WIDE SINGLE LAP SHEAR SAMPLES FOR EXAMINATION OF ENVIRONMENTAL EFFECTS OF BONDED REPAIRS

Jelena Ravic[a], Gregor Peikert[a], Patrick Böhler[a], Marc Gubser[a]

a: ZHAW, Zurich University of Applied Sciences, CH-8401 Winterthur, Switzerland

Abstract: *In the frame of the EU FP7 BOPACS (Boltless Assembling of Primary Aerospace Structures) project, the new Wide Single Lap Shear (WSLS) specimen was developed to test a more realistic application scenario for bonded joints. It represents a typical high load transfer configuration as e.g. a fuselage longitudinal joint or a repair joint. The implementation of artificial disbonds and different crack stoppers were part of the validation concept.*

The concept of this test sample was presented during ECCM17. Derived from the Single Lap Shear and the Cracked Lap Shear Coupon, the Wide Single Lap Shear (WSLS) specimen was developed. It marked the next level test setup beyond the basic coupon level for demonstration and investigation of crack growth behavior in bonded joints. [1]

In the BOPACS project two different sizes of WSLS specimens were used. While the test samples for validation tests were made with a width of 500mm, a smaller sample with only 180mm width was developed at ZHAW in order to allow parameter studies at lower cost. The small WSLS is used only for crack growth investigations on a comparative basis. However further work has been performed at ZHAW to develop this set up into a useful examination tool.

Keywords: Composites; Crack; Adhesive; Joint

1. Introduction

In the frame of the EU FP7 BOPACS project, several shear test coupons were examined and compared. To study the effect of crack stoppers the new wide single lap shear (WSLS) specimen was developed to test a more realistic application scenario for bonded joints. It represents a typical high load transfer configuration in Mode II with the option of including damages or crack stoppers.

One of the key elements of the WSLS concept is the crack propagation direction which is perpendicular to the load direction.

In the BOPACS project two different sizes of WSLS specimens were used. While the test samples for validation tests were made with a width of 500mm, a smaller sample with only 180mm width was developed by ZHAW in order to allow parameter studies at lower cost. The small WSLS does not provide an equal load distribution and is therefore used only for crack growth investigations on a comparative basis. Further work has been performed at ZHAW and is presented in this paper.

  doi:10.5075/epfl-298799_978-2-9701614-0-0

This paper focuses on:

- the sample lay-out, stress distribution and crack growth
- crack growth detection with Ultrasonic testing
- the damage introduction process using a combination of an artificial defect as crack inhibitor and subsequent impact damage as a real crack
- test parameters for the cyclic fatigue testing

Based on the defined test parameters, environmental studies were performed to demonstrate its capability to examine effects like:

- humidity and liquid water intrusion in the impact disbond
- effect of freezing of the water in the impact disbond

The results demonstrate that the small WSLS samples is a useful tool to study detrimental effects of environment etc. on crack growth on a bonded high load transfer joint.

2. Background / BOPACS project (2012-2016)

The BOPACS project aimed at developing means to stop or at least control the growth of a crack or disbond in a bondline.

Application as described in BOPACS project: longitudinal joint of fuselage sections. More recent application scenarios target at large repairs in shell structures.

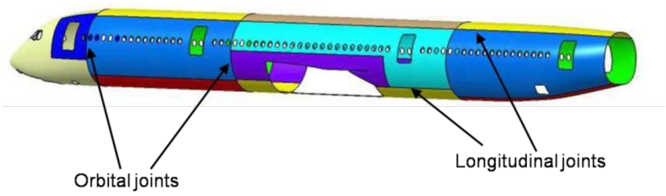

Figure 1. Application case BOPACS: fuselage joint [BOPACS consortium]

The following validation concept was followed within BOPACS:

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 comparison of the individual crack arresting capability of different design features the Cracked Lap Shear (CLS) test hast been selected. The CLS specimen features a mixed mode load (in plane shear & peeling).

