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DESIGN AND EXPERIMENTAL VALIDATION OF A *MDAF* BONDED STRUCTURE FAIL SAFE DAMAGE ARREST CONCEPT

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Abstract: The need for light-weight and cost-effective fibre reinforced airborne primary structures, drives the industry towards more integral design concepts. Adhesive bonding is increasingly employed as an attractive alternative to mechanical fastening. Aside from the weight reduction due to elimination of fasteners, the high stiffness of bonded joints and the smooth load transfer they provide, are major advantages of this concept. However, the lack of reliable bonded-joint damage-growth analysis combined with the inadequacy of commercially available non-destructive inspection methods to evaluate the strength of bonded joints – has inhibited full adaptation of such joining concepts. This work presents an innovative fail-safe *MDAF* (Mushroom Damage Arresting Feature) fail-safe crack arrest concept for bonded joints in order to ensure predictable slow damage growth. It was demonstrated both by numerical *FE* analysis and mechanical testing that by implementing a series of unique geometrical mushrooms and recesses along a stiffened panel's stringer foot, damage arresting capability may be achieved and once an initially dis-bond crack reaches the mushroom front, after an expected loading event, it will be stopped there and a significantly additional energy will be required to overcome the mushrooms bond-line and to further propagate the dis-bond crack. Subsequently, the load will drop and a rapid unstable crack propagation will take place until the next mushroom is reached, where additional energy will be required again to propagate the crack and so forth. On the other hand, it was shown that for the standard baseline specimen with straight stringer foot, an unstable catastrophically damage propagation is expected once the critical load is reached.

Keywords: composite structure, bond-line, damage arresting concept, FE analysis, experimental validation

INTRODUCTION

The US department of defence joint service specification guide No. JSSG-2006 for aircraft structures outlines the nature and the certification approach for fail-safe crack arrest structures (section 6.1.21). "Crack arrest fail-safe structure is structure designed and fabricated such that unstable rapid propagation will be stopped within a continuous area of the structure prior to complete failure. Safety is assured through slow crack growth of the remaining structure and detection of the damage at subsequent inspections. Strength of the remaining undamaged structure will not be degraded below a specified level for the specified period of unrepaired service usage". While previous attempts of Damage arresting concepts design for bonded joints were based on adding fasteners or "Z" pins, this work presents a fail-safe damage arresting concept for bonded joints that is based on novel design of the bond-line itself in order to ensure predictable slow damage growth.

A representative stiffened panel, reinforced by a bonded "T" section stringer, was selected to demonstrate this innovative design feature, exhibiting the following capabilities: slow matrix / adhesive damage growth under static and fatigue loading, matrix/adhesive damage arresting design for minimum load-drop relative to a panel without the design feature, subjected to similar loads. The designed damage arrest concept performance was numerically evaluated and successful tested. Controlled damage growth was demonstrated, validating numerical predictive capabilities.

DESIGN CONCEPT

A typical common aerospace (composite IM7 carbon/Ep prepreg Tape and AS4 carbon/Ep prepreg Fabric) structure stiffened panel, reinforced by bonded "T" section is presented in Figure 1. In the panel’s centre, a new innovative fail-safe damage arrest stringer concept – *MDAF* (Mushroom Damage Arresting Feature) is introduced. This novel arresting feature is based on "modified-stiffness" concept and is implemented using water jet manufacturing technique, where along the stringer flanges, series of geometrical mushrooms and recesses characterized by geometrical parameters such as recesses width, mushroom width, spacing and radius are introduced. It was demonstrated that these mushrooms, may reach the project goal and enable a slow and controlled dis-bond crack propagation growth and once an initially dis-bond crack reaches any of the mushroom fronts, it will be stopped there and only after an additionally significantly loading event (compression + pull) it may overcome the mushrooms bond-line and propagate further to the next mushroom.

