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EFFECT OF PREPREG GAPS AND OVERLAPS ON MECHANICAL PROPERTIES OF FIBRE METAL LAMINATES

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Abstract

During the automated manufacturing of fibre reinforced laminates, defects can be produced. Gaps and overlaps between adjacent prepreg layers can be produced in composites during the tape-layup process. However, the topic is not yet studied for hybrid materials, in which metal sheets and thin prepreg layers make different effects due to the defects than in full composites. Here, the effect of gaps and overlaps on the mechanical properties of the Fibre metal laminates (FML) is evaluated. Specimens are manufactured with a specified width of gaps/overlaps and the mechanical performance of the panels are evaluated by some selected mechanical tests. Gaps show to have a considerable effect on the mechanical performance of FML. Compression strength of samples with overlaps were rather increased. Discussions are presented on the influence on each mechanical property according to the severity of the defect (gaps/overlap) and also the failure mode(s) under consideration.

Keywords: Fibre Metal Laminate, GLARE, Manufacturing defects, Gaps, Overlaps

1 Introduction

Fibre metal laminates (FML) are hybrid materials composed of metallic and (fibre/polymer) composite constituents. Besides their high values of strength/weight ratios, alternating metal and composite layers in FML result in high structural performances like fatigue life, residual strength and damage tolerance [1,2] which enhance safety and performance to the aircraft. Fuselage panels and leading edges of tail planes are among structural parts of aircraft in which

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FML have found applications. For the aerospace, Glass Aluminium Reinforced Epoxy (GLARE) serves as the most common type of FML, consisting of aluminium sheets laminated with glass fibre epoxy prepreg layers (Figure 1).

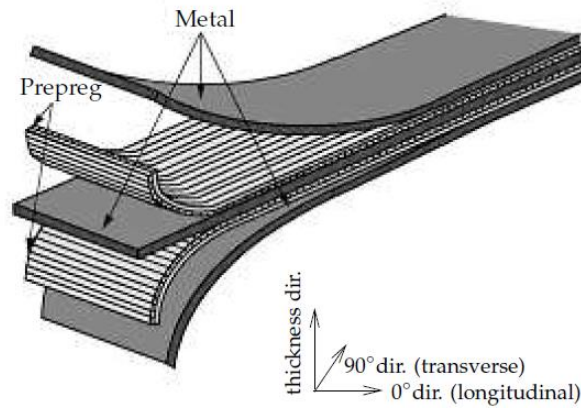


Figure 1: Typical configuration of GLARE [3]

Research is being conducted in the Faculty of Aerospace Engineering at TU Delft, on the analysis and prediction of manufacturing processes of fuselage panels made of FML. The reader can be referred to published papers in this regard which are mostly about the curing-induced phenomena during manufacturing of FML [4-7].

Although, the range, understanding and applications of FML are further developed by researchers [8-10], the effects of manufacturing processes on the final product are not studied in detail yet. The project “Effects of Defects during automated manufacturing of GLARE” at TU Delft aims (i) to develop techniques to detect the possible defects and (ii) to evaluate the effects of the defects on the mechanical performance of panels made from GLARE. Studies on the detection and evaluation of the gaps/overlaps in GLARE are presented in another paper by the authors [11]. In this paper, after an introduction to the manufacturing process of GLARE, the effects of gaps and overlaps are evaluated on the mechanical properties. Gaps/overlaps may occur during the automated tape-layup process. Until now, production of small number of GLARE was done manually. However, the need for manufacturing large number of panels necessitates an automated procedure. The automated layup process which incorporates narrow tapes of prepreg to be put on the aluminium sheets, increases the possibility of gaps and overlaps.

It should be noted that the manufacturing defects considered in this paper are common with full composites within an automated layup process. Therefore, some research already done on

full composites can be considered as references to study the similar phenomena occurring during the automated layup process for GLARE (see for example ref.'s [12] and [13]). On the other hand, the detection and the effects of gaps and overlaps are different in case of GLARE. During the autoclave curing (under pressure), aluminium sheets make difference by flattening the prepreg layers and therefore increase or decrease the gap or overlap width and also may need different detection procedures and techniques. Furthermore, the glass/epoxy layers are few number of thin prepreps between aluminium sheets which leads to more severe effect by the presence of a gap (missing fibres).

2 Material type and manufacturing of GLARE

The FML investigated here is GLARE which is composed of aluminium sheets (2024-T3) laminated with prepreg layers in between. The unidirectional (UD) prepreg layers have S2-Glass fibres and FM-94 epoxy adhesive [14]. For the details of the constituents' properties and the calculations for the laminate response in elastic and viscoelastic (temperature-dependent) regions, the reader can refer to a previous paper [6].

2.1 General manufacturing procedure

Hand layup is used in the conventional manufacturing of GLARE. Sheets of aluminium and prepreg layers are cut to size and laminated according to the desired layup. In Figure 2, the layup procedure is shown. Important to notice is that according to the standard layup of GLARE, fibre orientations of the prepreg layers are specified with respect to the rolling direction of the aluminium layers. In other words, the 0-degree fibre layers are along the rolling direction of aluminium and 90-degree fibre layers are put perpendicular to the rolling direction of aluminium. Accordingly, later in this paper, L and LT symbols refer to the directions along and perpendicular to the rolling direction.



Figure 2: Layup process for panels made from GLARE

The layup is done on a mould made from aluminium and after preparing a vacuum bag, the laminate is cured in an autoclave under pressure to cure the resin and to bond the layers. A standard cure cycle of GLARE is shown in Figure 3 in which the temperature profile together with the degree of cure development are illustrated. The autoclave pressure is set at 6 bar.