To demonstrate a more realistic application scenario the wide single lap shear (WSLS) specimen has been developed within BOPACS. Figure 2 shows the principal of the WSLS sample. The bondline is 5-10x wider than the overlap, the center section is prepared with an initial disbond. As a consequence of the force F, the disbond grows perpendicular to the direction of the force F.

  doi:10.5075/epfl-298799_978-2-9701614-0-0

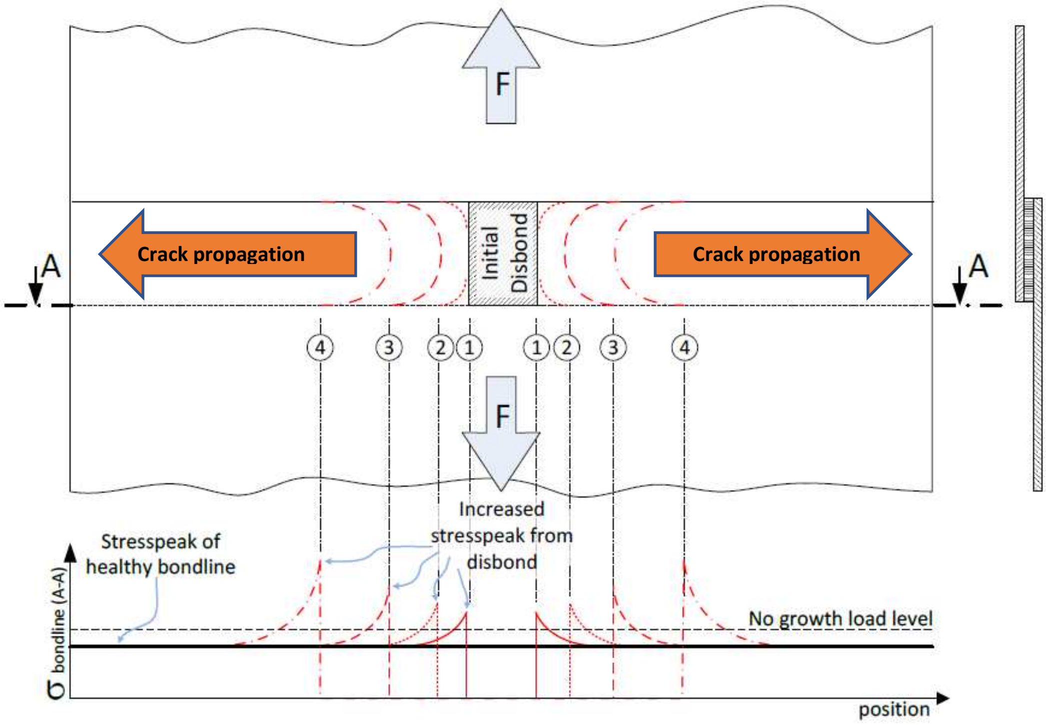

Figure 2. Structure mechanic principle on high load transfer (HLT) joints as applied in the WSLS test coupon, modified from [1], Th. Kruse, Th. Körwien and R. Ruzek, ECCM17.

3. Initial development of WSLS samples at ZHAW (2013)

Screening testing of WSLS samples began in 2013 at ZHAW complementary to CLS samples for crack growth research. While local loads in the CLS samples are rather low and dominated by Mode I and Mode II, the crack grows slowly under quasi-static loading, the effect of crack stoppers or the influence of damages in the bondline can easily be recorded.

A completely different behavior was observed with WSLS samples. Due to the dominating Mode II, the sample bears very high static loads, up to 100kN. This high load is only slightly reduced when damages are introduced. As soon as a crack starts, the sample ruptures immediately and crack growth cannot be investigated.