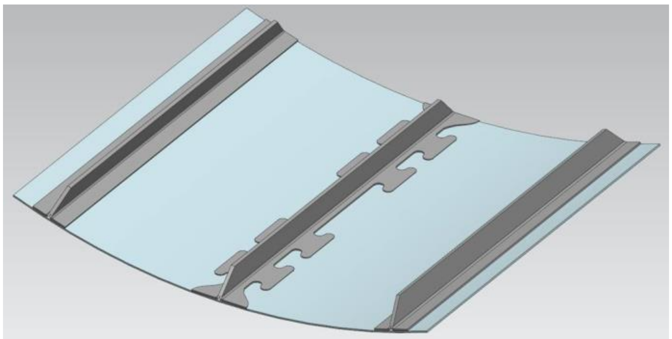

Figure 1: Typical stiffened panel

DESIGN OPTIMIZATION CYCLE

Design Objectives:
The following design goals were defined: (a) minimal weight increase relative to a panel without a design feature; (b) at least the same static load capacity for the *MDAF* in compare to a reference Flat specimen (c) slow adhesive damage growth under static / fatigue loading; (d) minimum load-drop relative to a panel without design feature, subjected to similar loads; (e) low manufacturing cost

Design Constraints:
The following critical design constraints were defined: (a) maximum/minimum strain criteria; (b) skin/stringer buckling is not allowed even after full skin/stringer separation is obtained; (c) the proposed MDAF concept shall have an equal bonding area compared to the "straight flanges" stringer configuration.

Preliminary Design:

MSC.NASTRAN and PATRAN finite element static analysis were performed in order to optimize (from weight, strength and icrack arresitng effieciency), the design arresting feature geometrical parameters such as the mushrooms unique geometrical shape (radius, area), mushrooms spacing, thickness and layup.

Concept validation:

SCB coupon (Single Cantilever Beam) was used to validate the proposed *MDAF* arresting feature. As shown in figure 2, two stringer flange design configurations were analyzed and tested: (a) Baseline flat configuration and (b) *MDAF* configuration with an equivalent bonding area. Both with an end initial dis-bond (represented using a teflon film). The tests were performed at room temperature and the specimens were loaded at a displacement rate of 10mm/sec. The specimen's skin edges were fixed by bolts to a rigid aluminum plate and the force was vertically applied through a piano hinge and with a 5 meter height offset in order to ensure that the loading direction remains essentially vertical during the test, preventing any shear loading along the dis-bond front,

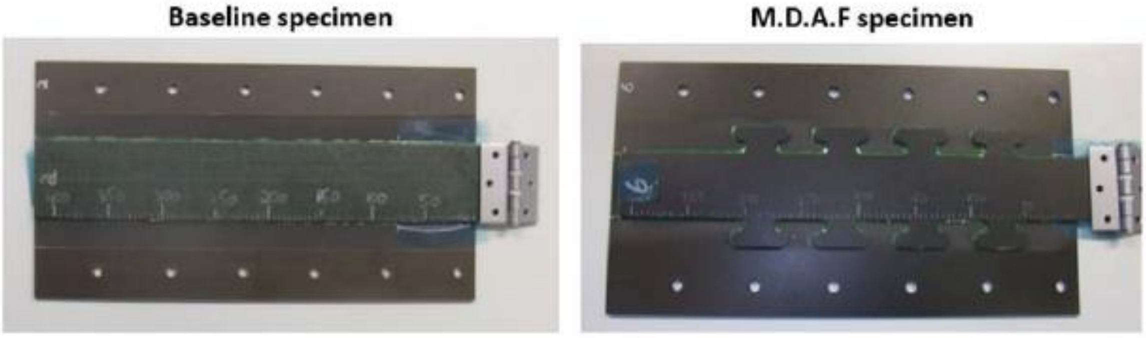

Figure 2: Typical stiffened panel

As shown in the force-displacement response illustrated in figure 3 it is seen that the proposed *MDAF* concept can actually inhibit the development of a dis-bond defect and as the dis-bond damage reaches the first mushrooms front, a significant additional energy is required to further enlarge and propagate the dis-bond crack. On the other hand, the baseline specimen test revealed unstable damage propagation once the critical load was reached.

