FATIGUE BEHAVIOUR AND DAMAGE TOLERANT DESIGN OF COMPOSITE BONDED JOINTS FOR AEROSPACE APPLICATION

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Abstract

Today the application of bonding technology for primary aerospace structures is limited due to the certification guidelines and standard means of comply. State of the art is the widely used chicken rivet which is limiting the benefits of the application of composite bonded joints due to thickness requirements for the bolt.
This paper will give an overview of the current research conducted within the European project BOPACS. The project is focussing directly on the application of Means of Compliance within AC-20-107B by investigating crack arrest by design features.
Derived from the conclusion of the Cracked Lap Shear (CLS) Coupon, the Wide Single Lap Shear (WSLS) Specimen has been developed. It marks the next level test setup beyond the basic coupon level for demonstration and investigation of crack growth behavior in bonded joints. This specimen is representing the generic geometrical condition of a high load transfer (HLT) joint, representing e.g. a fuselage panel joint.

The basic layout of the specimen and first results of the current test program as well as the specifics for the test setup and data acquisition strategy is discussed.
Results from the running test program are presented and the influence of individual test parameters highlighted. Finally, the influence on a certification strategy for structural bonding is outlined.

1. State of the Art Bonding Technology

With the entry into service of the A350XWB a consequent evolution of the usage of CFRP for primary structures within Airbus Group has reached the next milestone. After a long and excellent experience with CFRP in civil and military applications, first applied on secondary structures and since 1983 for the vertical stabilizer as first major primary structural component for civil aircrafts, Airbus Group has now reached the next step in the transition from a metallic to a composite aircraft with the first CFRP fuselage of an Airbus aircraft on A350 XWB.

One key technology for the future development of composite aircraft structures is a suitable joining technology. Mechanical fastening is still the state of the art joining method for primary airframe structures for metallic as also for composite structures. Bonding is one of the most promising alternative joining technologies especially for composite structures.

At the same time bonding is enabling new disruptive structural concepts based on new integration sequences, structure mechanic principles and joint geometries.

1.1. State of the Art Bonding Technology

1.1.1 Classification of Bonding Technologies

Figure 1 shows the three main categories of joining of composites with thermoset matrices representing the different stages of integration.

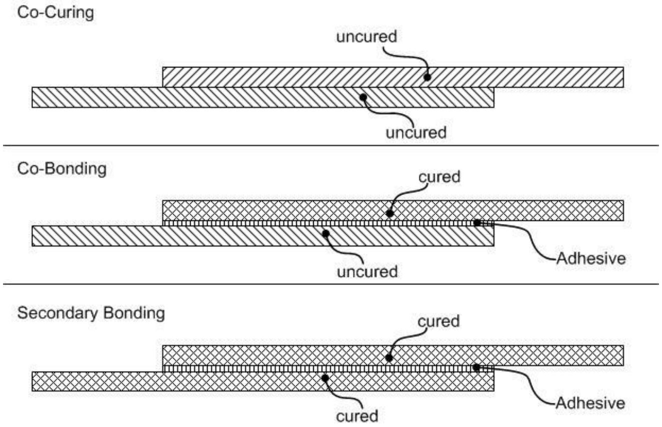

Figure 1. Classification of composite bonded joints

Co-Curing represents the highest stage of part integration, resulting in a fully integrated component. The joining mechanism is chemical cross-linking.

Co-Bonding represents an intermediate stage of product integration. An uncured part is joined with one or more cured parts to a component, typically with an additional layer of adhesive. The joining mechanism between the adhesive and the cured part is adhesion. Between the un-cured part and the adhesive chemical cross-linking is taking place.

Secondary Bonding represents the lowest stage of integration. Previously cured parts are joined by a film or paste adhesive to an assembly as e.g. a component. The joining mechanism between adhesive and adherend is adhesion.

1.1.2 Definition of potential failure initiation modes

The following three failure initiation modes are describing the most important origins of potential failures of bonded joints. There are different root causes for these initial failure modes and only major effects will be discussed in this paper.

Disbond

A disbond is an initial area within a bonded joint without connection between adherend and adhesive. A potential cause is a missed cover ply of a prepreg or film adhesive or failures within the adhesive application process (e.g. gaps within the adhesive layer). A disbond is detectable by means of nondestructive inspection technologies (NDI) as e.g. ultrasonic inspection within the individual limits of the detection threshold per technology.