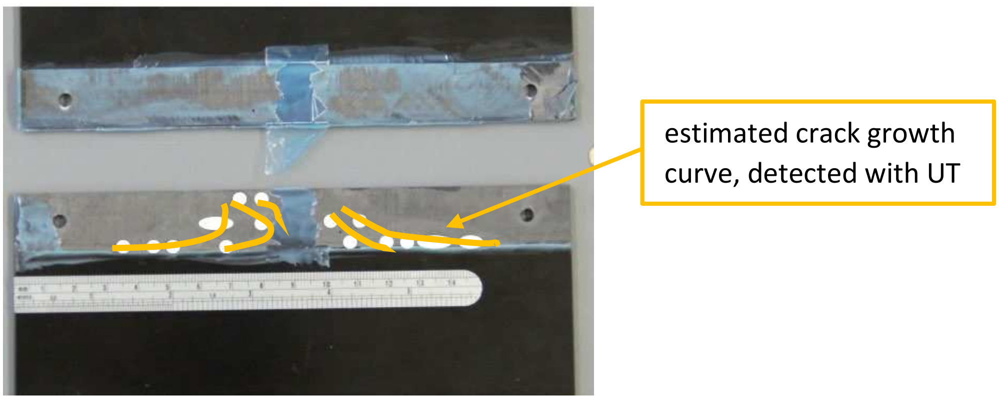

Figure 3. First WSLS sample with centered artificial disbond (blue film) and successful crack growth perpendicular to load direction under cyclic loading. [ZHAW, BOPACS, 2014]

Only the change from static to cyclic fatigue loading resulted in a steady slow crack growth. Figure 3 shows one of the first samples with detectable crack growth. Based on this success the WSLS sample was continuously improved. Major improvements were reached with introduction of a taper (inner and outer) on the adherends to reduce the stress peak in load direction. The single-film disbond was replaced by a double-layer disbond to ease NDT inspection. Finally, a rather constant crack growth could repeatedly be produced which allowed positioning of crack stoppers and studying their effect regarding crack growth speed.

The successful demonstration of crack growth perpendicular to the load direction led to the decision to develop, manufacture and test WSLS on a large scale.

4. Development of large WSLS samples in BOPACS

Highly loaded single lap shear joints shall mainly act in Mode II. The large WSLS sample was designed for Mode II and an even load distribution over the whole joint length. As a consequence, the load introduction is very massive which results in very large sample dimensions and complex clamping in the tensile testing machine. The height of the large WSLS samples is approx. 2m, including the load introduction adapter. However as soon as an initial disbond is introduced in the sample the load distribution is not even anymore as shown in figure 4. As a result of the disbond, stress concentrations arise just next of the disbond. The stress increases, the larger the crack grows. Bearing this in mind the small WSLS sample was designed with a simpler clamping design, using standard 60mm wide clamping devices.

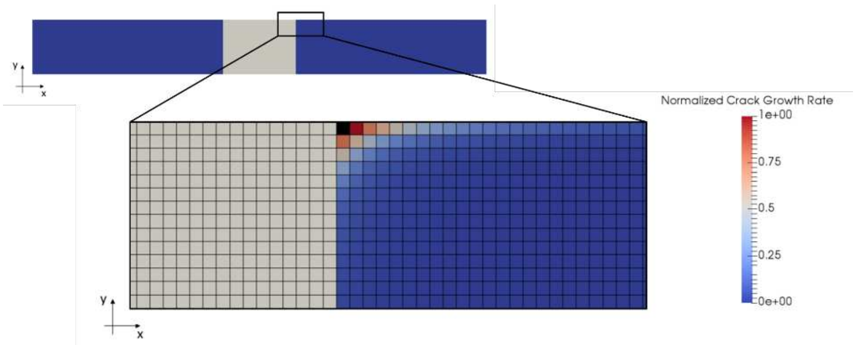

Figure 4. Simulation of crack propagation in WSLS samples showing stress peak (red colour) in corner area of the bondline, from [3], M. Santaniello.

In the ECCM 17 results of the large WSLS samples were presented.

The crack growth starts in the upper and lower corner, as analyzed by FEM, and grows continuously until the two cracks meet in the middle and start to form a uniform round crack line. The 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 [2].

