EAN 2019
57th conference on experimental stress analysis

Possibilities of airframe structures cost saving through reducing number of fasteners

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Keywords: Key, Word, Paper, Best conference, Contribution template (maximum of 5)

Abstract. Reduction of numbers of mechanical fasteners together with bonding technology application can be one of the possibilities how to decrease costs of the structure. In the paper, results based on fatigue testing of novel design approaches for damage tolerant high load transfer (HLT) joints, as e.g. panel joints, are discussed for carbon fibre reinforced plastics (CFRP) adherents. Fatigue experimental results and numerical simulations of Wide Single Lap Shear (WSLS) specimen are presented for different configurations to proof the crack stopping behaviour of "state of the art" fasteners as reference crack arrestor concept.

Introduction

One of the main aims of designers is application of cost-effective strategies. The composite structures can lower costs of an airframe significantly, but there are some obstacles to adopt of advanced technologies like adhesive bonding or welding and prevent to use full strength capabilities of these technologies to real structures. Nowadays, there is no fully certified bonded technology applicable to full-scale airframe structure which comply airworthiness regulations from viewpoint of damage tolerance criteria. Therefore, composite airframes have still a high number of fasteners. Reduction of numbers of mechanical fasteners together with bonding technology application can be one of the possibilities how to decrease costs of the structure. Unfortunately, adhesive bonded joints can lose their capacity without any previous announcement which can be detected by non-destructive inspections. This is the main reason why the application of adhesive bonding technology for primary aerospace structures is limited due to the certification regulations. State of the art is the widely used "chicken rivet" as crack arrestor which is limiting the benefits of bonding technology, particularly in composite bonded joints.

Taking into account airworthiness regulations the only AC20-107B [1] requirement "*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*" can be practically applied for the sizing and certification of bonded joints.

The paper shows the way for decreasing numbers of fasteners in the primary airframe structures and at the same time the way how to keep the required level of reliability of the structure.

Validation methodology

The target of the presented work is to show methodology, how to demonstrate possibility to decrease number of fasters together with bonded joint application, in other word to demonstrate ability a secured crack stopping or arresting in adhesive bonded joint under fatigue loads in case of the presence of a local defect as e.g. a weak bond. In generally the airworthiness regulations allow both experimental and numerical demonstration of a structure. But in practice both methods are necessary.

Damage growth can be classified in the no-growth, slow-growth and arrested-growth criterion [1]. The no-growth criterion allows, as its name already suggests, no crack propagation within the bonded joint. Therefore, the load at which no crack occurs and / or it is stopped is significant for this criterion. On the other hand, the slow-growth criterion allows a certain crack propagation rate, which does not lead to a failure of the joint under the Limit Load (LL). The third criterion states, that a certain crack length is tolerable, which is capable of bearing LL. Yet, the crack growth needs to be arrested using either features or geometry alterations so that it does not fall under LL capability. All three criterions need to be investigated in test campaigns in generally. Figure 1 summarizes all three criterions according to the allowable residual static strength and damage detectability.

