10,71	-3,76
(OHC) G_0/45/90_T	-6,5	-6,9	-10,1	-6,73	-6,67	-5,32	-4,68

### 3.2. Failure scenario analysis

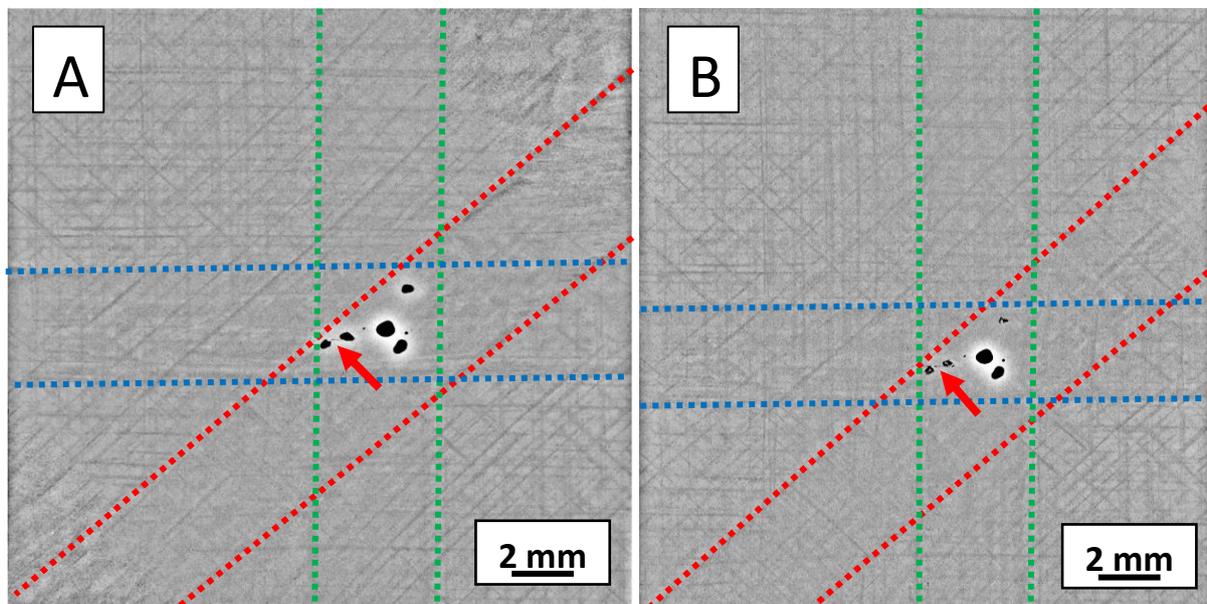
The experimental set-up for compression loading tests combines acoustic emission sensors and CT-scans to monitor the damage and failure scenario of specimens. Figure 5 presents two graphs with the curves of the normalized cumulative energy of acoustic emission (CEAE) function of the percentage of applied load normalized with respect of the failure load. The left graph presents the CEAE for all the PC specimens loaded until failure and the right graph present the CEAE for all the OHC specimens . It is worth noting that a steep increase of CEAE occurs after 90%/95% of the failure load. Indeed, these sudden increases are explained by high energy events. These high energy events might be related to damage mechanisms such as fibre breakage or delamination occurring before the total failure of the specimen.



**Figure 5.** Normalized cumulative energy of acoustic emission function of the percentage of failure load for plain compression coupons (left) and open-hole compression coupons (right)

To confirm that no damage occurs before 90% of the failure load, the CT-scan results are *post* treated in order to obtain a projection along the whole thickness of the specimen of the inner core of the scanned specimen. Figure 6 presents the projection along the thickness of the specimen of P2-PC-03 at its initial state (Figure 6-A) and after a load step at 90% of the failure load (Figure 6-B). The position of the singularities (gaps at 0°, 90° and 45° in this configuration) are highlighted with dotted lines. Voids are clearly visible as black dots in the area where all the gaps intersect each others. Despite the use of a Caul plate during the curing, the matrix and the adjacent plies are not able to completely fill the gaps. No important cracks can be seen and no damage mechanism can be observed. The red arrows point to a tiny crack (0.1 mm) between tow voids that is present at the initial state but no clear extension of the crack can be observed neither.

### P2-PC-03 [G\_0/45/90]



**Figure 6.** CT-scan image treatment result for a G\_0/45/90 specimen at its initial state (A) and after a step loading to 90% of the failure load (B)

In plain compression, the results in failure stress and strain exhibit a certain disagreement with respect of those found in literature. The reference coupons present the lowest failure strain and failure stress while the configuration with the most gaps G\_0/45/90 and G\_0/45/90\_T present the best failure properties with an increase of the failure strain up to 29.3% and 28.3% respectively. These results are not yet completely understood. To better understand the behavior of PC specimens, numerical simulation including boundary conditions measured from experimental test will be performed. Preliminary analyses of the out-of-plane fields suggest that the loading seen by the specimens is not of pure compression.

## 5. Conclusions

A total of 5 configurations of plain coupons and 6 configurations of open-hole coupons including gaps and overlaps were tested experimentally under compression loading up to failure and up to 90% of the failure load. The test were performed with a multi-instrumented set-up in order to monitor the failure scenario and characterize the effects of singularities on the mechanical properties and the failure scenario.

The effects of singularities are stronger on plain coupons than on the open-hole coupons due to the hole effect. However, the results from plain coupons test are unusual and requires deeper analysis. Numerical simulation including experimental boundary conditions computed with digital image correlation are considered in the future to better understand the test that were performed.

Despite the variation of the prepreg volume in the region of interest of the different specimens configurations, any correlation is found between variations in mechanical properties and variations in failure properties.

Regarding the effects of singularities on the mechanical and failure properties of open-hole specimens, the gaps reduce the stiffness and the failure properties of specimens under compression. The presence of overlaps along the loading direction limits the effects of gaps positioned along other directions. In addition, singularities positioned along the loading direction have the most important effect. The triangular singularities have a smaller effect than the rectangular singularities.

Coupling the analysis of acoustic emission data and the post treatment of CT-scan images able to state that no damage can be observed before 90% of the failure load. However, damage may appear after 90% of the failure load as high energy acoustic events are recorded near 95% of the failure load for most of the specimens. A new CT-scan of the specimens after a new step load at 95% of the failure load could confirm these results and help to characterize the effects of singularities on the failure scenario of coupons under compression loading.

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