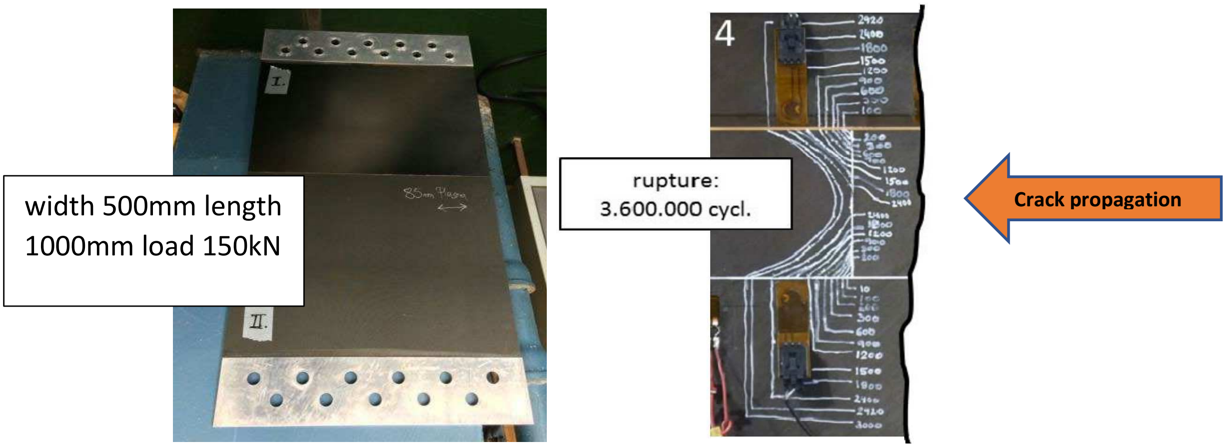

Figure 5. Pictures presenting a large WSLS sample prior to testing (left) and crack propagation detected with Ultrasonic Testing and indicated with white paint. [1]

5. Comparison between large and small WSLS samples

The main difference between the large WSLS samples and the smaller version used at ZHAW besides the dimensions is the stress distribution. The stress distribution of the undamaged large WSLS sample is rather equal over the whole bondline width. This is achieved with a large and sturdy adapter plate. However, as soon as an artificial disbond is introduced, a stress peak occurs as demonstrated in figure 2. The smaller WSLS samples is simply clamped with standard tensile test machine grips and therefore the stress distribution is very uneven over the sample width. A FEM analysis was performed at EPFL in Lausanne showing the stress distribution. As with the large WSLS samples a stress peak arises close to the artificial disbond. This means, that in both sample configuration a stress peak near the disbond is present and that both samples show comparable crack growth behavior. Yet the large sample cracks more evenly and the curved crack growth front line is more symmetric. This seems not achievable with the small samples, but for comparative tests, the small sample design seems appropriate.

Additionally, the small WSLS are designed with a taper which covers half of the overlap length. This complicates the UT (Ultrasonic Testing) investigation, since the first crack start is not detectable with impulse-echo UT. Through transmission testing of this section is foreseen.

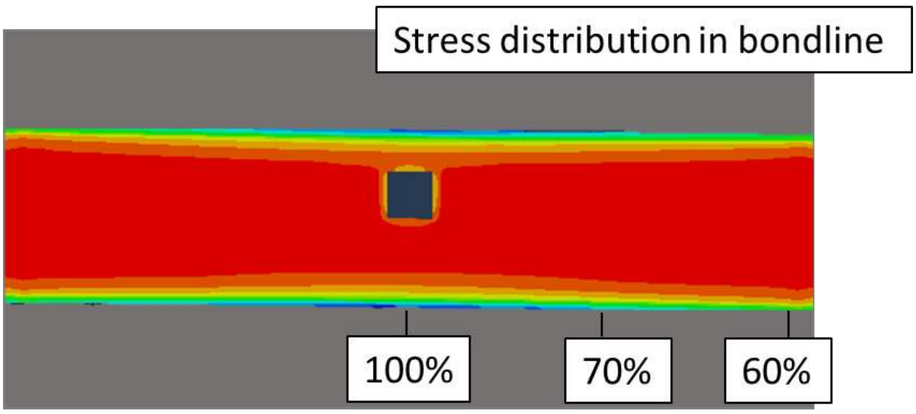

Figure 6. Stress distribution on the small WSLS sample with damage zone, D. Vadugappatty Srinivasan EPFL.