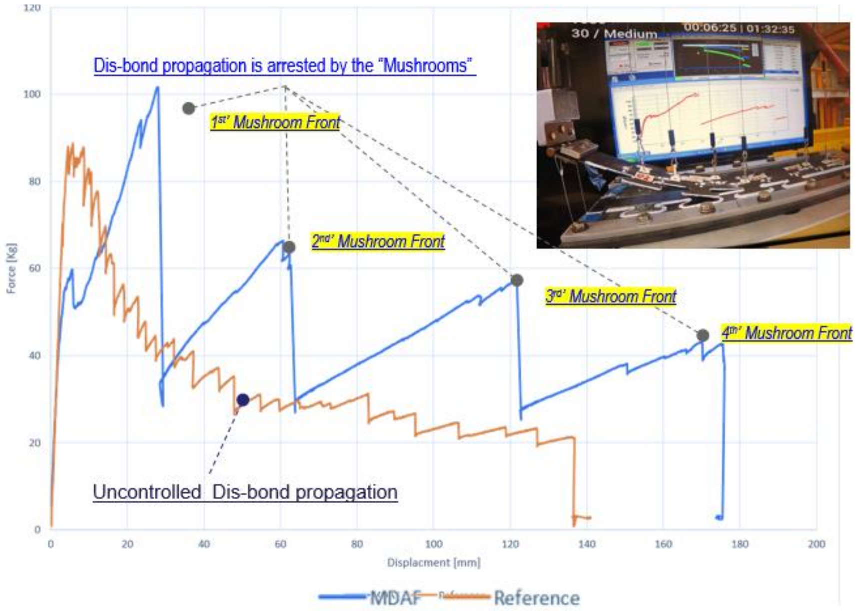

Figure 3: SCB specimens Load/Displacement curve and test fixture

Cohesive interface characterization:

The Cohesive skin to stringer interface properties were characterized using DCB (Double Cantilever Beam) coupon testing and were used to calibrate the numerical MSC.NASTRAN Finite element analyses for the element and SCB testing. Mean value of 1.7mJ/mm^2 was obtained.

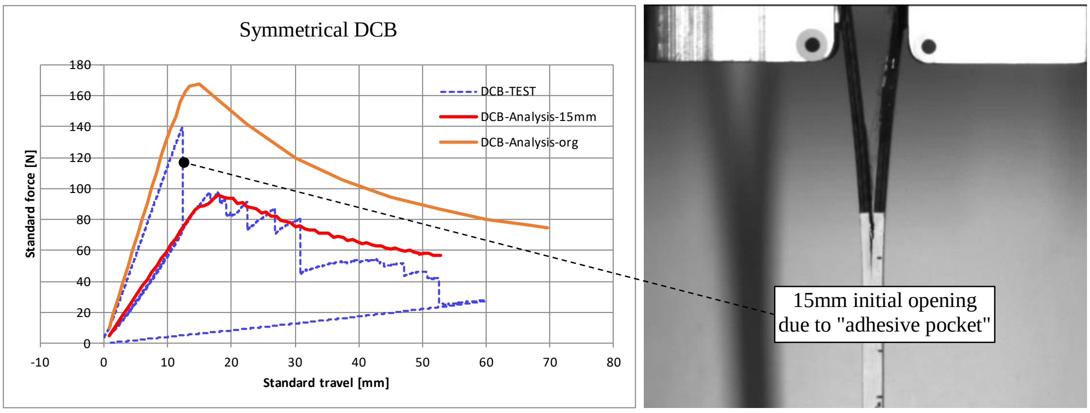

Figure 4: DCB testing and F.E calibration

Component Testing Experimental Results

I. Shear Mode Experimental Verification:

As shown in figure 5, "double shear" reference and *MDAF* specimens for both static and fatigue loading were designed and manufactured. All Specimens were fabricated using M21 prepreg tape with quasi-isotropic layup (skin thickness=6.9mm; stringer thickness=4.8mm) and were bonded using AF163-2 film adhesive (thickness=0.2mm). By implementing a Teflon strip along the specimen's span, an equal bonded surface area for both the reference and the *MDAF* specimens, was reached. The test specimens were loaded in tensile displacement-controlled loading for the static test and in load-controlled loading for the fatigue test in a 110Kip Servo-hydraulic MTS test frame with hydraulic grips. Several inspection systems were used: Ultrasonic inspections - both in-situ and pre/post experiment were conducted to provide the iterative information of the dis-bond growth. Several methods were used during the fatigue loading to assist personnel when to conduct these inspections. Acoustic emission was used to help and determine possible dis-bond growth based upon the sound level heard by the sensors. The sensors were also purposefully placed, and the software set to provide location data of the sounds. The Thermography camera provided indication of dis-bond propagation such that the personnel could visualize the growth towards the *MDAF*. Digital Image Correlation provided full field strain information to help understand the redistribution of strain as the dis-bond growth moved from one *MDAF* to the next. All of these systems were used to provide the personnel the ability to compare and correlate responses to better understand the performance of the *MDAF*.

