New Enhanced Acoustic Damping Composite Material for the Aeronautics Industry

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Abstract. The present article investigates an innovative structural composite material concept with the additional functionality of acoustic damping. It is achieved by introducing an embedded elastomeric layer within the composite laminate, which constitutes a constrained layer damping (CLD) system. The main objective is to increase the acoustic performance of the baseline material, while its mechanical properties are maintained. In addition, material processability and inspectability have been considered as important drivers for the technology development. In order to identify the most promising candidate, a set of alternatives has been explored and analysed, giving rise to a compromise solution between the enhanced acoustic performance and the structural properties of the baseline material.

1 INTRODUCTION

The aim of the present study is to investigate a structural composite material concept with the additional functionality of acoustic damping. To this end, a standard modulus Carbon Fiber Reinforced Plastic (CFRP) prepreg is used as the baseline material. The damping performance of this substrate prepreg is enhanced by the addition of an elastomeric layer (EL), which becomes embedded in the composite structure when formed. The elastomeric layer, which is designed to co-cure with the thermoset prepreg, acts as part of a constrained layer damping (CLD) system. This confers vibration damping performance on the cured laminate.

The target application of the present study is the fuselage skin. The existing solution requires the manual addition of heavyweight, bespoke damping elements that are applied following part production and assembly. Such an approach adds inventory, time, weight and, ultimately, cost. The main drivers for the exploration of this technology are the potential for weight saving, maintaining or increasing production rate and the cost savings associated with these benefits. These are all key targets in the commercial aerospace sector. Weight savings and cost reductions are delivered in part by the embedded nature of the damping solution. The modified prepreg can be processed using established manufacturing techniques such as

Automated Fibre Placement (AFP) or Automated Tape Laying (ATL). This allows for high production rates.

Acoustic performance of a range of elastomers and composite structures was assessed within the range -55°C to 70°C using a modified Oberst beam test. Modal analysis was performed on the resonant peaks of test specimens, and the loss factor for the second and third resonant modes were determined using the half-power bandwidth method.

With regard to structural performance, it would be desirable to maintain substantially the same level of performance as the reference CFRP. The introduction of a rubbery layer within a laminate is likely to have a detrimental effect on its mechanical performance. However, it is recognised that a decrease in mechanical performance may be tolerable if a substantial weight saving or cost decrease can be achieved. Additional measures may then be taken to recover performance. A mechanical test campaign has been performed in order to quantify the structural behaviour of the multifunctional solution proposed.

It has been demonstrated that damping effectiveness is related to the relative amount of shear stress in the x-y plane, the best damping performance being associated with the positioning of the damping element at the location of maximum shear during bending. Placing the damping element centrally within the simple test specimen of this study was found optimal from a damping perspective, but then delivered the poorest mechanical performance. Strategies to mitigate this contradiction were explored.

2 CLD SYSTEM

The present technology is conceived to enhance the acoustic damping performance of a structural layered CFRP. The elastomeric layer is deposited uncured over a thermoset prepreg CFRP layer as shown in Figure 1. In this way, the hybrid material is readily processable and is suitable to be used in ATL and AFP processes.