6. Improvements of small WSLS at ZHAW

Smaller test coupons are considerably cheaper and allow more testing. They can be considered one level lower in the test pyramid. More testing also means, more material combinations to compare, more defect types to study, more environmental conditions to examine, etc.

One important development was achieved through changing from release film disbonds to the creation of real cracks. Artificial disbond using release film do not behave like real cracks, since real cracks have a sharper crack tip. Therefore, the release film disbond was reduced in size and acts now as a crack inhibitor for an impact damage. The goal was to develop a process which repeatedly results in an impact damage with dimension of 20-30mm.

The WSLS sample with 180mm width and a real disbond resulting from an impact damage is considered as the new baseline sample configuration. From this starting point investigations like influence of humidity, liquid water, temperature changes etc. can be investigated.

7. Current Status: WSLS samples with impact damage

7.1 Test coupon description

Adherends: UD-prepreg cmp UD HTS45E, 150gsm, layup: quasiisotropic, starting with 45°. Thickness: 3.35 mm. Adhesive: Loctite EA 9394 AERO; dimensions shown in figure 7:

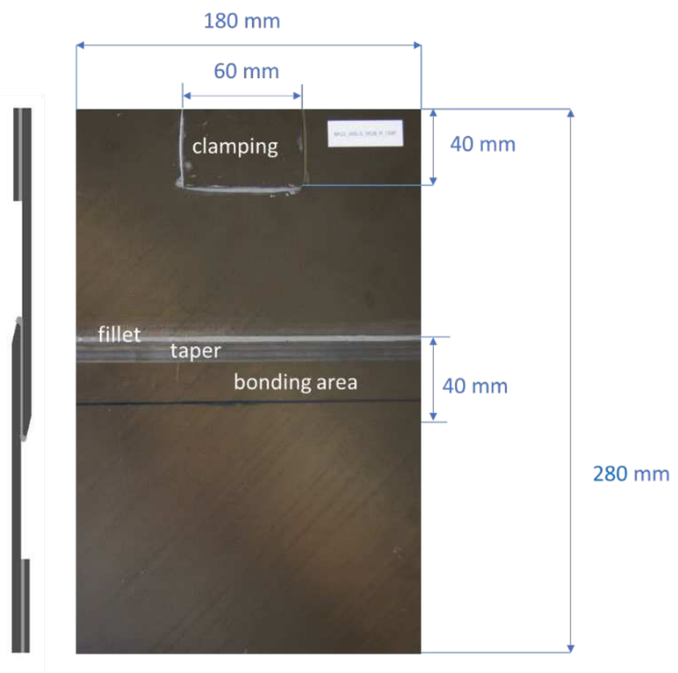

Figure 7. Dimensions of small WSLS coupon. The fillet is controlled with the bonding jig.

7.2 Impact damage process

WSLS samples are used to investigate crack growth in the disbond; hence they must be manufactured with a crack starter. ZHAW investigated several crack starter ideas during the BOPACS project. The WSLS samples are made with a simple square release film (double for NDI

  doi:10.5075/epfl-298799_978-2-9701614-0-0

reason), followed by an impact, which cracks the release film spot into a realistic impact damage with reasonable size. The aim was to produce an impact which is about 15-to 20% of the bondline area.

