

Cracking Stopping in the Bondline of Adhesively Bonded Composite Adherents by Means of a Mechanical Fastener: Numerical and Experimental Investigation

Samuel Baha II
Fraunhofer IFAM

ABSTRACT

The use of composite materials in aircraft manufactures increases more and more with the need of light weight and efficient airplanes. Combining composite materials with an appropriate joining method is one of the primordial ways of exploiting its light weight potential. Since the widely-established mechanical fastening, which originally, was developed for metallic materials, is not a suitable joining method for composite materials because of its low bearing strength, the adhesively bonding technology might be an appropriate alternative. However, adhesively bonding in the aircraft manufacturing, especially for joining of primary structures is liable to certification requirements, such as testing of every bond up to limit load before the operation begins or non-destructive testing of every bond before the operation begins as proof of the joint characteristics, which cannot be fulfilled with the current state of the art. Combining adhesively bonding with mechanical fastening as a so-called "bonded/bolted hybrid joint" is one of the possible solutions to this problem. The mechanical fastener also called Disbond Stopping Feature (DSF) shall guarantee the structural integrity of the aircraft so that in case of cracking in the bondline, limit load can still be stood. To achieve this goal, it should be able to stop or reduce the cracking speed so that within a maintenance interval the structure integrity is still unharmed. It is therefore necessary to understand the bondline cracking behavior of an adhesively bonded joint and the influence of the mechanical fastener on it.

This paper deals therefore with the investigation of cracking in the bondline of an adhesively bonded joint and the influence of the mechanical fastener by means of the cracked lap shear (CLS) specimen. The short term cracking behaviour has been investigated using numerical simulation method, while the long term behaviour has been investigated experimentally. The CLS specimen consists of adherents made of the composite materials IM7-8552. The fastener considered is specified by the standards ASNA2042 / ASNA2045. The bondline consists of a non-traded adhesive which is a mixture made up of 80% of Hysol EA9395 and 20 % of Hysol EA9396. As for the investigation of the short term behaviour, a simulation model has been developed and validated by comparing the simulation results with experiments regarding the adherents' strain, the force-displacement curve, the crack length-force curve and the shape of the crack front. The fastener installation takes place in a fully automated C-frame riveting machine with all-electric drilling and riveting operations aptitude.

Topic category: Manufacturing/Material/Structure-Composite fabrication and joining, Simulation

Keywords: Bonded/bolted hybrid joint, crack stopper, preload, Simulation

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1. INTRODUCTION

The use of composite materials in aircraft manufacturing increases more and more with the need of light weight and efficient airplanes. Combining composite materials with an appropriate joining method is one of the primordial ways of exploiting its light weight potential. Since the widely-established mechanical fastening, which originally, was developed for metallic materials, is not a suitable joining method for composite materials because of its low bearing strength, the adhesively bonding technology might be an appropriate alternative. However, adhesively bonding in the aircraft manufacturing, especially for joining of primary structures is liable to certification requirements, such as testing of every bond up to limit load before

the operation begins or non-destructive testing of every bond before the operation begins as proof of the joint characteristics, which cannot be fulfilled with the current state of the art. Combining adhesively bonding with mechanical fastening as a so-called "bonded/bolted hybrid joint" can yield to the fulfilment of the alternative certification requirement namely, the limitation of cracking in the bondline so that the structure is still able to carry limit load. In such a joint configuration, the mechanical fastener also called disbond stopping feature (DSF) shall guarantee the structural integrity of the aircraft by stopping cracking in the bondline or reducing its speed so that within a maintenance interval the structure integrity is still unharmed. Against this background, the necessary to

introduce adhesively bonding of primary structure as established joining methode in aircraft manufacturing drives researchers to a better understanding of the bondline cracking behaviour in adhesively bonded composite structure as well as the influence of the mechanical fastener on it.

Several investigations have been conducted on bonded/bolted hybrid joint. Cracking stopping in the bondline of a bonded/bolted hybrid joint by means of a mechanical fastener as well as the influence of the internal stress state after the fastener's installation on the bondline cracking behaviour seems not to have received much of the researcher's attention in literature. However, several researchers have used finite element methods to investigate bonded/bolted hybrid joints in terms of damage mechanisms. Kelly [1] [2] used a single lap joint to show that in most cases, cracking occurs in the bondline because of the peel stress at the overlap ends. Fu et al. [3] assert that the mechanical fastener yield a reduction of the peak stress in a bonded/bolted hybrid joint. Crack initiation and propagation depends on the load transfer level as potter shows in [4].

This paper deals therefore with the investigation of cracking stopping in the bondline of adhesively bonded composite structure by means of a mechanical fastener. For this purpose, the cracked lap shear (CLS) specimen configuration was used. The short term cracking be-haviour will be investigated using numerical simulation method, while the long term behaviour is going to be investigated experimentally. The CLS specimen consists of adherents made of the composite materials IM7-8552. The fastener considered is specified by the standards ASNA2042 / ASNA2045. The bondline consists of a non-traded adhesive named "Mojo-Mix" which is a mixture made up of 80% of Hysol EA9395 and 20 % of Hysol EA9396. As for the investigation of the short term behaviour, a simulation model has been developed and validated by comparing the simulation results with experiments regarding the adherents' strain, the force-displacement curve, the crack length-force curve and the shape of the crack front. The fastener installation takes place in a fully automated C-frame riveting machine with all-electric drilling and riveting operations aptitude.