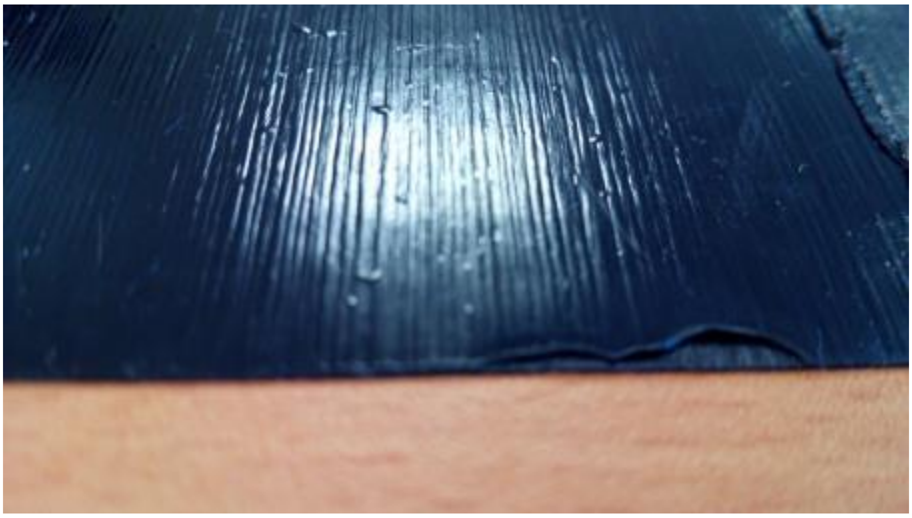

Figure 1: Detail of the elastomeric layer, deposited over a CFRP layer.

Figure 2 shows a laminate cross section, where the EL is perfectly visible at the centre of a composite panel.

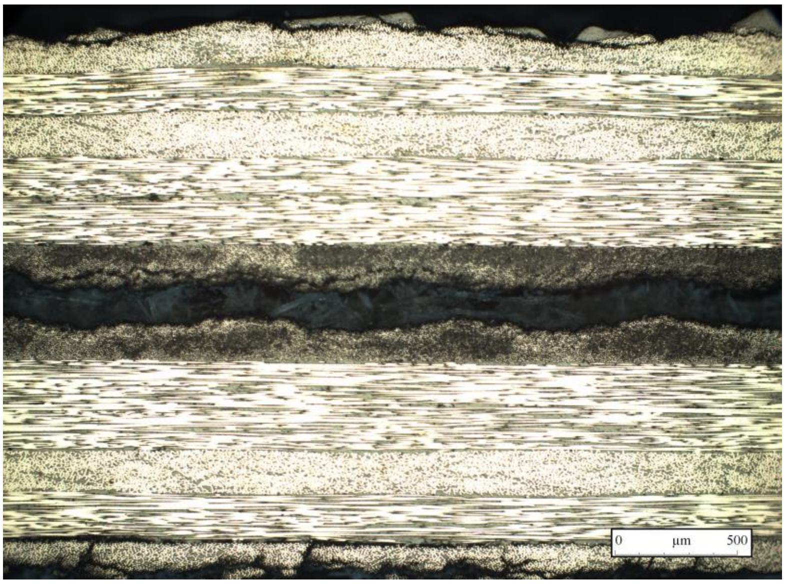

Figure 2: Microscopy of the transverse section of a coupon with a centred elastomeric layer.

2.1 Elastomer formulation

A polyisoprene based rubber was selected following the preliminary screening of three engineered rubber compounds: a nitrile rubber compound (NBR), an ethylene propylene diene monomer rubber compound (EPDM), and a polyisoprene based rubber compound. For the temperature range of particular interest, -30°C to 20°C, the polyisoprene based rubber compound performed the best, with the highest loss factor for resonant mode 2 in the range 800 Hz to 1100 Hz.

The elastomer is formulated to vulcanize, and thus co-cure, in the same conditions as Hexcel's 180°C epoxy prepreg systems. The novel use of an unvulcanised system takes advantage of the adhesion properties of the material to give benefits in automatic processability.

2.2 Laminate architecture

One of the most critical decisions of the present research project has been to propose a laminate architecture that fulfils both acoustic and mechanical requirements. To this end, a [+45/0/-45/0/0/90]s laminate is used as the reference lay-up. On this basis, one or more elastomeric layers have to be embedded within the reference lay-up in order to maximise the acoustic performance with the minimum effect on the mechanical properties.

In a first phase, the main driver for the selection of the laminate architecture was the fulfilment of the acoustic performance at minimal additional weight. Subsequently, several alternatives have been tested in order to keep the mechanical performance above an acceptable level. The definition of each architecture contemplates the following modifiable parameters:

- Position of the EL. The EL is placed at a certain distance from the laminate mid-plane.
- Thickness of the EL. Normally, an elastomeric layer thickness increment implies

better acoustic performance, compared with thinner layer in same position, penalizing weight.