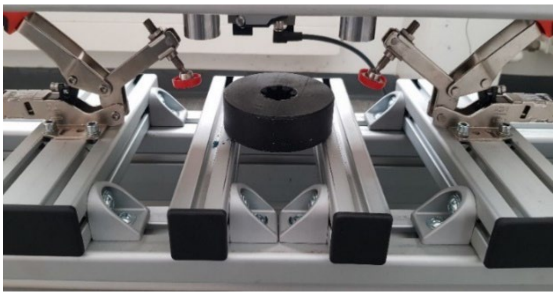

Figure 8. For the drop tower impact, a round steel plate with 30mm bore hole is used as hard support and the WSLS sample is fixed using clamps as shown.

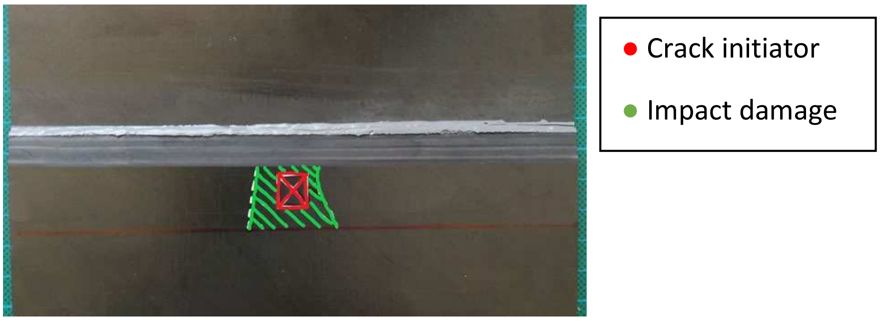

Figure 9. Damage of approx. 15 % bondline width, achieved with impact energy of 7 Joule.

7.3 UT determination of damage growth

A Krautkrämer USM36 UT detector was used in pulse-echo mode for the determination of the disbonded area. This limits the inspectable area to the parallel section of the bondline. The zone with the taper cannot be inspected. This is a disadvantage since the crack start in the corner cannot be detected. Therefore through-transmission mode would be more appropriate. This will be applied in the coming period of the project. Testing under load, for easier determination of open crack size is also possible, if allowed by security restrictions.

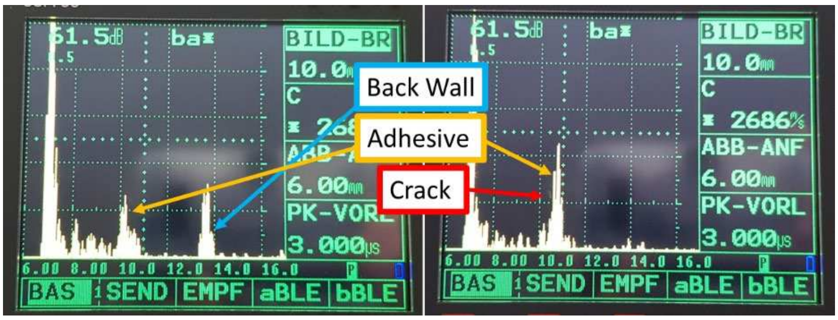

Figure 10. UT-Scans on the WSLS-samples. Left: measurement on bonded area with visible adhesive- and more intensive back wall-echo. Right: measurement on a large crack without back wall-echo due to disbond.

8. Recent results from ZHAW

Following a discussion with aircraft industry, ZHAW performed studies with the goal to expand the capability of the WSLS test with environmental exposures targeting at adhesively bonded repairs. Starting with impacted samples, tested dry at room temperature (RT), followed by testing with liquid water in the impacted area, followed by testing in the frozen state with ice in the impacted zone and finally combined with intermittent high peak loads.

8.1 Reference coupons with impact at room temperature

The load level for the dynamic testing was determined by increasing the load until first signals for crack growth could be detected. That load level could be found at 25kN. For further tests the load was kept on this level. The R-value for fatigue testing was always kept at 0.1.