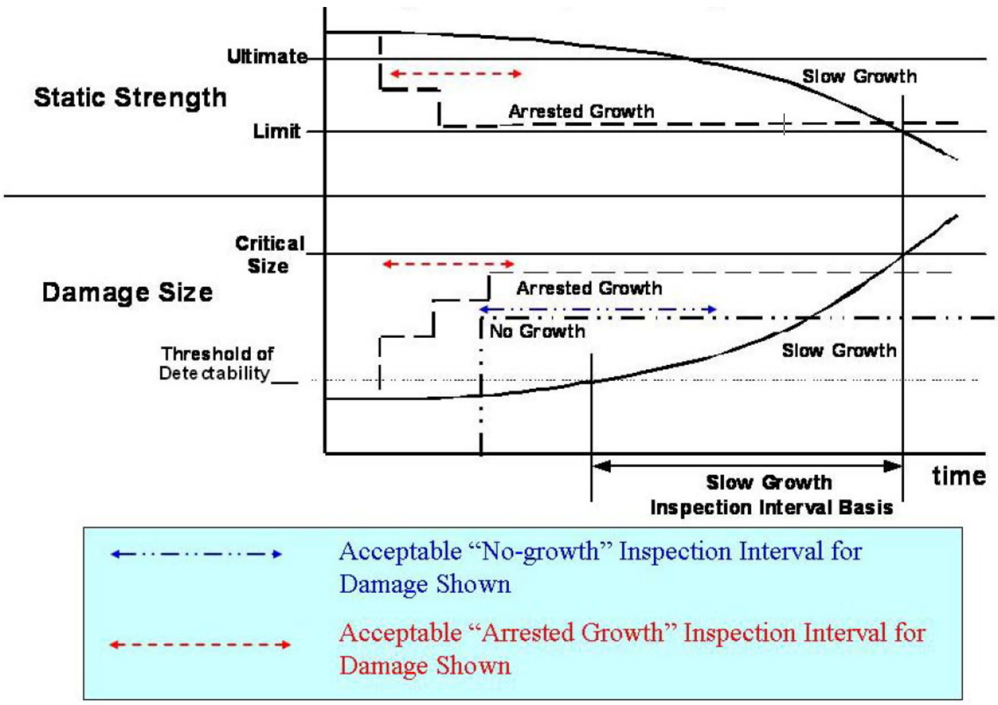

Fig. 1: Schematic diagram of residual strength and damage size relationship for different approaches to composite structural damage tolerance substantiation [1]

The validation of the crack arresting principle can be divided into the two steps [2]. Firstly, the Cracked Lap Shear (CLS) test can be used for the evaluation of individual crack arresting capability of different design features. Under tension, it features a mixed mode load (in plane shear & peeling) at the bondline interface. Secondly, the wide single lap shear (WSLS) specimen can be used to demonstrate a more realistic application scenario. WSLS specimen has been developed and investigated within the BOPACS project [3]. It represents more realistic 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. The main idea is to fulfil the no-growth criteria according the certification requirements. This paper is focused on the crack arrest demonstration by using of WSLS panels.

The evaluation of the damage tolerance and crack arresting behaviour for HLT configurations of bonded joints is based on the expected principle behaviour as sketched in Fig. 2.