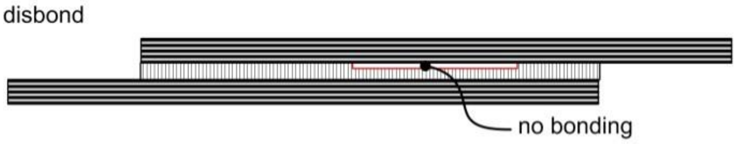

Figure 2. Failure initiation mode disbond

Weak bond

A weak bond is characterized by an adhesive failure mode between adherend and adhesive. Its strength ranges from close to zero to almost full strength. The root cause is an insufficient adhesion of the adherend interfaces e.g. due to contaminations of the surface or unfavorable process conditions.

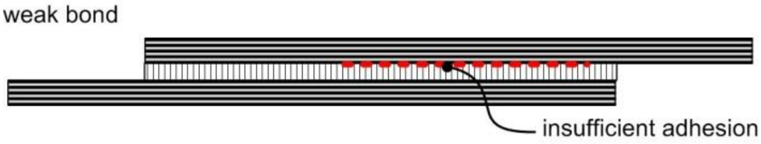

Figure 3. Failure initiation mode weak bond

A weak bond is not detectable by means of today's NDI methods due to the absence of a detectable interface layer. Research addresses the problem but results are not expected short- to mid-term for industrial usage.

Impact

Impact events within manufacturing and in service can lead to initial damages of the adherend and the adhesive. Damages resulting from impact are detectable by NDI within the individual limits of the detection threshold.

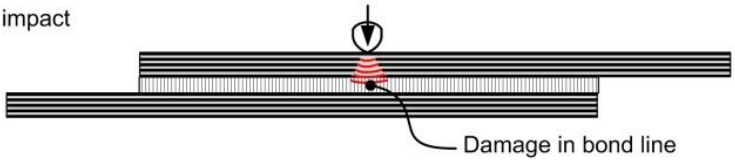

Figure 4. Failure initiation mode impact

2. Certification compliance

2.1. Bonded Aerospace structures within the context of certification boundary conditions

Resulting from the described State of the Art within the composite bonding technology today‘s certification guidelines according AC 20-107B [5] are limiting the certification of composite bonded joints to the following possible approaches for civil aircraft applications:

"For any bonded joint, the failure of which would result in catastrophic loss of the airplane, the limit load capacity must be substantiated by one of the following methods:

(i) The maximum disbonds of each bonded joint consistent with the capability to withstand the loads in paragraph (a)(3) of this section must be determined by analysis, tests, or both. Disbonds of each bonded joint greater than this must be prevented by design features, or

(ii) Proof testing must be conducted on each production article that will apply the critical limit design load to each critical bonded joint, or

(iii) Repeatable and reliable non-destructive inspection techniques must be established that ensure the strength of each joint." [5]

Today, no suitable NDI method to full fill the requirement [5]; *(iii)* of a secured measurement of the failure strength of a joint is in place. Moreover, it is not affordable to establish a full single part testing of each bonded joint within an industrial environment of a commercial aircraft manufacturing according to requirement [5]; *(ii)*.
Therefore, the only requirement [5]; *(i)* is practically taken into account for the sizing and certification of bonded joints.
The state of the art to certify a structural composite joint is to follow approach [5]; *(i)* by the usage of additional fasteners which have to be capable to carry the relevant loads taking into account a global failure of the bondline. This boundary condition and the corresponding technical concept of additional fasteners are limiting the benefits of the application of composite bonded joints in terms of weight, cost and performance.

3. Crack arresting approach

3.1. Context for certification

To follow directly the directive provided by AC20-107B [5]; *(i)* the limitation of the maximum disbond to a non-critical size for each structural application is one feasible way within todays certification boundaries. The European funded Project BOPACS is focused on the development of crack stopping concepts to improve today's state of the art additional fasteners concept by two means:
First, by understanding of the crack stopping mechanism in composite bonded joints for primary structures with high and low load transfer configuration.
Second, by development of novel crack stopping features as alternative to state of the art used fasteners.