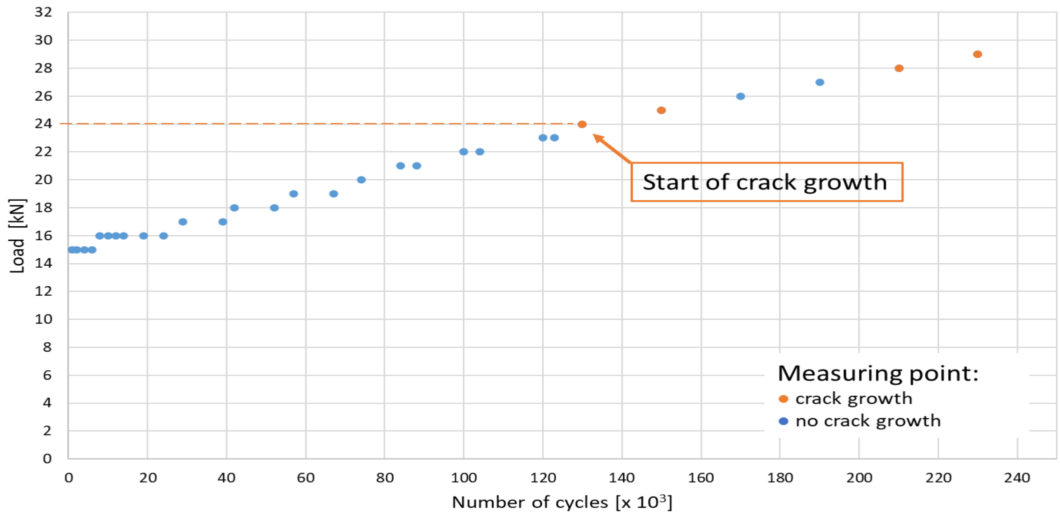

Figure 11. Load-cycle plot showing how the test load was defined, starting at 15kN and increasing the load until a crack growth could be recorded.

Based on this pretest, the load level for further tests was set to 25kN (constant amplitude, R=0.1, 0.3Hz). Yet this is still a rather low load level, and cracks grow very slowly, resulting in time consuming tests. Shorter tests with faster crack grow were run at 30kN.

8.2 Intrusion of liquid water into the damaged zone

To be able to inject water into the impacted and disbond zone, the sample had to be impacted multiple times with less energy. This procedure did not increase the damaged size, but it allowed to slightly open up the disbond. Afterwards 3 small holes were drilled into the adherend and water was injected with a syringe in one hole until the water spilled out of the other holes. The complete filling of the disbond area was confirmed with UT.

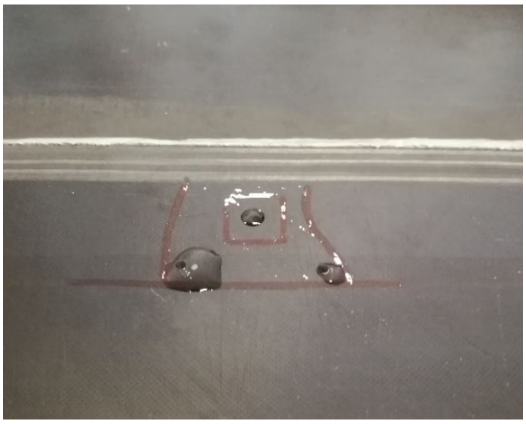

Figure 12. Water injection in impact damaged adhesive joint.

Water usually masks the crack when scanning with UT. Subsequently the water needs to be evaporated prior to the NDI check each time.

Cycling of WSLS coupons with water in the disbond was demonstrated. Scientific investigations to study the influence are not yet planned.

8.3 Intrusion of liquid water, freezing and testing at cold temperature

WSLS test coupons with liquid water were deep frozen and tested at RT and also at cold temperature for demonstration purpose. Again, the current procedure for each UT check is to warm up the coupon and to evaporate the water.