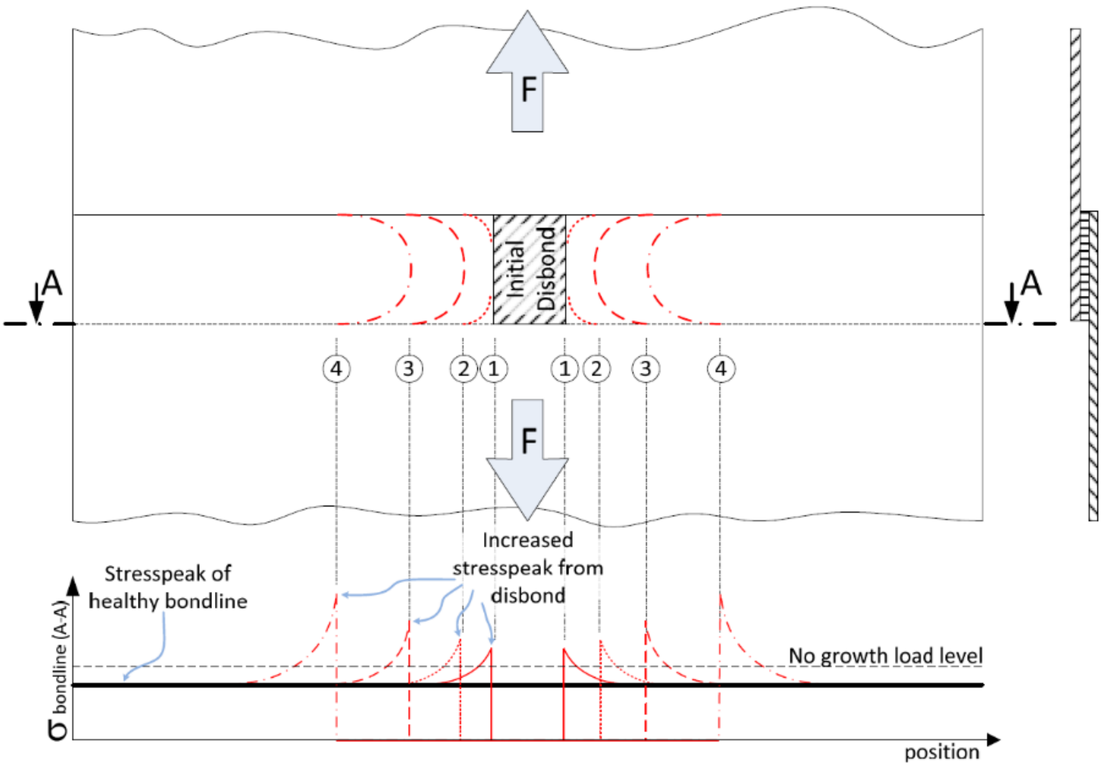

Fig. 2: Structure mechanic principle on high load transfer (HLT) joints

Presence of a local manufacturing defect (weak bond) or in-service damage (impact) in the bondline results in the load transfer interruption. This leads to an increase of the stress peak next to the damage (Figure 2, position 1). Depending on 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 2, positions 2 to 4). The target of the fasteners is to arrest or guarantee a safe, controlled disbond growth at loads below a limit load (typical fatigue spectrum) similar to the slow-growth criteria for metallic structures.

No-growth criterion

A no-growth criterion and the amount of fatigue cycles needed to represent a design life depends on the structure of the aircraft. Due to the probability of 10^{-5} for a LL event, 100.000 cycles can be representative for one design life of a fuselage seam, which the WSLS specimen stands for. Generally, a fuselage is exposed to loads, which occur due to thermal expansion, differences in pressure and bending moments. Thereby, one flight cycle can be regarded as one fatigue cycle. There are different approaches like the life-factor and load-factor to determine a fatigue life. A composite structure must demonstrate the ability to contain intrinsic manufacturing defects and the maximum allowable service damage(s) in adverse operational conditions and throughout the design life of the structure [4]. For practical reasons, the decision has been made to perform 500.000 cycles, which represent five design lives. This is sufficient to draw the first conclusions out of the testing and apply them to further investigations.

Experimental validation

WSLS specimens were used to investigate the influence of disbond stopping features (DSF) on crack growth. Therefore, it is necessary to have a relatively wide specimen in order to put several DSF in one line. This specimen resembles a longitudinal joint of an aircraft. To realize a homogeneous load distribution the specimen's dimensions were analysed by using a Finite Element Analysis (FEA). A WSLS specimen with a width of 500mm and an overlap of 60mm together with application of ASTM E647 standard clamping conditions has been selected as optimal solution.

The WSLS specimens were made out of Hexcel 8552 resin and IM7 uni-directional fibers, having a quasi-isotropic layout. The adherends were bonded together using an EA9695 film adhesive. Prior bonding, the surface of the adherends was treated with atmospheric plasma in order to activate the surface and to ensure a strong bond. The plasma treatment activation of the surface improves the surface energy leading to higher adhesion [5]. Fig. 3 shows an initial WSLS specimen scheme including its dimensions and components.