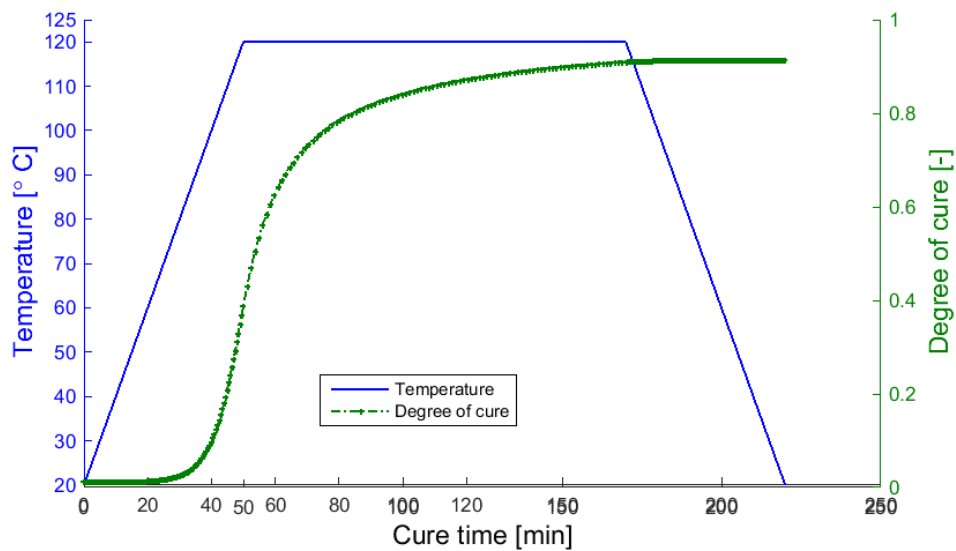
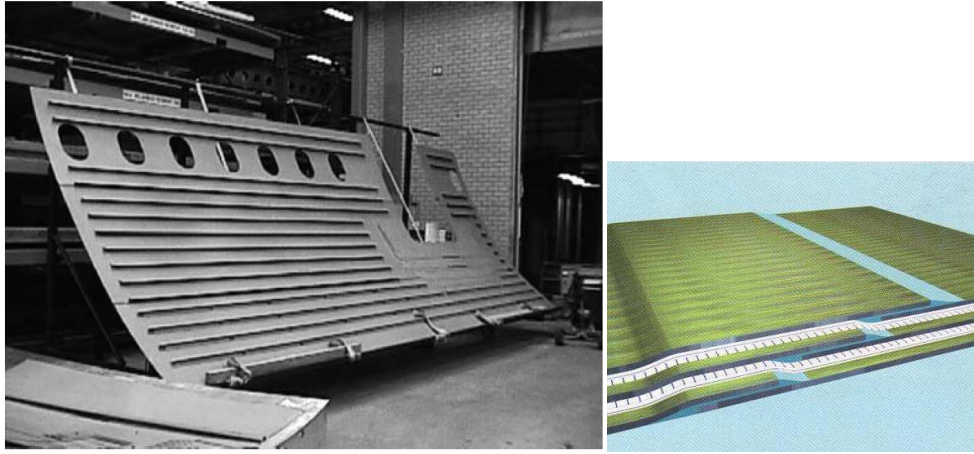


Figure 3: Cure cycle of GLARE [15]

Fuselage panels made from GLARE can be complex with features including thickness changes, splices, doublers and stringers (see Figure 4). Splices are used to attach adjacent panels and make larger fuselage panels. Doublers are extra aluminium sheets that locally reinforce the panels which can be seen around the cut-outs. Reinforcements like stringers which are used to stiffen the panels against buckling (increase stability) and also large doublers may be bonded to the panel in a second autoclave cure cycle which is actually called a bonding cycle.



**Figure 4: A fuselage panel made from GLARE including cut-outs, doubler reinforcements and bonded stringers
left: doublers and stringers & right: overlap splice between adjacent panels**

Up to now, the layup process is being carried out manually. This made possible the accurate placement of fibre layers between aluminium sheets and works for a small number of products. Manufacturing time can be decreased through automated layup processes which becomes especially critical when a large number of panels is going to be produced. One example would be smaller airplanes like Airbus A320 which a larger number of production is aimed for, compared to large aircrafts like Airbus A380. On the other hand, the automated manufacturing may cause defects like gaps and overlaps more probable to occur.

2.2 Defect types-features during manufacturing

The defect type of gaps and overlaps is not new within the manufacturing of full composites. As an example, in 2011, Croft et Al. have investigated the effects from the existence of gaps, overlaps, half gap/overlap, and twisted tows during the automated fibre placement process of composites [12]. They have done measurements on the properties at the laminae and laminate levels, separately. As a result, the ultimate strength was decreased by 5% at the laminae level and by 13% at the laminate level. Another work was reported by Seon et Al. in 2013 [16] who studied the effect of porosity on the inter-laminar tensile fatigue response of carbon fibre epoxy laminates. Another rather elaborate study was carried out by Lan et Al. in 2015 and 2016 [13,17] to measure the effects from the embedded gaps/overlaps during the automated fibre placement process on some properties of the carbon-epoxy composite including tensile, inplane shear, and compression. C-scan and Scanning Electron Microscopy (SEM) were used to study the microstructure of the laminate with defects, as well.

In case of GLARE, the defect types which are likely to happen are of two kinds: the ones within the prepreg layers which are common to full composites, and the ones related to the

metal sheets. Gaps and overlaps happen while putting prepreg layers in the laminate next to each other. Local plastic deformations, occurring during handling of the aluminium sheets, are called kinks which will be studied in the further steps of this research. In this study, as the most important and critical defect occurring during automated manufacturing of the fuselage panels made from GLARE, gaps and overlaps are chosen to study their influence on the material performance.

3 Test material

All of the samples for mechanical measurements are made from a GLARE-3-2/1 type laminate and have 2 aluminium 2024-T3 sheets and 2 prepreg layers with 0/90 layup. This makes the contribution of the fibre layer more critical when a gap (missing fibres) or overlap exists in the laminate to see the effects on the mechanical performances. The thickness for the aluminium sheets are chosen as to be 0.3mm and 0.4mm as the commonly used thicknesses in the FML industry and also to see the effect of the aluminium contribution in the laminate.

4 Experimental study

The aim of this project is planned to study the possible effect of defects, with different severities, occurring during manufacturing and investigate their effects on the mechanical performance of panels made from GLARE. As GLARE has already been developed and commercially used in the airplane industry, experimental tests were selected according to the most critical ones used for the design evaluation of this material for GLARE panels in Airbus A380 [18]. The tests show how different mechanical properties are influenced by the defects. This experimental study will enable us to define corresponding thresholds for each defect, although in some cases more case studies are needed to be done in the future. All the tests are performed in the “Aerospace Structures and Materials Lab” at the Delft University of Technology.