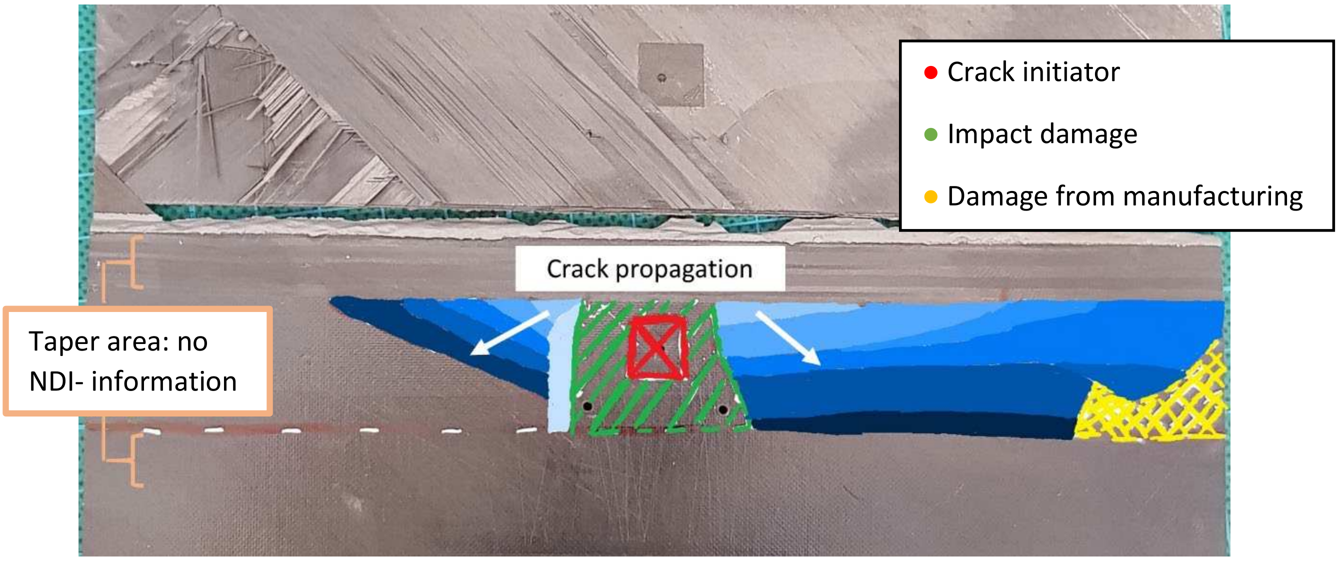

Figure 13. WSLS sample after rupture at 30kN after 114'000 cycles, tested at RT, following several freezing cycles at -28°C with water/ice in the disbond. The crack grows from light- to dark blue, initial crack start area is not indicated (not detected with UT in the taper).

  doi:10.5075/epfl-298799_978-2-9701614-0-0

9. Outlook

The work performed so far demonstrates that a real impact crack can repeatedly be produced and its growth under environmental influence of water and ice can be studied.
The concept of small WSLS-samples was proven to work but it is evident that the large WSLS samples used during the BOPACS showed a more symmetric and steadier crack growth. Currently the crack propagation in the tapered area is unknown. The lack of information must be minimized by upgrading the NDI e.g., with trough transmission method using a second US-sensor.

10. Way toward standardization of WSLS samples

The current status of sample definition, impact generation and fatigue testing is quite mature and provides a good starting point for individual investigations. Cooperation with partners is welcome. The standardization of the test can be considered.

Acknowledgements

SNF: funded by Swiss National Science Foundation
EU-COST Action CA18120
EPFL for cooperation

References

1. Th. Kruse, Th. Körwien and R. Ruzek; Fatigue Behaviour and Damage Tolerant Design of Composite Bonded Joints for Aerospace Application, ECCM17, 2016.
2. Th. Kruse, Th. Körwien, Th. Meer, Matthias Geistbeck; Certification by means of Disbond Arrest Features and Results (EU-FP7 Project BOPACS)
3. M. Santaniello; Numerical Assessment of Defects Effect on Boltless Composites Longitudinal Joints