3.2. Validation approach

The target within BOPACS is to demonstrate a secured crack stopping under fatigue loads in case of the presence of a local defect as e.g. a weak bond. For the validation of the crack arresting principle a two step approach has been established.
For comparison of the individual crack arresting capability of different design features the Cracked Lap Shear (CLS) test hast been selected. The CLS specimen consists of a lap adherent and a partially bonded strap with an artificial disbond. Under tension it features a mixed mode load (in plane shear & peeling) at the bondline interface. The mixed mode ratio can be considered nearly constant throughout the crack propagation in the bondline. The mode mixity can be tuned by the stiffness ratio of the lap and strap adherend. The crack growth rate [mm/cycle] is representing the individual crack stopping capability of each tested configuration. The significance has been demonstrated within the coupon test campaign [1].

To demonstrate a more realistic application scenario the wide single lap shear (WSLS) specimen has been developed within BOPACS. It represents a typical high load transfer (HLT) configuration as e.g. a fuselage longitudinal joint. The implementation of artificial disbonds and different disbond stopping features is part of the validation concept.

4. Experimental investigation – Wide Single Lap Shear (WSLS) specimen

4.1. Principle definition

The evaluation of the damage tolerance and crack arresting behavior for HLT configurations of bonded joints is based on the expected principle behavior as sketched in Figure 5.