- Number of EL. The usual configuration involves just one elastomeric layer. However, a trial has been carried out considering two symmetric off-centred films inserted within the laminate.

3 TEST PLAN

After a preliminary phase in which a great number of alternatives were proposed and investigated, a concise test plan is conceived, in which the most promising laminate architectures are considered. The test plan is conducted in order to achieve the best combination of mechanical and acoustic performances. Although other targets are sought and analysed, as processability and non-destructive inspectability, the preferred laminate architecture is selected just in view of the mechanical and acoustic results. The alternatives analysed in the test plan are shown in Table 1.

Table 1: List of tested configurations

Code	Designation	EL formulation	EL thickness	Lay-up	Additional weight (gsm) (1)
REF	Reference	--	--	[+45/0/-45/0/0/90]s	0
ARC-01	Centred	E11516/9	100 μm	[+45/0/-45/0/0/(90/EL)/90/0/0/-45/0/+45]	120
ARC-02	External with four constraining plies (100 μm)	E11516/9	100 μm	[-45/+45/+45/(-45/EL)/+45/0/-45/0/0/90/90/0/0/-45/0/+45]	1296
ARC-03	External with four constraining plies (200 μm)	E11516/9	200 μm	[-45/+45/+45/(-45/EL)/(EL/+45)/0/-45/0/0/90/90/0/0/-45/0/+45]	1416
ARC-04	Two symmetric EL	E11516/9	2x100 μm	[+45/(0/EL)/-45/0/0/90/90/0/0/-45/(EL/0)/+45]	240

(1) With respect to the reference architecture. Current SoA implies approximately 3000gsm.

It should be noted that the architectures that require the use of constraining plies (ARC-02 and ARC-03) are heavier (with respect to the reference laminate). However, these architectures are optimal for the structural performance, since the EL is moved outside from the coupon centre.

3.1 Acoustic performance

As a target for the investigation a temperature range of interest of -30°C to 20°C, and a loss factor of ≥0.05 for the second and third resonant modes was defined in agreement with the Airbus S.L. The targets reflect the early technology stage of the concept, and do not constitute a full specification for the damping requirements of an aircraft.

Acoustic performance is assessed using a modified Oberst test method. The method is based upon the testing standard ISO 16940 [1], with two modifications: i) the representative layup is used instead of a 4mm thick beam, ii) the test is performed at multiple temperature ranges in 5°C ± 1°C intervals. To accomplish this, a 300 mm steel stinger rod at 5 mm diameter is used to hold the sample in an environment chamber for testing. The stinger rod has an undesirable contribution effect to the results at 600 Hz, 700 Hz and 950 Hz, but is sufficient for the benchmarking and comparison purposes of this study. The results of acoustic testing of resonant mode 2 are shown in Figures 3 and 4.

From the results, two important design variables for a successful CLD approach can be extracted; the thickness of elastomeric layer, and the proximity of the EL to the central axis of the material.

In the interest of minimizing the additional weight of any new structural material, it is clear from the results that for a given material the proximity to the central axis is important for achieving the maximum damping potential of this technology. ARC-01 has the highest peak loss factor performance of all the samples tested with the smallest amount of additional weight. This is because the elastomeric layer is placed in the location of the laminate that experiences the highest shear stress during bending, maximizing the potential for energy dissipation through shear deformation. Whilst the correlation between shear stress and damping performance was not explicitly investigated as part of this study, this is a reasonable conclusion when one considers that the primary mechanism for energy loss in CLD systems is shear deformation.