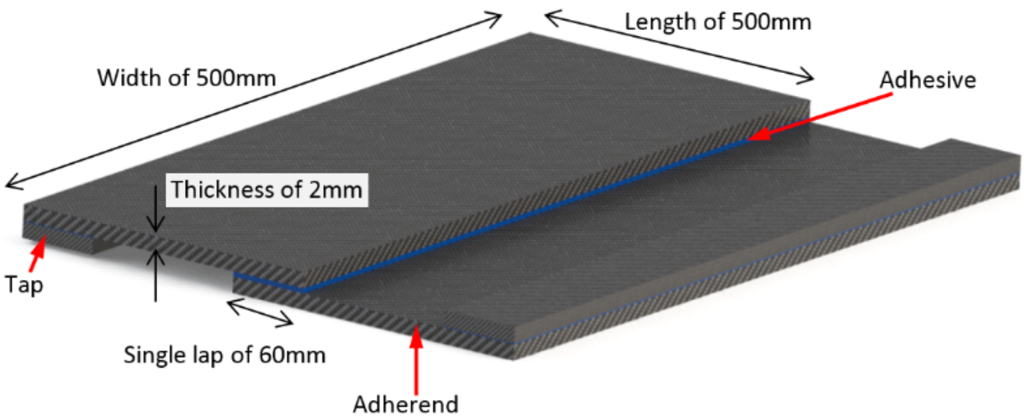

Fig. 3: Dimensions and components of WSLS specimen

The specimen was fixed on both ends, where the taps serve as a fixture for symmetrical clamping. By doing so, an axial misalignment between the direction of force and the adhesive layer is prevented which can result in bending moments. The WSLS were tested for tensile fatigue load. Hence, there occurs a mixed mode behaviour, which is schematically shown in Fig. 4. The specimen is exposed to Mode I, where the ends of the overlap get peeled off due to the occurring moment, as well as to Mode II.

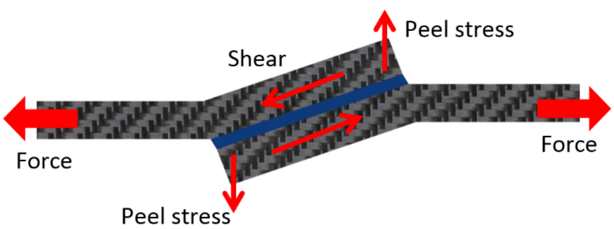

Fig. 4: SLS specimen under tensile load

Uniformity of strain distributions for WSLS specimen in longitudinal and transverse directions were investigated both by experimental and numerical tools. During the experimental investigations the ARAMIS optical contactless digital correlation system together with resistance strain gauges was used. Numerical simulations were performed by using of the NX NASTRAN [6] software. Fig. 5 shows measured uniform load distribution along to perpendicular direction to the applied tension load (see lines 1, 3 and 4 in Fig. 5). The non-uniform strain distribution in longitudinal direction (parallel direction with the applied tension load) in the surrounding of panel (adherends) bonded joint was defined (see line 2 in Fig. 5). The strain measurement and displacement data in longitudinal direction based on strain gauges measurements are shown in Fig. 6. Due to WSLS panel geometric asymmetry additional bending moment of 45% was measured near at the end parts of adherends close to outer sides of bondline. Bending moment induces peel stresses which can have a significant influence on the crack propagation inside of bonded joint of WSLS panel. This self-feature invoked by geometric asymmetry of the panel is not influenced by the gripping concept.