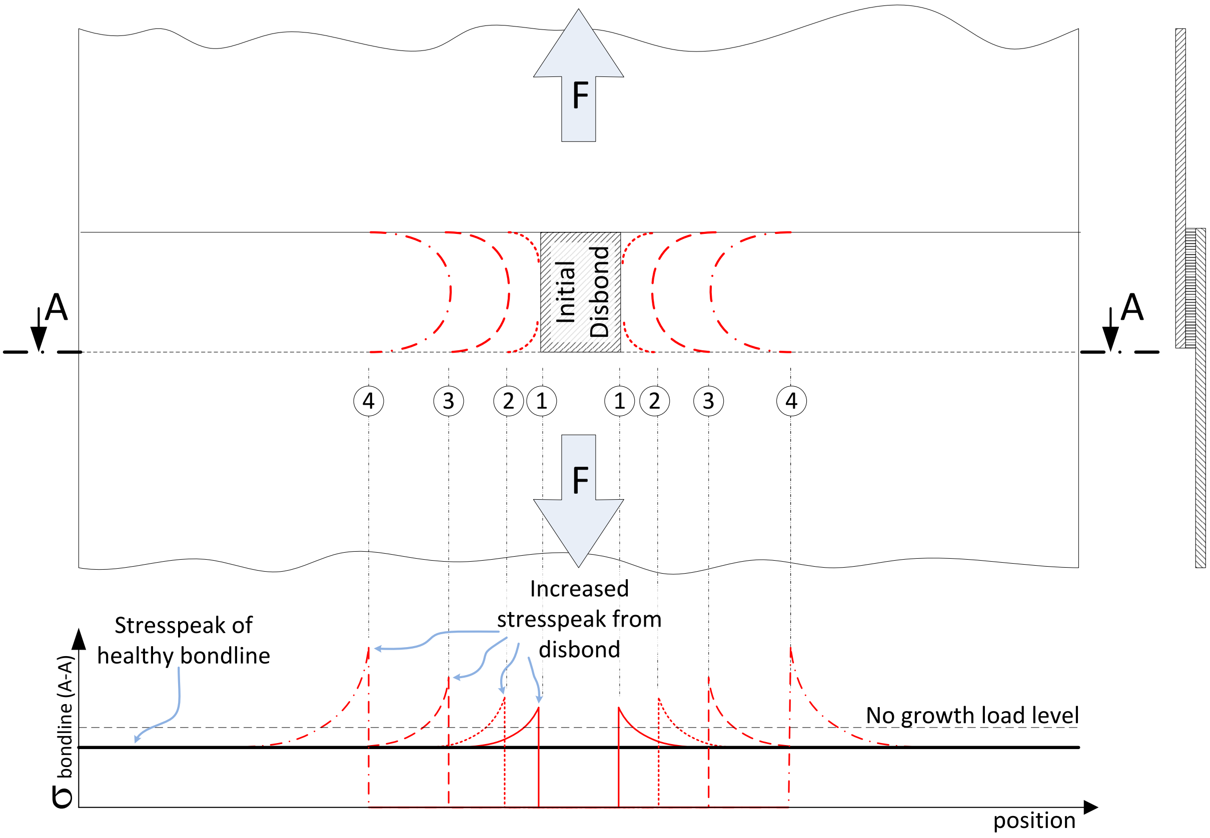

Figure 5. Structure mechanic principle on high load transfer (HLT) joints

The sizing of a bonded joint has to fulfil the no growth criteria according the certification requirements. In case of a local manufacturing defect (weak bond) or in-service damage (impact) of the bondline the load transfer is interrupted. This leads to an increase of the stress peak next to the damage (Figure 5, position ①). Depending of the initial disbond size, the stress peak will exceed the no growth load level. Therefore, it is assumed that cyclic loading will lead to an accelerated crack growth with increasing stress concentrations at the edges of the disbond (Figure 5, position ② to ④). Within BOPACS the target is to demonstrate for this configuration a safe, controlled disbond growth at loads below limit load (typical fatigue spectrum) similar to the slow growth criteria for metallic structures. A secured crack arresting has to be demonstrated before the critical disbond length is reached to ensure limit load capability with arrested disbond growth. In this arrested condition criteria AC-20-107B [5]; *(i)* “*The maximum disbonds of each bonded joint consistent with the capability to withstand the loads in paragraph (a)(3) of this section must be determined by analysis, tests, or both*” is again the baseline for certification.

Following this principle a suitable test setup has to enable a crack growth perpendicular to the load direction. Also the width has to be defined in accordance with the desired maximum disbond growth to be investigated to limit the risk of a static rupture by increased mean stress in the far field of the undamaged bondline. Also a relevant pitch for placement of crack arrestors has top be ensured.

4.2. WSLS test setup and results

The WSLS test configuration has been defined with a width of 500 mm and has been equipped with a bolted load introduction with metallic doublers as displayed in Figure 6. Adherent material is made of Hexcel 8552 / IM7 prepreg tape with quasiisotropic stacking, the used adhesive is EA9695. The initial disbond for the conducted tests is located in the center of the specimen by means of a Teflon strip. The inspection of the crack growth has been performed by means of ultrasonic at damage growth adapted intervals.

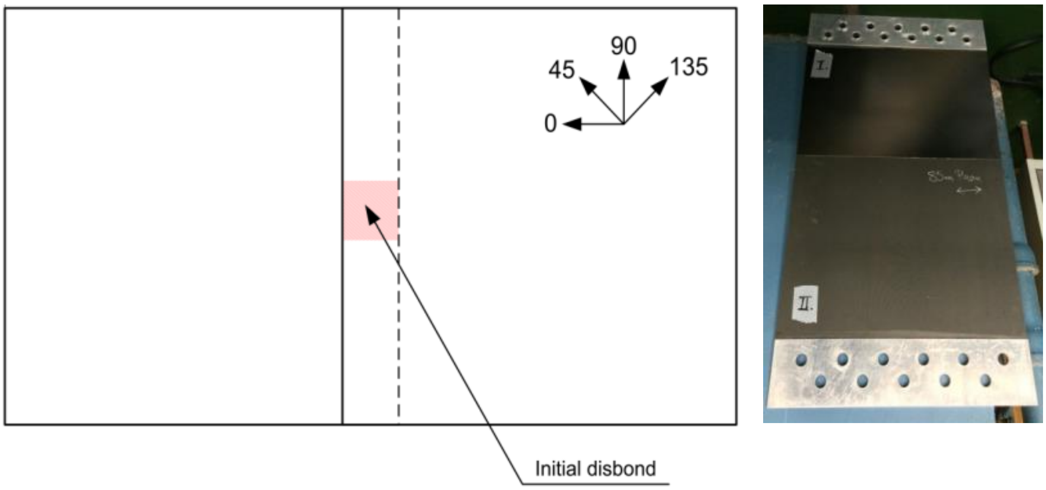

Figure 6. WSLS geometrical definition and load introduction

The proof the stress distribution resulting from the load introduction has been performed by direct image correlation (DIC) technique under static loading using a DANTEC Q-400 DIC system. A homogeneous strain/stress distribution over the panel width has been observed, correlating with previous simulation. The results of the DIC measurement is shown in figure 7.