Figure 5: Reference and MDAF shear specimens

Figure 6: shear specimens test Rig

A similar failure load was obtained for both reference and *MDAF* specimens and for both a full uncontrolled dis-bond propagation occurred after reaching the maximal load. Although DIC measurements revealed high strain peaks (figure 7) at the 1st pair mushrooms (suggesting of the mushroom's geometrical efficiency), the load drop was apparently too high, and the 2nd pair mushroom's features were not able to prevent a total dis-bond crack propagation as was demonstrated for the SCB specimen [1]. Further effort is required to design and evaluate the appropriate geometrical and stiffness properties for the shear specimen.

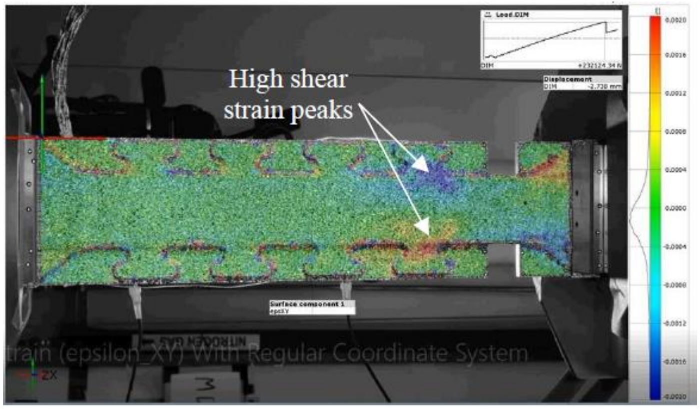

Figure 7: Reference and MDAF shear specimens

The *MDAF* fatigue specimen was loaded according to table 1, where each cycle block consisted of 999 cycles with load level of 0.7*Fs/1.5 (Where Fs represents the failure load obtained in the static test) and single one Limit load (Fs/1.5) cycle that was applied after each block. Ultrasonic inspections were made during the fatigue test and as shown in figure 8, a slow dis-bond propagation was obtained and total of 108 Fatigue Block cycles were required to cause a full dis-bond damage.

Load Level	Tensile Load		
	max	min	cycles
1	0.7*Fs/1.5	0	999
2	Fs/1.5	0	1

Table 1: Fatigue cycle blocks

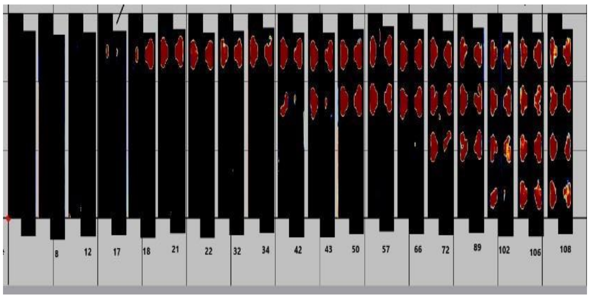

Figure 8: Phased Array UT inspection during Fatigue test (red color indicates dis-bonds)

II. <u>Stiffened Skin/T-stringer in Pull Mode</u>

A stiffened skin with T-stringer (2.2mm back to back, L-shaped channels stringers were fabricated using UD IM7/8552 and PW AS4/8552 prepreg material with quasi-isotropic layup; The stringers were bonded to a 6.9mm M21 skin using AF163-2 film adhesive) subjected to tensile displacement-controlled Pull loading were also investigated and it was demonstrated both by numerical F.E analysis and mechanical Pull test that the *MDAF* feature is efficient too in a T-shaped stringer compared to reference panel with a standard stringer constant foot width (the same bond-line area was designed for both specimens). It is shown in figure 9 that siginificant additional energy was required to propogate the initially dis-bond damage (implemented by a 110mm thin *Teflon* film) through even the 1st mushrooms set (red curve) then for the entire bond area with the refernce specimen (blue curve)