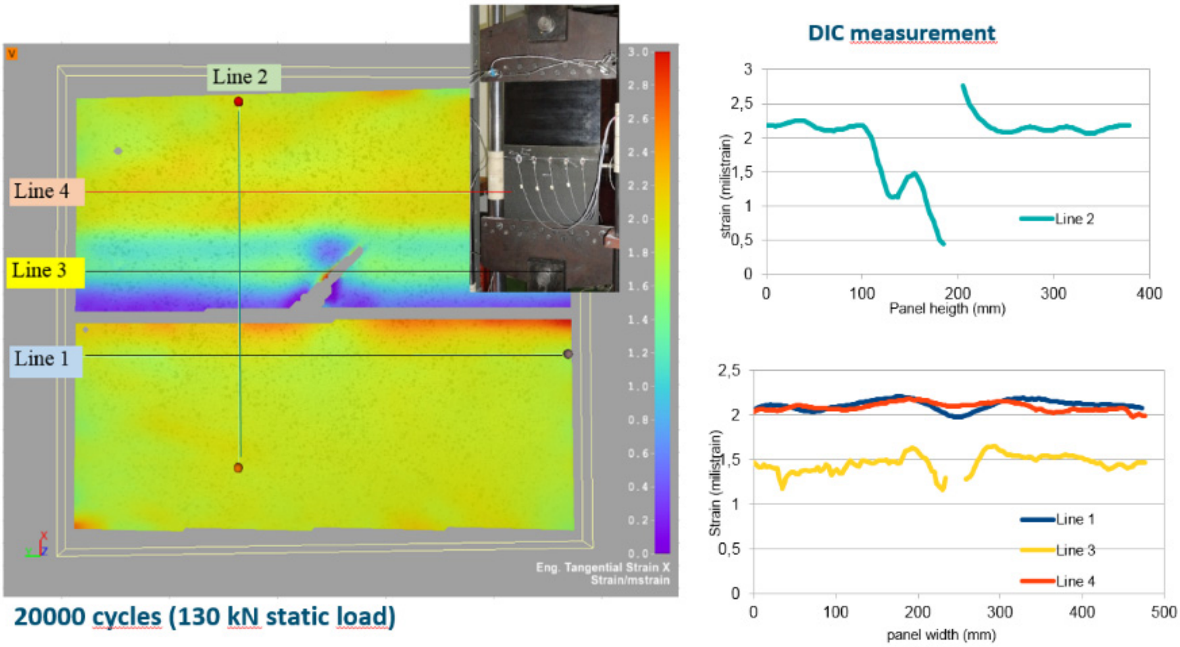

Fig. 5: WSLS panel - Optical measurement result in longitudinal and transverse direction