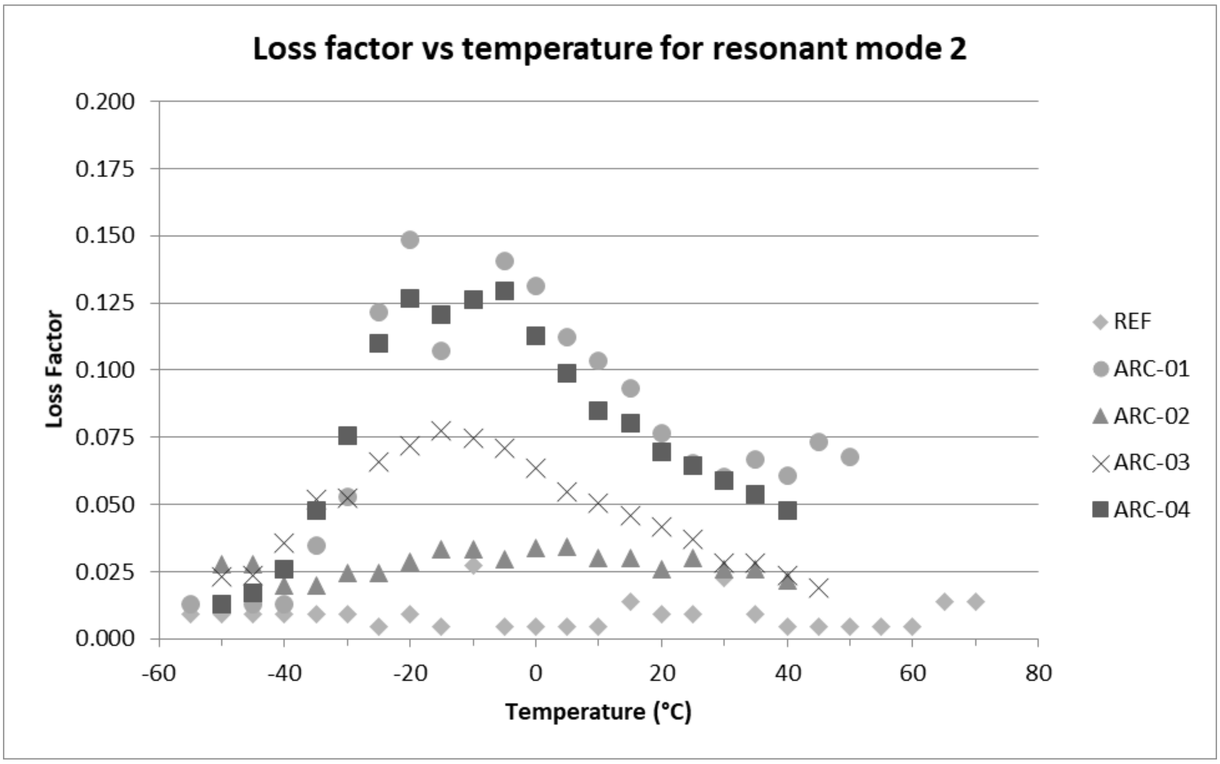

Figure 3: Loss factor vs temperature for the second resonant mode of tested samples.