2. INFLUENCE OF MECHANICAL FASTENER ON THE BONDLINE SHORT TERM CRACKING BEHAVIOR OF ADHESIVELY BONDED COMPOSITE STRUCTURE

The investigation of the bondline cracking behavior as well as the influence of the DSF was conducted by means of finite element simulation.

2.1. Configuration of the CLS Specimen

With the cracked lap shear specimen, a stable bondline cracking in comparison to a single lap shear specimen can be achieved. The design investigation performed prior to modelling has shown that the

specimen's width does not influence the bondline stress state. Therefore, the adherent width could be chosen depending on the necessary space for the considered DSF. Furthermore, it was found that independently of the joint stiffness the mode ratio in the bondline of a CLS specimen is still nearly constant. According to findings, the specimen's configuration presented in Figure 1 was used.

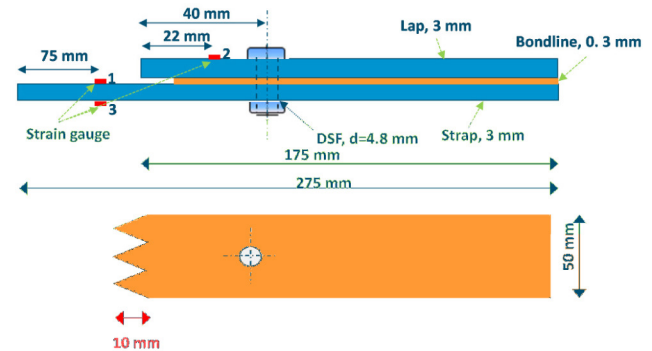


Figure 1. Configuration of the CLS specimen used for the characterization of the cracking stopping effect of a mechanical fastener

2.2. Simulation Model

As no plane deformation condition can be fulfilled by a hybrid joint, it is necessary to use a 3D simulation model. The considered hybrid joint consists of two adherents made of the composite material IM7 8552, a bondline made of the non-commercialized paste adhesive named "Mojo-Mix" and a DSF described by the above mentioned mechanical fastener. It is well known that using a 0° ply as outer layer in adhesively bonded composite adherents yield a change in the joint stiffness that could have catastrophic consequences on the joint integrity. As a general rule to avoid this problem it is recommended to use a stacking sequence with 45° outer ply. However, pre-testing have shown that using a 45° outer ply in CLS specimens yield a delamination of the outer ply but no cracking in the bondline, see Figure 2.

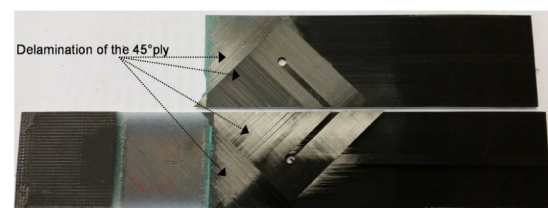


Figure 2. Damage of an adhesively bonded CLS specimen with 45° outer ply

To avoid the delamination of the outer ply during the mechanical loading, the following stacking sequence, in opposite to the mentioned rule, (0/+45/90/-45/0/+45/90/-45/0/+45/90/-45)S with a total thickness of 3 mm was applied to the adherents. The "Mojo Mix" adhesive consists of 85 % of HysolEA9395 and 20% of HysolEA9396. The adhesive and adherent material data for the simulation are collected in Table 1 and Table 2, respectively. As for the considered through thickness DSF the pin is made of the titanium alloy TiAl6V4 and the collar is made of unalloyed titanium.

Table 1. Material data for Mojo-Mix, FM300-05-05 and the ply-interface for IM7-8552

Adhesive	E [MPa]	σ [MPa]	τ [MPa]	ν	G [MPa]	G_c [N/mm]	G_{Kc} [N/mm]	ρ [N/cm ³]
80% HysolEA9395 + 20% HysolEA9396	4500	60	35	0.3	1446	0.32	0.5	1.25e-09
FM300-05-05	2700	35	11	0.33	907	0.85	2.5	1.25e-09
Ply-interface IM7 8552	12000	35	35	0.36	3800	0.3	0.7	1.2e-09

Table 2. Material data for IM7-8552

Adherent	E1 [MPa]	E2 [MPa]	E3 [MPa]	ν_{12}	ν_{13}	ν_{23}	G12 [MPa]	G13 [MPa]	G23 [MPa]	ρ [N/cm ³]
IM7-8552-40°	164000	12000	12000	0.32	0.32	0.5	4688	4688	2833	1.65e-09
IM7-8552-45°	13300	12000	13300	0.38	0.25	0.26	3391	10970	3391	
IM7-8552-90°	12000	12000	16400	0.5	0.02	0.02	283	4688	4688	