Manufacturing procedure for laminates with gaps/overlaps together with the performed non-destructive (by C-scan) and destructive (cut specimens under microscopic) measurements are discussed in the previous paper from the same authors [11].

4.1 Gaps

In the case of gaps, certain distances (gap widths) are created between adjacent prepreg layers during hand layup. Gaps are made in the middle of the specimens in both L and LT

directions, e.g. parallel and perpendicular to the aluminium rolling direction. It should be noted here that according to the measurements reported in [11], the gap width of the specimens are decrease to some extent due to the autoclave pressure during the cure cycle. The final manufactured gap width of different specimen configurations are given in Table 1.

Table 1: Gap width of specimens after manufacturing [11]

Al 0.3mm	Intended gap width	Final gap width
	2mm	2.0mm
Al 0.4mm	4mm	3.8mm
	2mm	1.7mm
Al 0.4mm	4mm	3.5mm

4.1.1 Tensile strength

Tensile strengths of the GLARE are measured with dog-bone shape specimens (see Figure 5). Specimens are loaded in a Zwick 250 KN machine with a cross-head speed of 2.0 mm/min, according to the standard ASTM D3039 [19]. Each test set contains three specimens except for reference samples with aluminium thickness of 0.4mm which were six specimens. Note that there was a limitation on the number of samples that could be made out of laminates having specific width of gaps. In the figures, the median values are plotted, the average values are also mentioned to make the comparison easier. A typical force-deformation curve and failure shape of the tensile samples is shown in Figure 6. As it can be observed, there is a yield point before the ultimate rupture which is actually seen to be due to the fibre breakage in the GLARE (Figure 6). It is noted that fibres have the biggest contribution in carrying the load in the fibre direction and therefore, at the ultimate point, the fibres are seen to break.

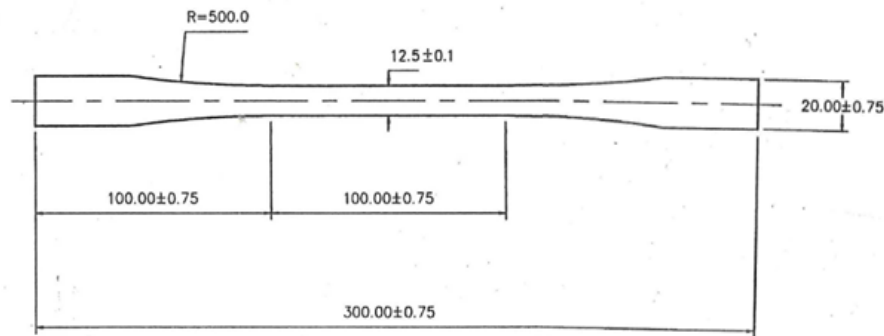


Figure 5: Dog-bone shape for tensile tests

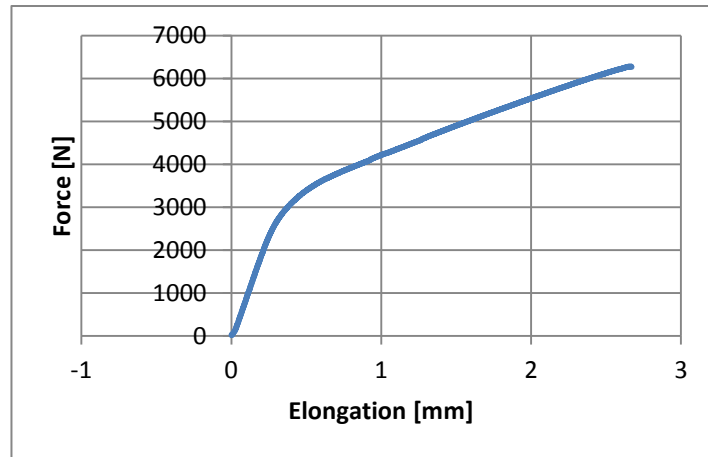
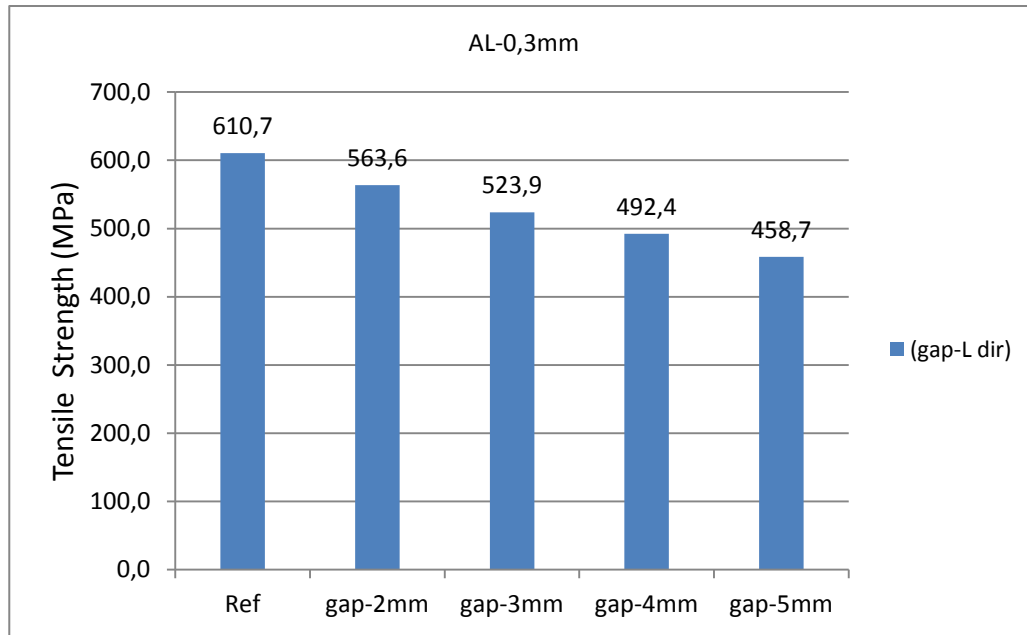
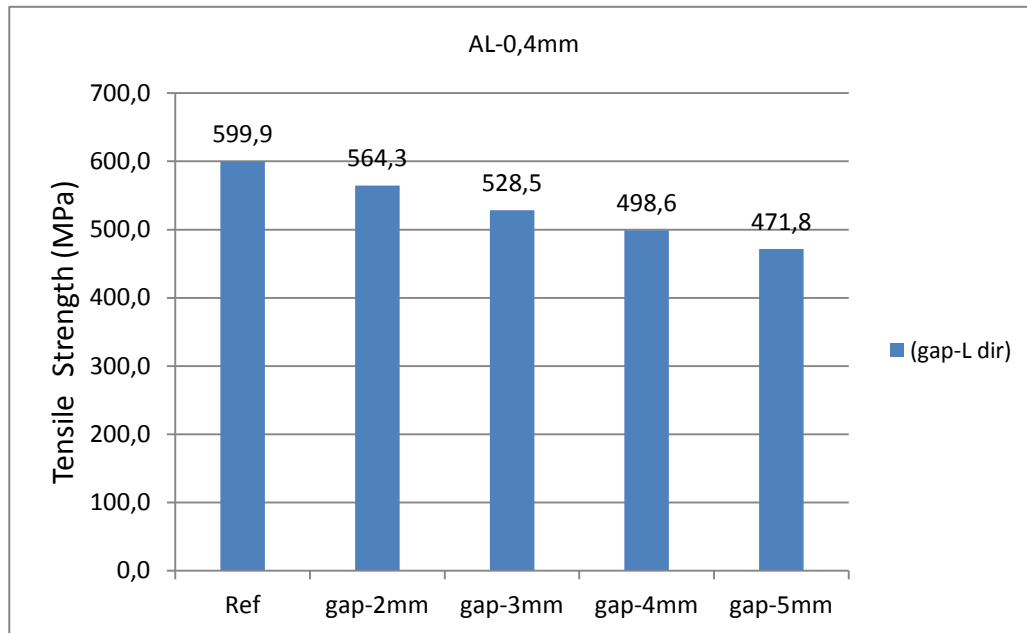