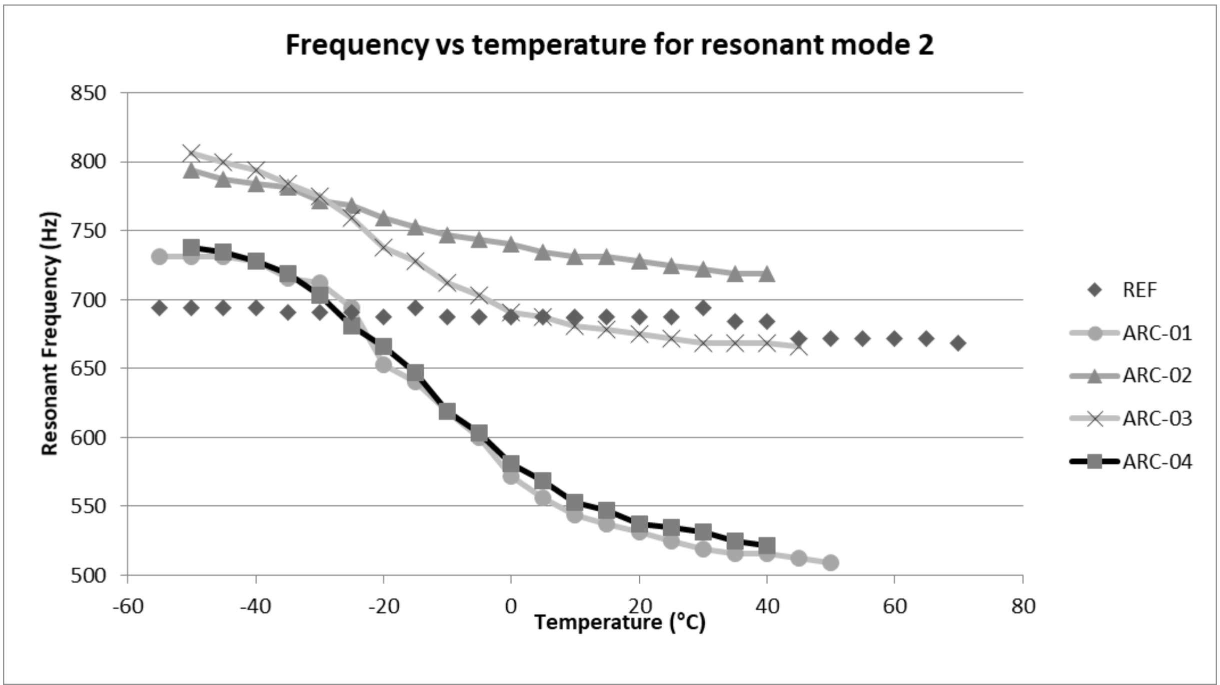

Figure 4: Resonant frequency vs temperature for the second resonant mode of tested samples.

3.2 Mechanical performance

From the requirements presented in the introduction, the mechanical performance of the laminate should remain at the same level as the reference, or slightly below if provided a significant improvement on the component weight with respect to the current state of the art (~3000 gsm).

Mechanically, the elastomeric layer acts as a physical division or barrier inside the laminate. The shear loading capacity of the elastomer is very limited due to its low stiffness. In fact, this is why the elastomeric layer has an outstanding acoustic performance. Clearly, this effect is counterproductive from the mechanical point of view, and hence it is desirable to have the EL as far away from the laminate centre as possible.

In order to test the influence of the elastomeric layer in the laminate a mechanical test campaign is conducted. Although a complete characterization has been performed, it was the 3-point bending test (acc. to EN2562 type A [2]) that leads to the most valuable results. The results are compared with respect to the reference in Table 2.

Table 2: Mechanical performance of the laminate architectures tested, with respect to the reference, based on 3-point bending test

Code	3-point bending test strength (%) (1)	Failure mode
REF	100	Bending
ARC-01	50.5 (2)	Out-of-plane shear

ARC-02	102	Out-of-plane shear
ARC-03	117.8	Out-of-plane shear
ARC-04	47.3	Out-of-plane shear
(1) With respect to the reference coupons. (2) The test have been carried out with Uni-Directional coupons (UD), the results are compared with a UD CFRP set of coupons.		

Here, architectures ARC-02 & ARC-03 show an improved mechanical strength with respect to the reference, which is expected since it is the same laminate with an extra EL and 4 additional plies. The coupons with 200 µm of EL thickness show higher strength than the coupons with 100 µm EL.

Finally, it should be mentioned that the failure mode changes with the inclusion of the elastomeric layer. The coupons with elastomeric layers normally fail by a combination of out-of-plane shear and bending, while the failure of the reference coupons is caused by pure bending. Figure 55 shows the differences on the failure of both configurations, the out-of-plane shear failure affects uniquely to the interface of the elastomeric layer with the adjacent CFRP layers, causing a slippage phenomenon during the test. This phenomenon causes the early failure of specimens with architectures ARC-01 and ARC-04.