The simulation considers the DSF installation and the mechanical loading. It takes place in two steps. The DSF installation that takes place in the first step is performed to take into account the joint stress state after the installation process in the conducted numerical investigation. The second step takes place after the DSF installation. At this step, the adherents, the bondline and DSF, including the stress state resulting from the DSF installation, are used as simulation model of the CLS test. As for the model discretization, different element sizes were used. So, in relevant areas like the DSF and the area next to, element size of 0.08 mm was applied. In the rest of the simulation model the element size varied from 0.35 to 1.5 mm. A plane-symmetric boundary condition normal to the z-direction was applied to the adherents, DSF and bondline to reduce the computing time. The loading case and the applied boundaries conditions for the fastener's installation and the mechanical testing are presented in Figure 3 and Figure 4.

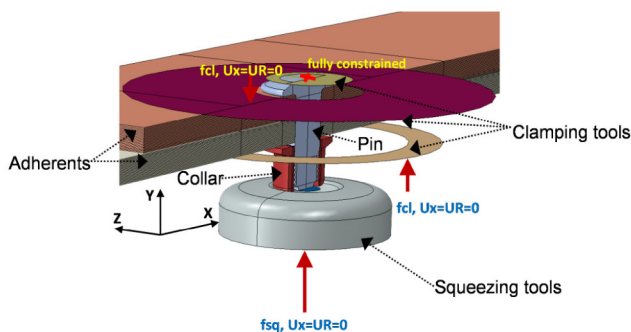


Figure 3. Loading case and boundaries conditions of the fastener installation

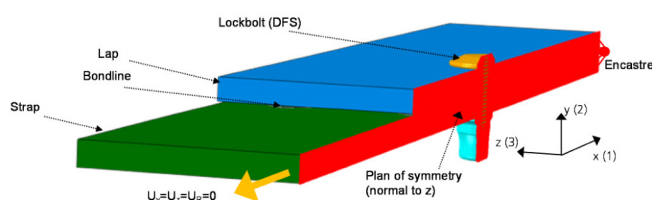


Figure 4. Loading case and boundaries conditions of the CLS-test

2.3. Experimental Validation of the Simulation Model

Quasi-static tests were performed to validate the simulation model. The validation is carried out by comparing the simulation results with those of the quasi-static test. The following joint characteristics were considered: The force-displacement curve, the adherent strain, the crack front contour, and the crack length-force curve. The quasi-static tests took place in a universal testing machine MTS810. The test speed was set to 1 mm / min. In order to determine the joint stiffness the specimen displacement was recorded by measuring the relative displacement between the upper and the lower clamping with an extensometer, see Figure 5 right.

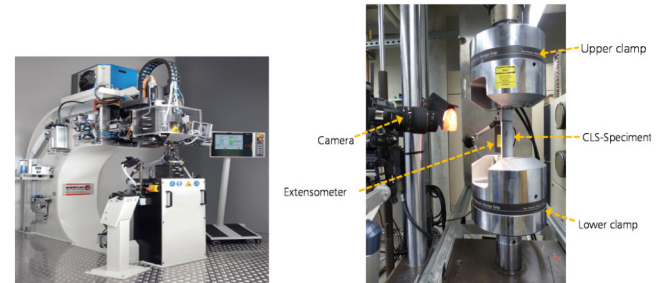


Figure 5. C-frame riveting machine (left) and the setup for testing (right)

The following results were obtained:

• The adherents' strain

The adherent's strains were measured by means of strain gauges placed at three positions (s. Figure 1). The specimens were loaded up to the allowable strain of 3000 $\mu\text{m}/\text{m}$ in a CFRP aircraft part. The load at this strain level was about 23 kN. No bondline cracking was registered at this load. The progression of the adherent strain depending on the applied load and the strain gauge positions are presented in Figure 6.

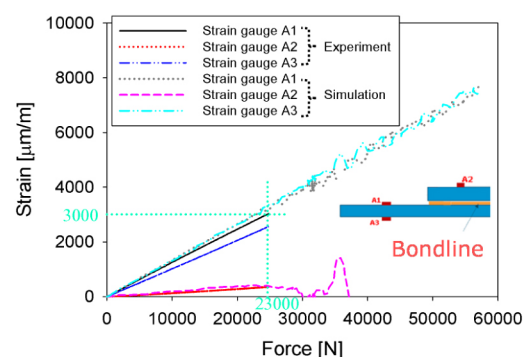


Figure 6. Adherent strain in a bonded/bolted CLS specimen

• Joint stiffness, joint strength, and the crack front

To evaluate the joint stiffness and strength, the force-displacement curves were considered. During testing, the specimens were loaded up to damage. The obtained force-displacement curves of a bonded and of a hybrid joint are presented in Figure 7. After testing, the DSF was sawed off so that the crack front contour could be evaluated, see Figure 8 left side.