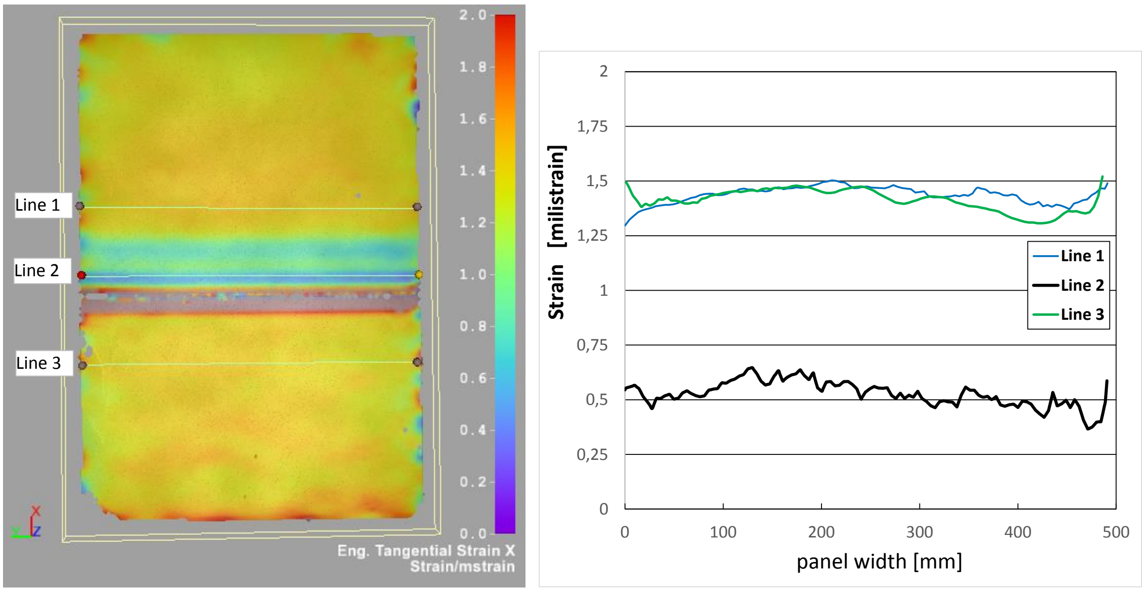

Figure 7. DIC measurement of stress distribution of WSLS panel without initial damage

Fatigue testing has been conducted to determine the no growth strain level first. With the given configuration this strain level was found at 30% of the static strength.

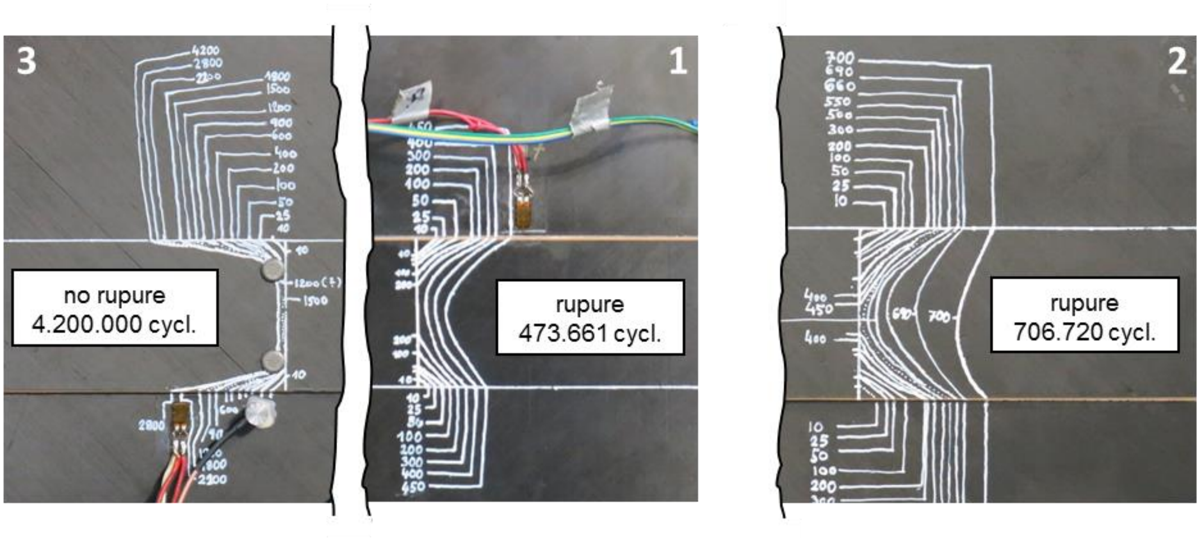

Figure 8. WSLS test comparison

Figure 8 shows the disbond propagation evaluated by ultrasonic inspection in k-cycles for three representative configurations with a similar size of the initial disbond. Beside the two reference configurations without disbond stopping feature (figure 8, WSLS panel 1 & 2) a configuration with lockbolts as crack arrestor (figure 8, WSLS panel 3) have been tested.