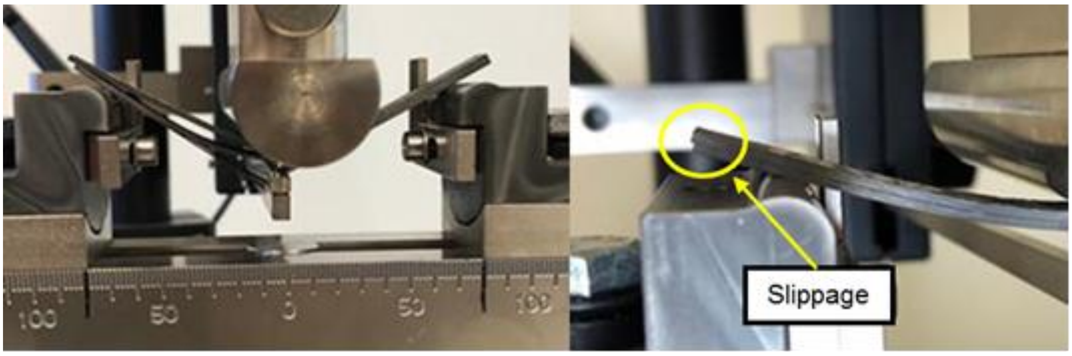

Figure 5: Bending failure mode of a reference coupon (left) and slippage phenomenon on a coupon with elastomeric layer (right).

3.3 Overall performance

The following conclusions are extracted by comparing the hybrid laminates with respect to the reference:

- The elastomer placed centrally gives rise to the best acoustic performance at the expense of reducing substantially the mechanical performance. The best solution from the structural point of view is to position the elastomeric layer near one of the external faces, under some constraining plies.
- Using a thicker elastomeric layer is beneficial from the acoustic point of view, and has been reported not to affect the mechanical performance negatively. Elastomeric layers up to 200 µm have been analysed.

- The use of two symmetrical elastomeric layers enhances the acoustic performance, but the mechanical performance is excessively poor.

Thus, the best combination of mechanical and acoustic performances is reached by using the configuration designated as ARC-03. A 200 µm EL is placed off-centre under 4 constraining plies.

5 OTHER ASPECTS OF PERFORMANCE

5.1 Processability

The material has been slit to 300 mm, 150 mm and 75 mm for Automated Tape Laying (ATL) production, using a release liner to avoid the self-bond of the material. It is always laid-up with the EL positioned upwards, and the CFRP ply downwards.

ATL manufacturing trials demonstrated that the adhesion of the EL to the next ply of CFRP is high enough to facilitate standard lay-up processes. In addition, the automated trimming systems have demonstrated an excellent performance with the hybrid material.

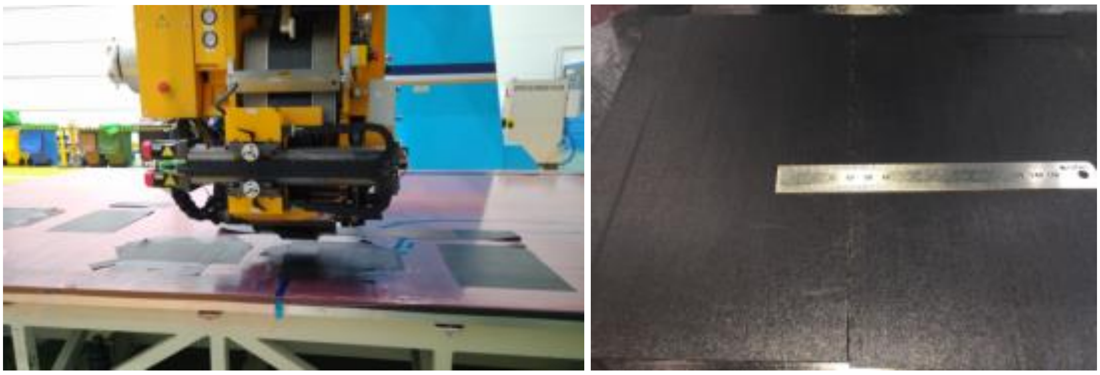

Figure 6: Automated deposition of the hybrid material by using ATL.