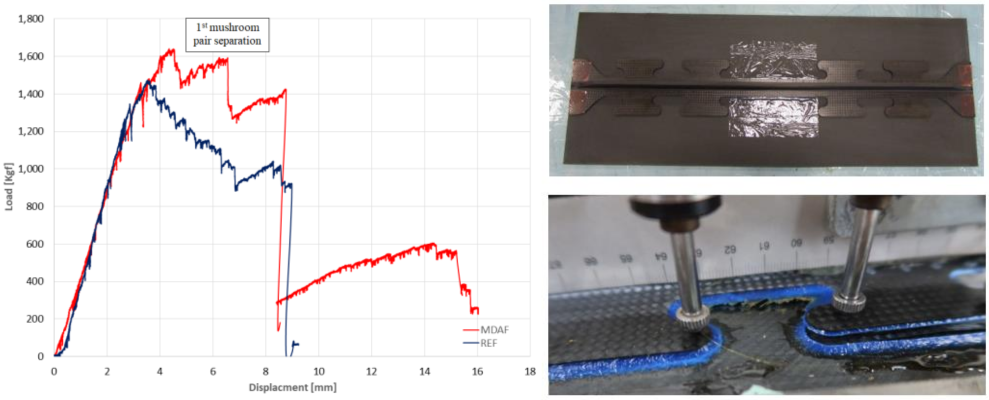

Figure 9: Pull Test - MDAF V.S. Reference Stiffened T -Stringer Skin Load/Displacement curve

III. <u>Stiffened Skin/T-stringer in combined Compression and Pull Mode</u>

The next step is to perform proof testing for a reference and a *MDAF* skin/stringer panels under combined pull and compressive loading, both in static and fatigue loading and to validate the concept in combined and more realstic loading secanario.

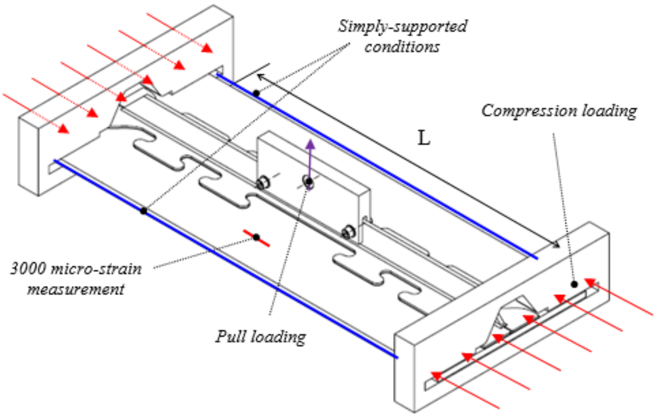

Figure 10: Reference and MDAF shear specimens

At the first stage, a load controlled compression loading will be applied at the panel's edge to cause tyipical damage tolerance strain levels in the composite structure. Then, tensile displacement-controlled Pull loading will be applied until the initially dis-bond damage (implemented by a 110mm thin *Teflon* film) will fully propagate and a full skin/stringer separation shall be obtained. Figure 11 shows the expected Load/Displacement curve expected for the *MDAF* specimen and the load peaks required to overcome the mushrooms bonding.

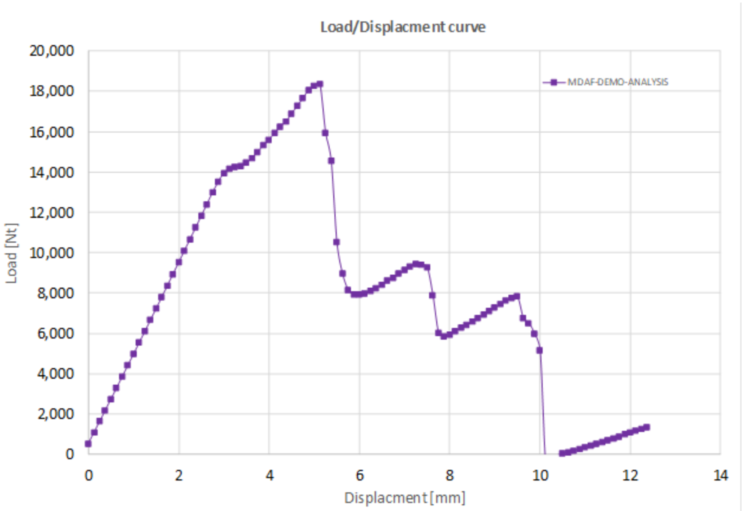

Figure 11: Load/Displacement curve for the MDAF specimen based on F.E predictions