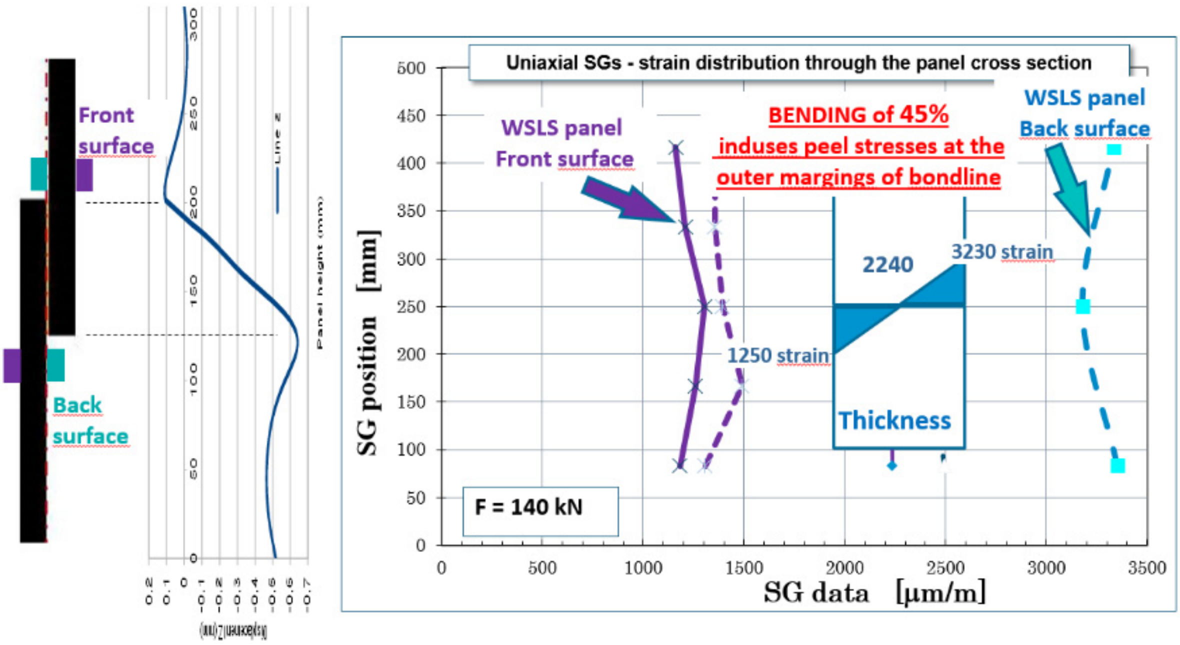

Fig. 6: WSLS panel – Strain and displacement data in longitudinal direction

The WSLS panel behaviour in bending was numerically evaluated for different disbond configurations. The FE results were compared with experimental results based on strain gauges measurement bonded on the panels. Nonlinear analysis (geometry) using the NX NASTRAN solver was used. 2D geometry model for skin and 3D model for adhesive layer was applied [7]. Fig. 7 illustrates the FE results of simulation of geometry eccentricity influence and low bending stiffness behaviour. Both FE analysis and experimental results prove the significant bending effect on strain development together with load level increasing. At the same time, the significant influence of the strain gauge location can be derived. Only a relatively small difference in strain measured (analysed) point can case a high change in strains. Results of peel and shear stress analyses for disbond length of 20 mm and 80 mm are shown in Fig. 8 and Fig.9. Based on additional analyses it was state that increasing disbond length results into decreasing peel and shear stresses. Shear stresses are more uniform with increasing disbond length.