Figure 9 gives the comparison of the disbond area growth of the selected configurations. A difference between WSLS 1 & 2 (reference panel without crack stopping feature) in terms of crack growth rate and final failure size before rupture was observed. Therefore, further repetitions have to be conducted to validate the results for all configurations.
For specimen WSLS 3 (incl. disbond stopping features) no significant progress of the damage has been observed after more than 3.000.000 cycles.

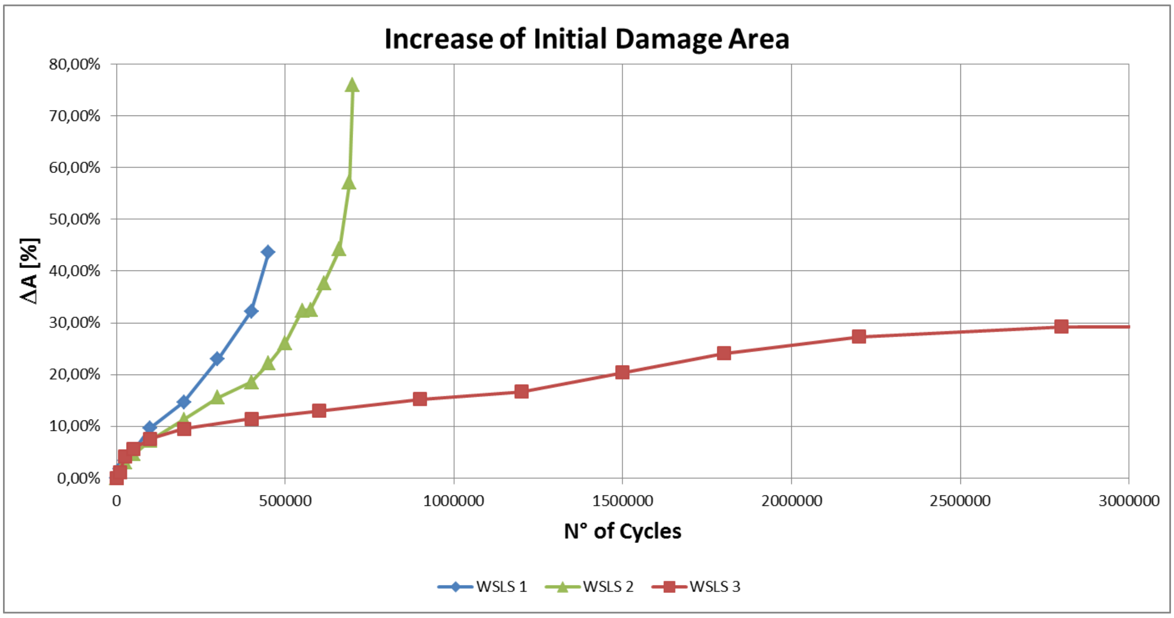

Figure 9. Disbond area evolution comparison

5. Conclusions

The developed wide single lap shear test setup has proven to be suitable for evaluating the crack arresting capability for high load transfer joints. Also the general assumed and theoretically predicted crack growth behavior transverse to the load direction of a WSLS configuration has been validated. The selected crack arresting concept by lockbolts readily available provides a significant arresting of the crack and slow growth behavior of the damage. Further crack arresting features will be tested in future campaigns and compared. Currently, the development of suitable numerical fatigue crack growth and arresting prediction methods for bonded joints is ongoing within BOPACS [4]. To verify these developments additional tests have to be performed. Nevertheless is has been demonstrated that a significant increase of fastener pitch beyond the “second loadpath at limit load via bolted joints” is feasible without negative impact on the damage tolerance of the bonded joint.

Acknowledgments

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