Figure 6: Typical behaviour of the tensile samples (GLARE3-2/1 in L-direction)



(a)



(b)

Figure 7: Tensile results for GLARE3-2/1 with gaps in L direction. Aluminium thickness: (a) 0.3mm, (b): 0.4mm

Results are observable in Figure 7 which shows considerable decrease of the tensile strength with increasing of the gaps width. As seen from the failed specimen, the final strength is governed by the fibre rupture from which a missing fibre would make the final breakage of specimens occur earlier. The layup which contains only one 0-deg fibre layer is evident to have major contribution to the strength of the laminate. Therefore, missing fibres are lowering the ultimate failure. Of course, for defining threshold for the gap widths, there is a need for

other tests with other layups like GLARE3-3/2 which is more practically used in the airplane industry, e.g. a laminate consisting of three aluminium layers: Al-0/90-Al-90/0-Al.

4.1.2 Compression strength

Compression strength of the GLARE could be affected by the gaps in GLARE. Compression test specimens are cut from the laminates manufactured with gaps. In order to avoid global buckling during the test, an anti-buckling fixture is used (see Figure 8) to measure the compression strength of the laminate. In the same figure, the specimens' shape and dimensions are illustrated.

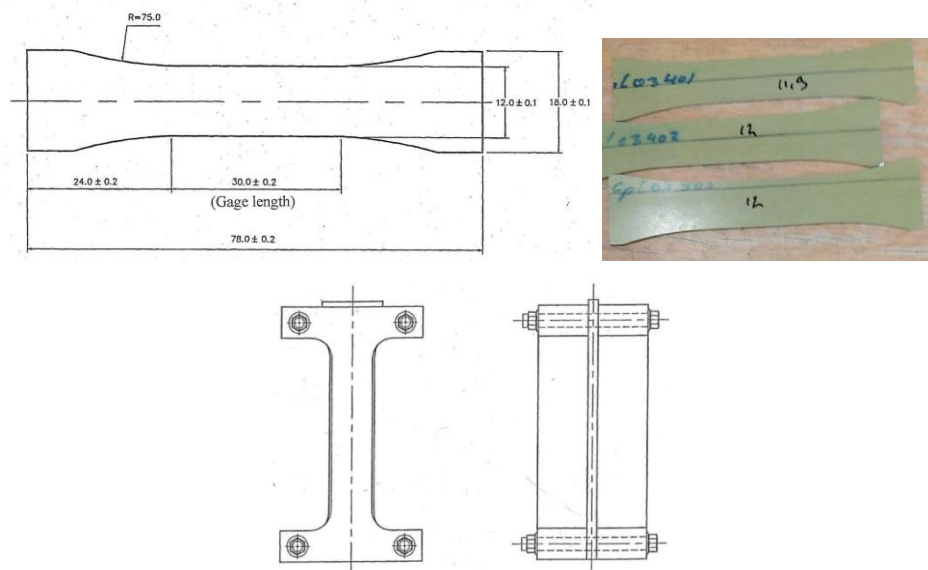


Figure 8: Compression test samples with the anti-buckling fixture [18]

The deformation response of the samples is shown in Figure 9, from which a local failure can be observed. Compressive yield and the final failure are visible from the load-deformation curve. Failure mode(s) of the laminate can be better recognised from the microscopic photo (Figure 10) which shows the side-view of the failed regions of two samples. For the compression tests, there are two different modes of failure acting together: the compressive bending of the aluminium layers and the delamination within the fibre layers which is the main cause for the separation observed between the aluminium sheets. This latter notation can be verified by the thickness measurements assigned on the photos in Figure 10. For instance in the top specimen in Figure 10, the distance between the aluminium sheets which was initially about $206 \mu m$ has increased to $357 \mu m$ within the delaminated area. The bottom image in Figure 10 is the enlarged (by microscope) picture of the region illustrated in Figure 9.