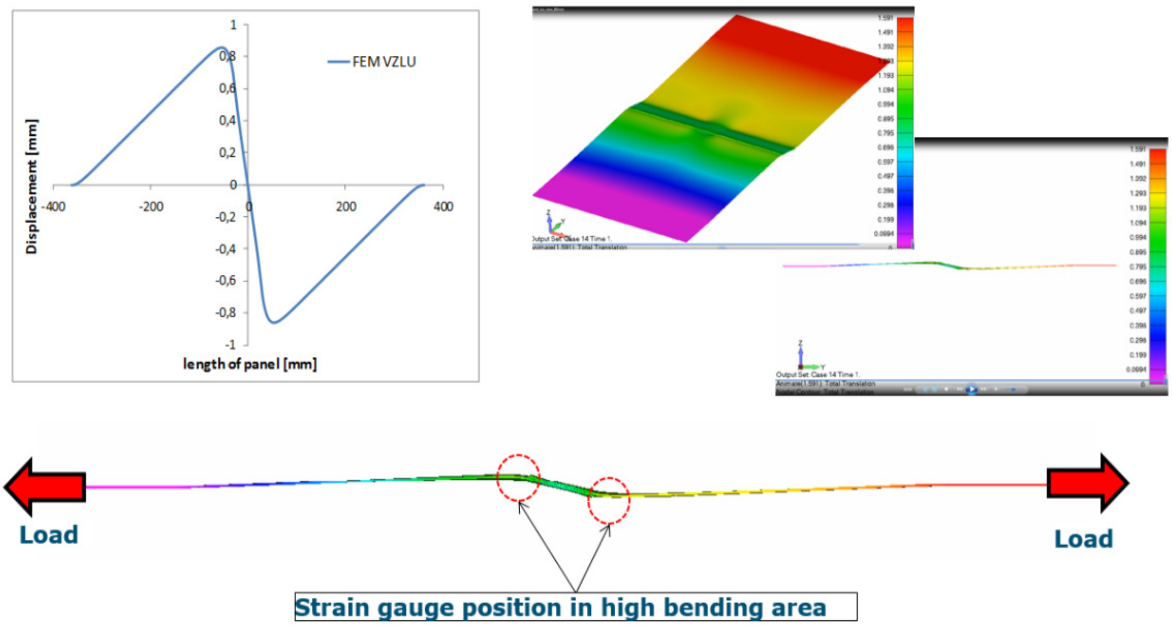

Fig. 7: WSLS numerical simulation – additional bending

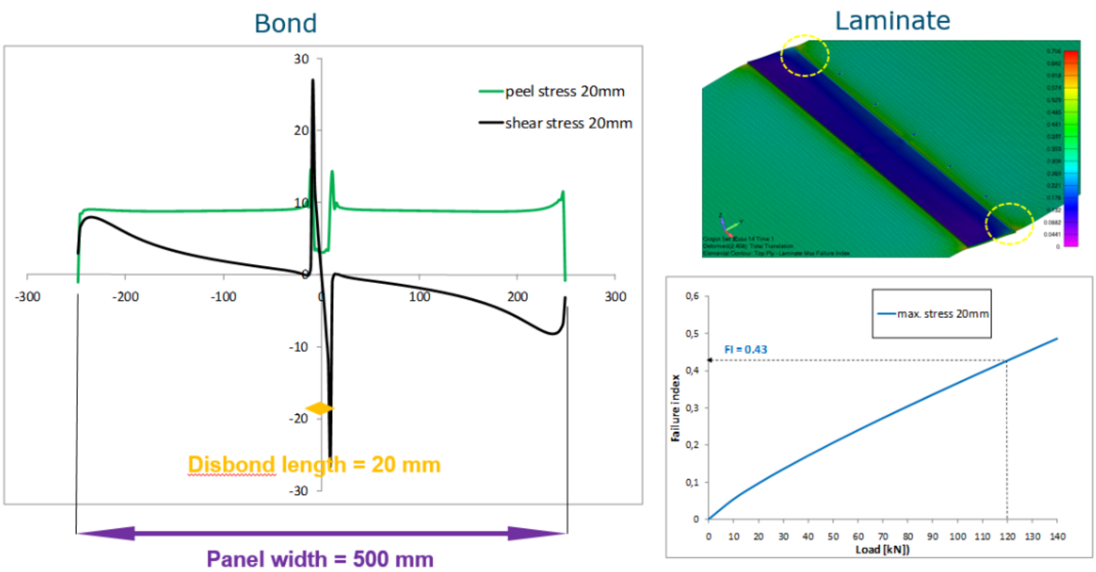

Fig. 8: Peel and shear stresses analysis for 20 mm disbond length (90 kN load level)

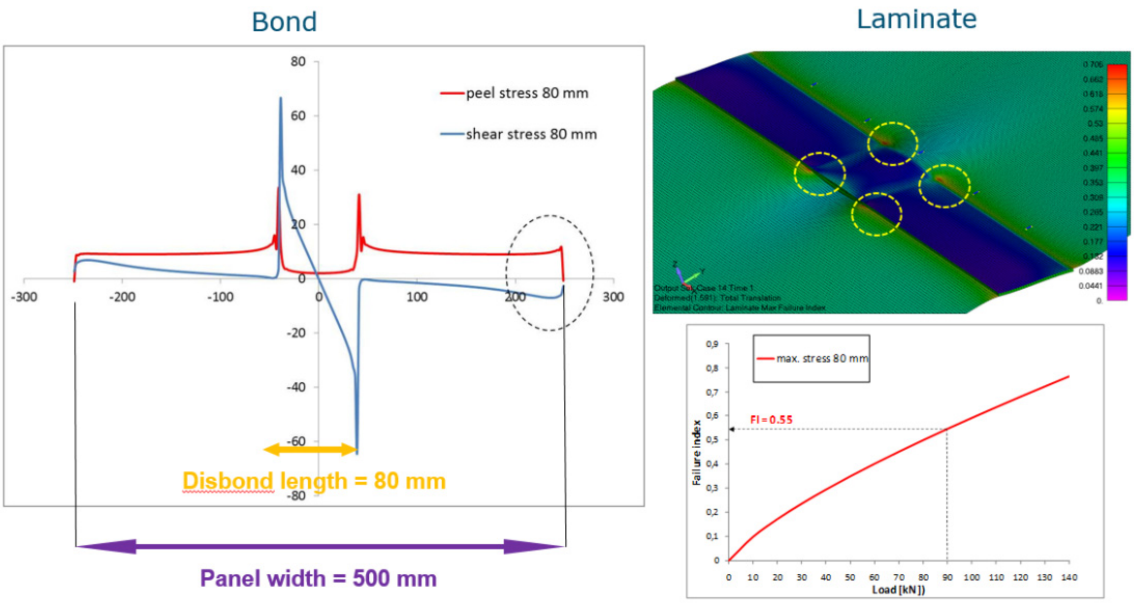

Fig. 9: Peel and shear stresses analysis for 80 mm disbond length (90 kN load level)