Figure 12 show the strain level after a full dis-bond propagation is reached, suggesting no pre-mature skin or stringer failure is expected before a full skin/stringer separation occurs.

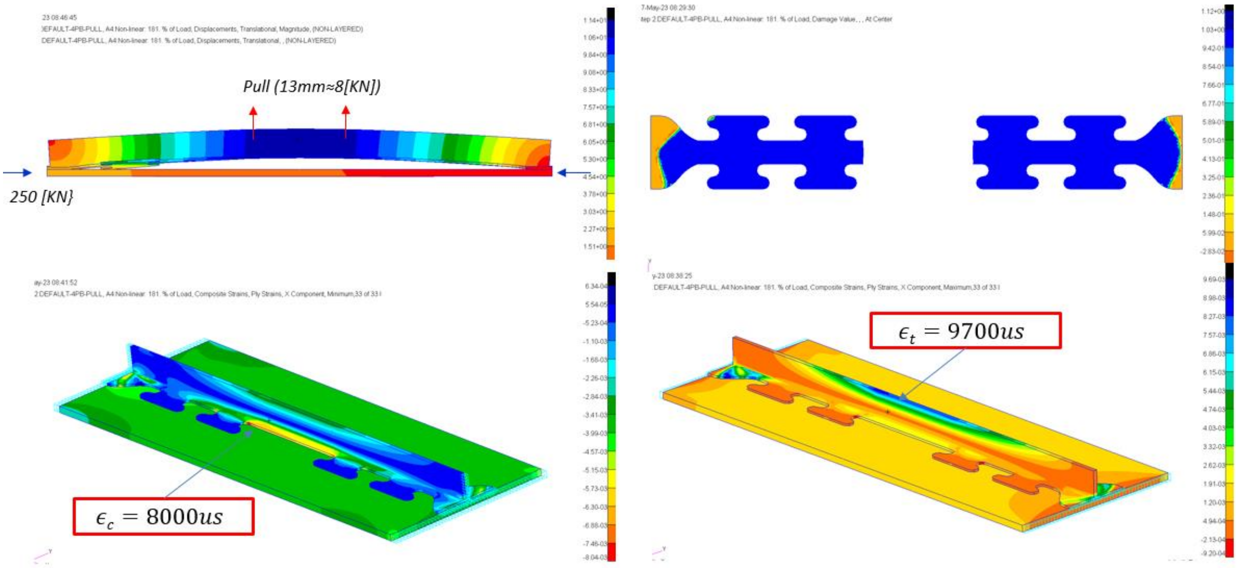

Figure 12: Reference and MDAF shear specimens

The test will include the use of a full DIC measurements, S.G, deflectometer and in situ/pre/post live Acoustic emissions, an incremental phased array C-scan UT inspection and Thermoelastic stress analysis, in order to capture damage propagation.

Summary and Conclusion

An innovative fail-safe crack arrest concept for bonded joints was developed and successfully validated for Mode I (tensile mode) and Mode II (shear mode) by mechanical experiments. The fail-safe concept was validated on a bonded stiffened panel, but may similarly apply to different structural parts, such as wing spars and ribs.

Further research and development should include design optimization, analysis, and experimental validation for combined Mode I and Mode II loading conditions. The final paper will include the details of the design, analysis and testing of the shear specimens.

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References

[1] D. Bardenstein, A. Lukatsky, Z. Deutsch, A. Levi-Sasson, I. Kressel, N. Shemesh, and S. Clay, “Design and Experimental Validation of a Bonded Structure Fail-Safe Damage Arrest Concept,” Proceedings of the AIAA SciTech 2022 Conference, San Diego, Jan 2022.