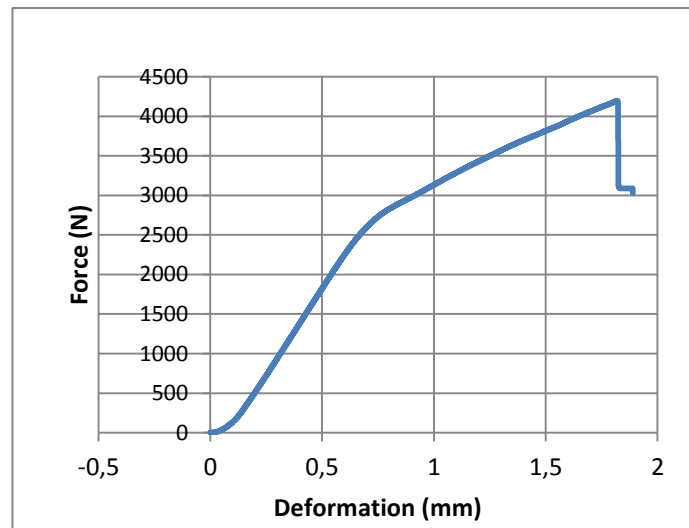


Figure 9: Typical behaviour of the samples with gaps during compression tests (L-dir gap, Al th.=0.3mm)

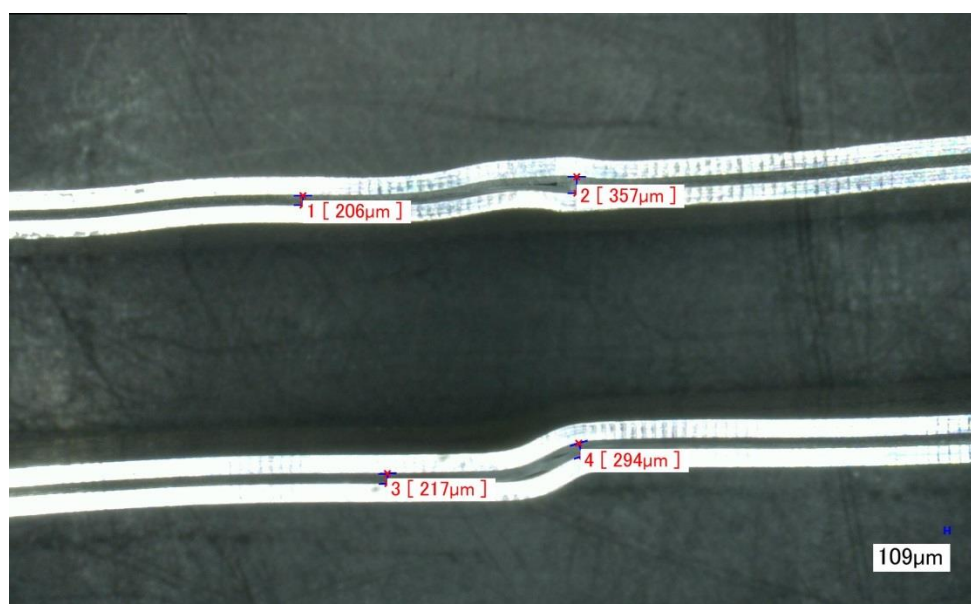


Figure 10: Failure in compression samples with gaps

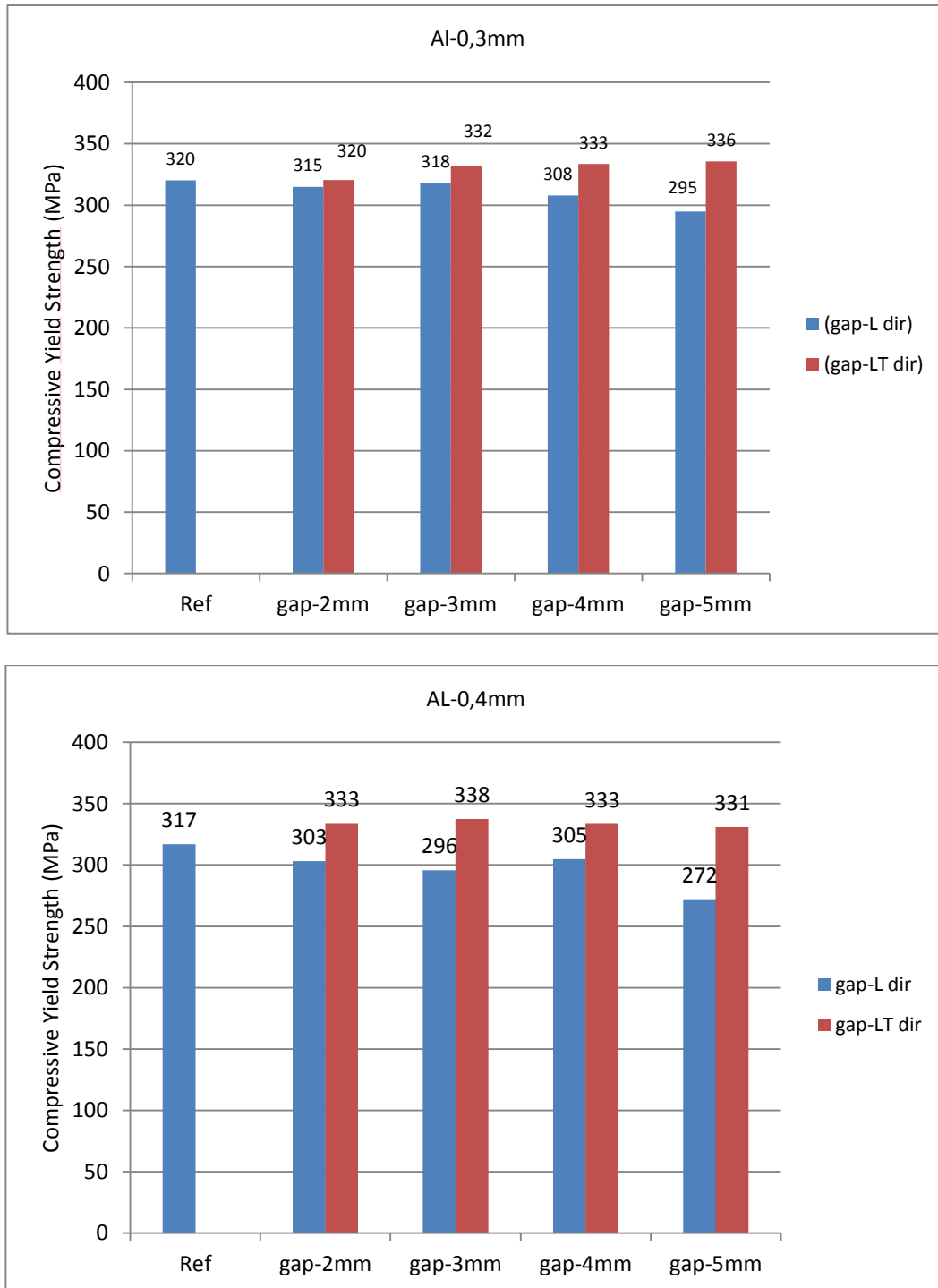


Figure 11: Compression test results for GLARE3-2/1 with gaps in L and LT directions; Aluminium thickness=0.3mm & 0.4mm