In addition to ATL material, it has been produced slit-tape material for Automated Fibre Placement (AFP) lay-up processes. However, no manufacturing trials have been performed for the time being.

5.2 Non-destructive testing (NDT)

In CFRP laminated composites, it is essential to be able to detect internal defects in the laminate, since hidden damage could lead to an unexpected failure of the structure. Usually, the detection and characterisation of defects is performed by using non-invasive techniques, such as the ultrasonic inspection (US).

Some interesting conclusions are drawn from the analysis of inspected CLD specimens. The elastomeric layer embedded into the laminate behaves as a damper that attenuates the ultrasonic wave. In fact, an attenuation of approximately 6 dB is found on the CLD specimens with respect to the reference (just CFRP) specimens. This attenuation is not worrisome, since it is uniform and well distributed over the surface.

In addition, a 4-step flat panel with thicknesses of 2.308, 3.412, 4.516 and 5.620 mm respectively and Armalon inserts of 4x4 mm and 6x6 mm as defects has been manufactured and US inspected. The conclusions obtained are that the defects are detectable by manual and automatic inspection. However, the depth of the defects is hardly identifiable due to the elastomer insertion into the laminate, see Figure 7.

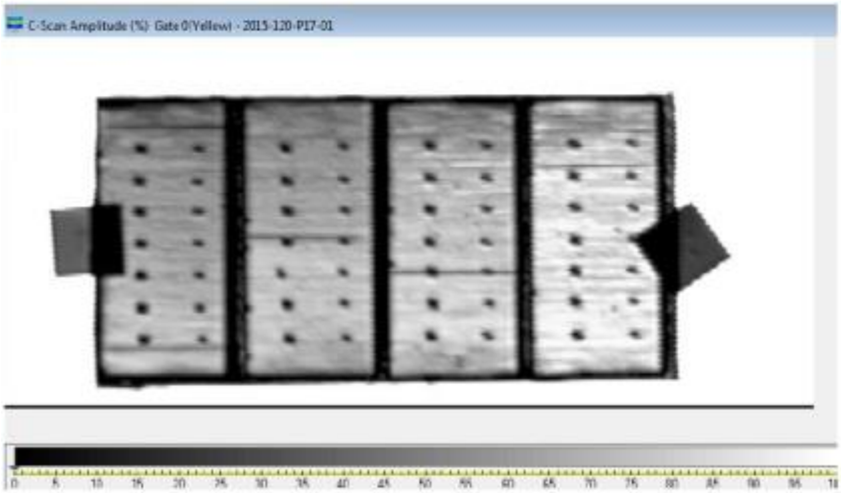

Figure 7: Amplitude C-Scan for a 4-step flat panel manufactured. Intentionally introduced defects are visible as dark spots.

6 CONCLUSIONS

The best acoustic performance is reached by placing the EL centred with respect to the laminate thickness. In this way, the energy dissipation provided by the EL is maximised, and thus the performance of the damping is optimal. On the contrary, the mechanical performance is benefited by a laminate architecture in which the EL does not interfere with the load path. This is achieved by positioning the EL outside of the load path of the structural laminate, and by introducing additional constraining plies to ensure that the EL experiences the required shear deformation during bending. In this way, the CFRP plies placed beyond the “structural part” of the laminate are important design variables, along with EL thickness and the type of EL, for achieving any specified level of acoustic performance.

A compromise solution for acoustic and mechanical performance has been found, which consists of placing an elastomeric layer of 200 µm thick externally under four constraining plies. The multifunctional material developed has proven itself interesting for the aerospace industry in terms of acoustic and mechanical performance. Additionally, the automated processability of the CLD system has been demonstrated, as well as its inspectability by means of NDT.

Finally, the drivers initially suggested for this development are completely fulfilled. In the first place, a potential weight saving is foreseen with the chosen architecture with respect to the current SoA. Secondly, the production rate could be significantly improved, since the investigated CLD system is suitable for automated lay-up processes, while the current reference requires a manual installation process. Improvements in production rate yield a significant reduction in the cost of the finished component.

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