The most important phase of work was to identify the behaviour of the WSLS panels containing different disbond, impact damage, laminate lay-up near bondline and crack stopping features. During the verification phase of the disbond crack stopping features (DSF) efficiency different configurations of damage or disbond and DSFs were tested. All the tests were performed under fatigue with a sinusoidal load type. Different influence of DSF can be observed. Fig. 10 shows influence of crack/disbond stopping features (red line) to crack retardation mechanism under fatigue loading for initial disbond length of 80 mm. The DSF increases the lifetime of the adhesively bonded joint with disbond significantly. The lifetime of the joint increases by 10x whereas no additional crack propagation was observed and test was terminated without failure of the bonded joint.

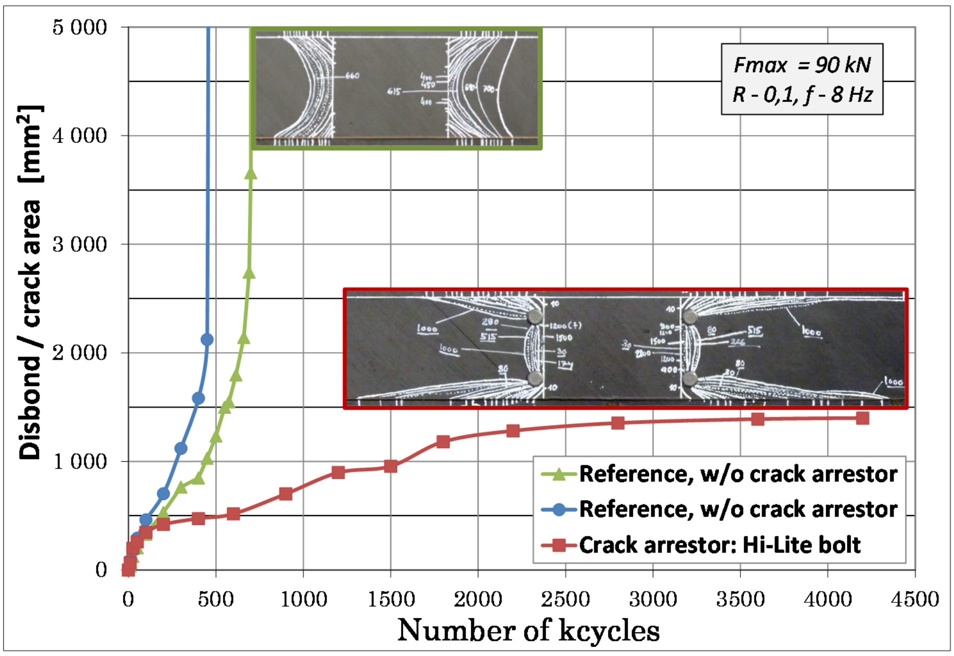

Fig. 10: Disbond area evolution comparison CFRP

Conclusions

FE and SG results confirmed the high sensitivity of the panel geometry (local thickness, disbond length) on stress distribution and accuracy of strain gauges positions on the measured and analysed strain values. The FE simulations also shown load transfer distribution in bond line and mixed mode (peel and shear) disbond propagation. Significant influence of DSF was proved. Multiply lifetime of WSLS panels is achieved compared with reference panels without DSF application. In some cases, full crack stopping is achieved when fasteners are placed close to the disbond area. Slow crack propagation for DSF configurations with bolts positioned close to initial disbond demonstrated no critical spontaneous rupture within a typical lifetime. The position of fasteners has an influence to the crack tip development. Fasteners as a crack arrestor prove high efficiency.

Acknowledgement

This work was funded by the European Union Seventh Framework Programme under grant agreement n° 314180 – Project BOPACS: Boltless Assembling of Primary Aerospace Composite Structures and by Ministry of Industry and Trade of the Czech Republic in the framework of Institutional support of Research organizations.

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