Compressive yield strength of the samples are measured and plotted in Figure 11, again for two aluminium thicknesses 0.3mm and 0.4mm. The samples have gaps of different widths along L and LT directions. As it can be seen, for both aluminium thicknesses, the values for the LT-gaps are higher than the L-gaps. As it would be expected, the contribution of L-direction fibres to the compressive strength is much higher than LT-direction fibres. Also,

comparing to the reference values, there seems no degradation in the LT-gap samples as gap in the 90-degree fibres of 2-5 mm has no significant effect on the compressive strength of the GLARE. Deviations of the strength values for LT-direction gap specimens are within the scattering range of the test data and could be neglected. In case of L-gaps, a reduction of strength is observable for gap-5mm. It should be noted that in GLARE, the compressive load is carried mostly by the aluminium sheets rather than the fibre layers, therefore, as also observed from the results, the gaps did not have much impact on the ultimate compression strength.

4.1.3 Inter-Laminar Shear Strength (ILSS)

In order to evaluate the effects of gaps on the inter-laminar properties of the material, short beam tests are carried out. The samples, tested in a 3-point bending setup (see Figure 12), failed in the inter-laminar shear mode. They had gaps in L-direction only. Samples with LT-gaps were also tested but since, bending line is in the LT direction, the effect of the LT gap could not be accurately defined and determined. Therefore, the results for the L-direction are only presented here. Each test set contained a minimum number of 4 samples which resulted in low scattering (standard deviation) of the results.

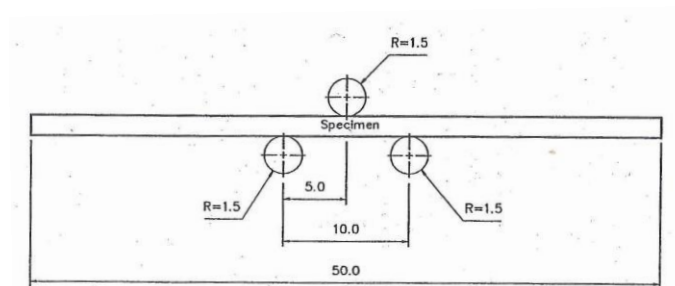


Figure 12: Three-point bending setup with short-beam specimens to measure ILSS

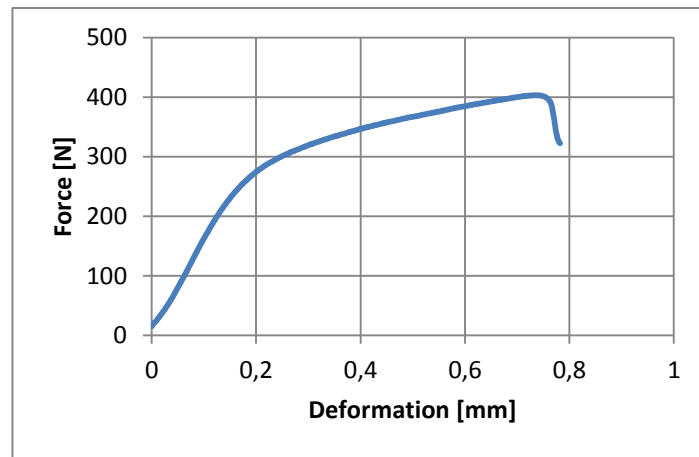


Figure 13: Typical behaviour of the ILS tests

The deformation and final deformed shape of the specimens are illustrated in Figure 13, from which a material yield and then a final failure can be observed. On each SBS sample, two bending tests are done at its two sides. In order to analyse the failure mode, a microscopic photo of the bent region is illustrated in Figure 14. Delamination between the two aluminium faces are dominant to make the laminate fail. This can be discussed to be due to the inter-laminar shear caused by the bending load.

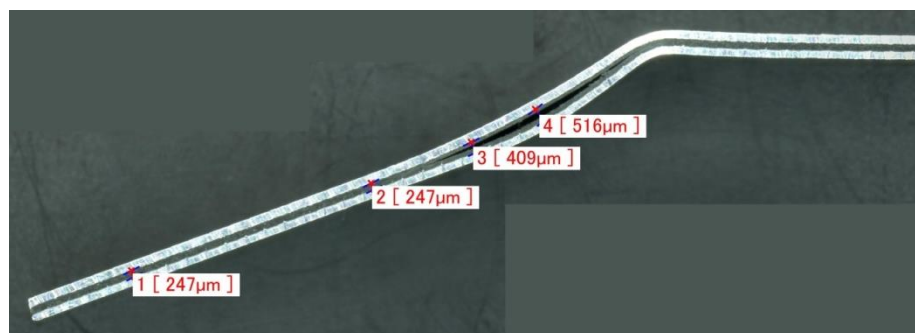


Figure 14: Failure in SBS samples with gaps

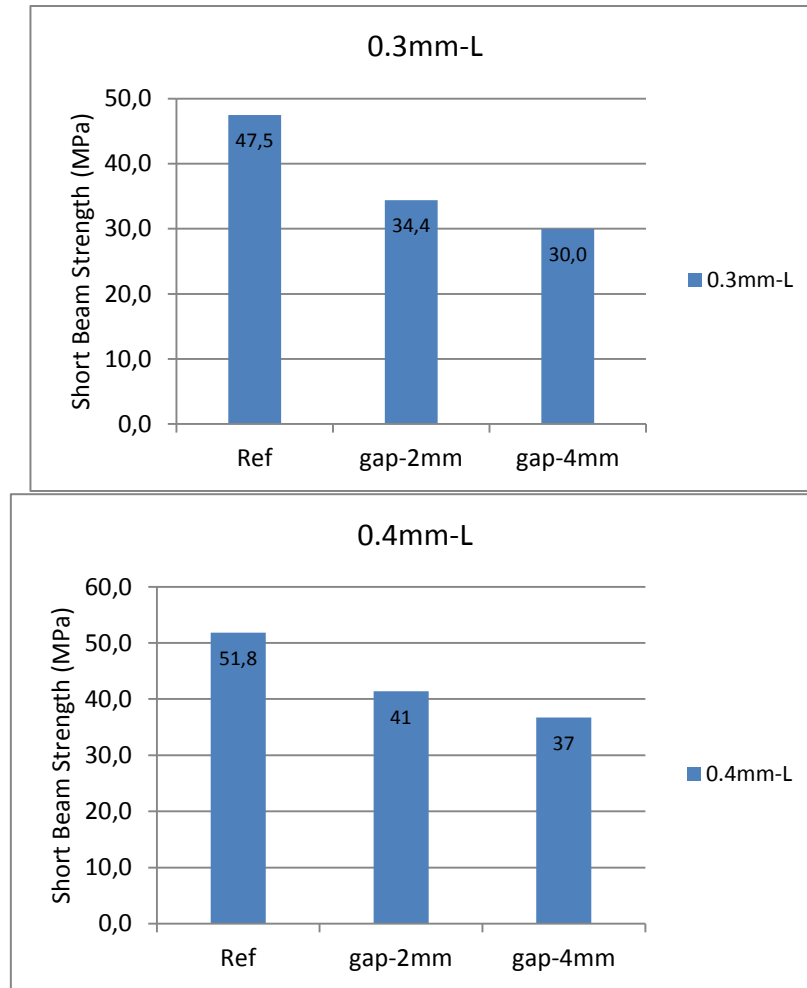


Figure 15: Short-beam test for GLARE-3-2/1 with gaps in L direction. Al. thickness=0.3mm & 0.4mm

Short-beam tests are carried out on GLARE with aluminium thicknesses of 0.3mm and 0.4mm with gap widths of 2mm and 4mm in the L-direction. For each configuration at least four tests are performed. As it can be seen from Figure 15, there is a decrease for gap widths of 2-mm and 4-mm.

5 Overlaps

During the automated tape layup, it could happen that some prepreg layers are overlapping to some extent. Regarding the mechanical properties, it is expected that there would be no decrease since fibres are locally accumulated. In order to validate this hypothesis, compression tests are done on samples with manually made overlaps of specific widths between adjacent prepreg layers. The test fixture and also the specimen configuration are shown in Figure 16 which is based on the test standard ASTM D6641 for compression testing of polymer composites [20]. For each configuration, three samples are made and tested.

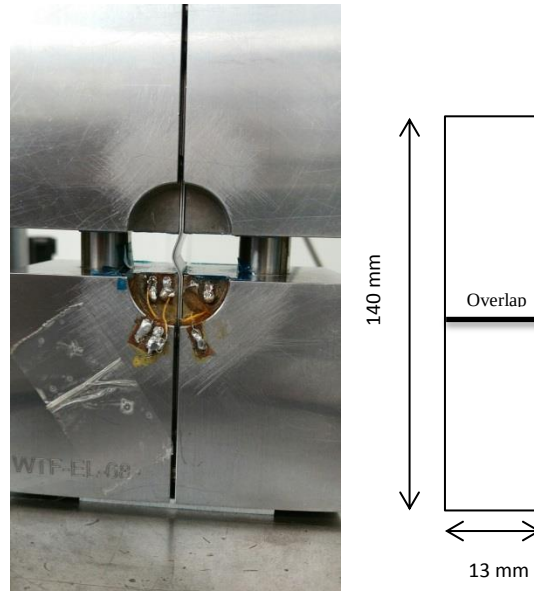


Figure 16: Text fixtures for compression tests with overlaps

This test setup allows for a space in the middle of the specimen to be free of the jig, allowing to have local thickness change due to the overlap. The overlaps are in the LT direction and placed in the middle of the samples. In the compression test, the load-carrying fibres are in L-direction which do not have any overlap. On the other hand, the LT-direction overlap could cause a local deformation in the aluminium sheet. Therefore, any effect from the locally weakened area of the overlap can be evaluated during this test. From Figure 17, it can be seen that there is only one ultimate failure in the specimens which seems to be a local buckling mode of failure. The overlap area (region A-B) is enlarged by a microscope in Figure 18. There is also a delamination in the deformed area that the aluminium sheet is deformed at the same place (overlap area). As discussed by Remmers & Borst in 2001[21], the initial delamination in the GLARE causes a local buckling in the aluminium layer. In our case, both of the aluminium layers, which are adjacent to the delamination area, are locally buckled.

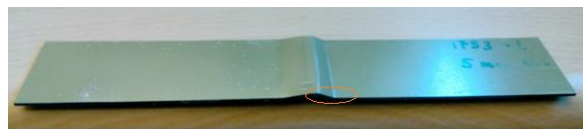
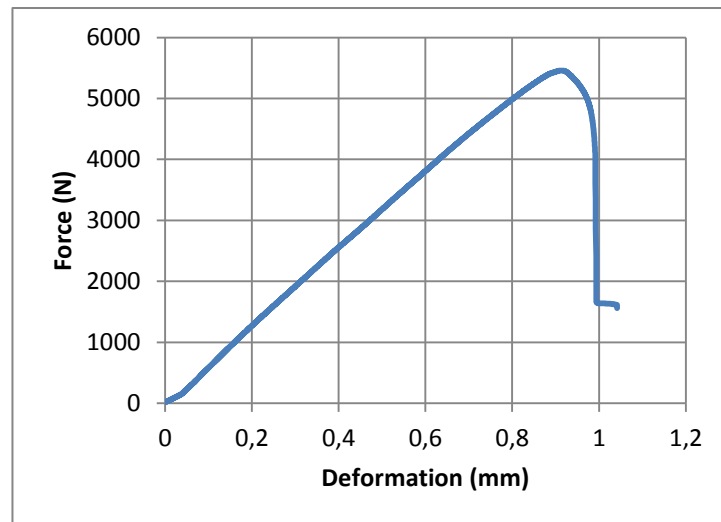


Figure 17: Typical behaviour of the samples with overlaps during compression tests

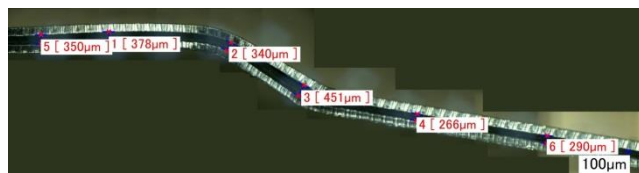


Figure 18: Failure in the compression samples with overlaps

The compression test results are shown in Figure 19, again the thickness of the aluminium sheets is chosen to be 0.3mm and 0.4mm. In both cases, the compression strength is rather increased by the presence of overlaps.

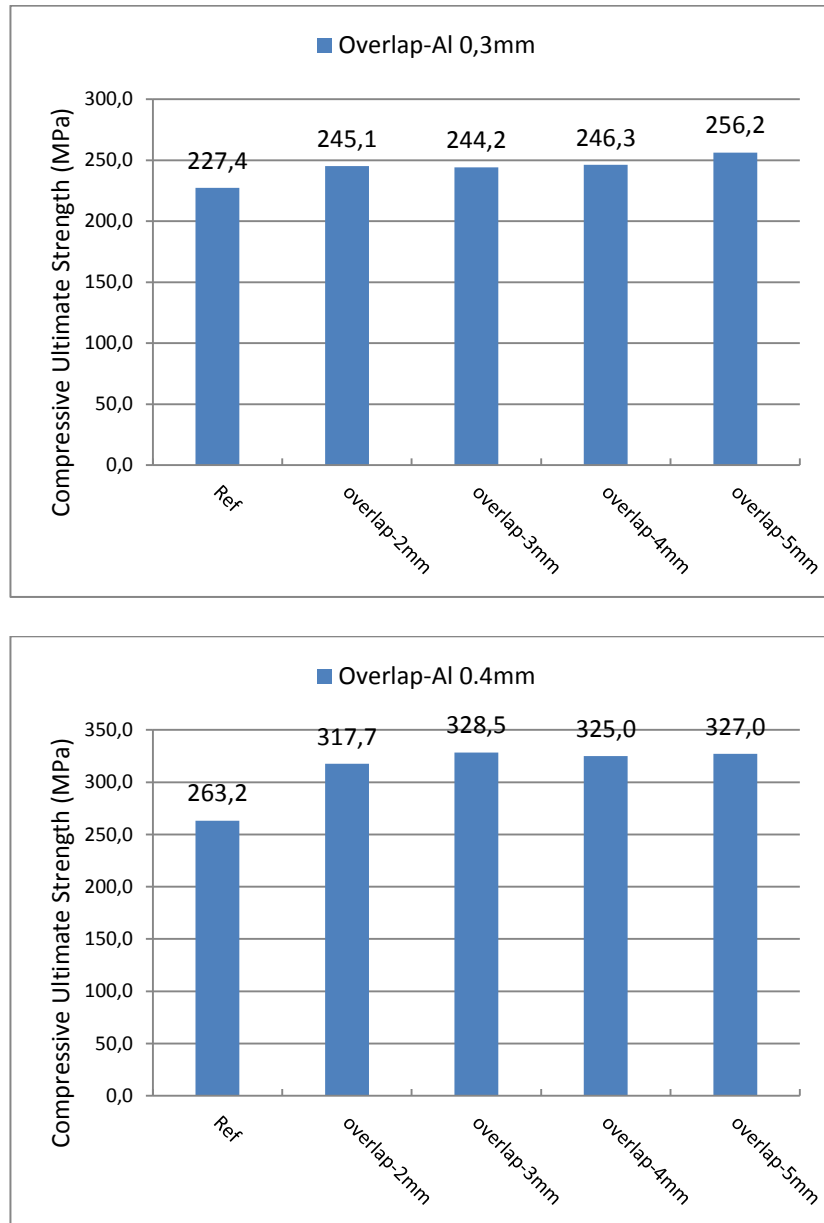


Figure 19: Compression test for GLARE3-2/1 with overlaps in LT direction. Al. thickness=0.3mm & 0.4mm

Although, there was no decrease in the compression strength, in order to make the conclusion on overlaps, tests on other properties are required. For example, it is possible that there is some influence on the fatigue fracture response by the overlap. This will be a topic to be followed in the next steps of this research. Another issue to consider is the appearance of the fuselage panels that, regardless of the mechanical performance, might be affected by the change of thickness and is not desirable for the airplane manufacturers.

6 Concluding remarks

In order to investigate the effect of defects during automated manufacturing of fuselage panels from GLARE, gaps and overlaps were studied as the most probable ones occurring during the tape layup procedure. Gaps produced a decrease in the mechanical performance of the material which was in different levels for different properties. Some properties like tensile and inter-laminar shear strength are more sensitive to the presence of gaps compared to the compression strength in which degradation started with wider gaps.

Of course, it should be mentioned that the L-direction gaps are created within the specific width of the specimens which means a certain ratio of gap to specimen width. This is a topic for further investigation to see what happens if this ratio changes. Two approaches are possible for this purpose: first to make an analytic prediction of the influence of the ratio “gap width/specimen width” using the static load equilibrium in the layers of the GLARE, accounting for the contribution of fibres and metal sheets. Second option is to make specimens having different widths with the same gap-width to see the possible influence on the properties reported in this paper.

On the other hand, overlaps increased the compression strength but this is not necessarily true for all other properties especially the dynamic (fatigue) ones. Other mechanical measurements are needed to conclude the severity of the effects due to prepreg overlaps. If overlaps are prone to be safe for the panels, specific amount of overlaps can be specified in order to prevent possible gaps between prepreg tape layers. Of course, for the purpose of preliminary investigation, limited number of specimens were made and tested. Actually, to have higher reliability on the exact degradations, more tests will be carried out in the future. Furthermore, for defining the manufacturing tolerances in order to avoid severe degradations in the properties of the panels, extended evaluations on different layups and gap configurations are needed.

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