Technical Evaluation Report

Lucas F M da Silva
Faculty of Engineering of the University of Porto,
PORTUGAL
lucas@fe.up.pt

ABSTRACT

AVT-361 Research Workshop on "Certification of Bonded Repair on Composite Aircraft Structures" took place at NLR in Amsterdam. Repair of primary structures using adhesive bonding with composite materials offers many advantages, such as lower weight gain, performance, and practicability. It is however important to have a certification that can be applied to as many cases as possible. The certification comprises the repair design for strength and damage tolerance, the validation with analysis and proof testing and the service monitoring with devices that can detect defects that may occur.

The workshop had 33 participants from nine countries and the agenda of three days comprised 17 presentations from seven countries being the USA the most represented country with seven presentations. The presentations were 30 minutes long and had a period of discussion of approximately 10 minutes. All the topics related to repair certification were covered, i.e., design for strength and damage tolerance, theoretical analysis (e.g. numerical modelling, machine learning, etc.), proof testing, ageing and certification.

The works presented are very impressive in terms of innovation and technological impact. The most advanced theoretical and experimental analysis tools are used such as damage mechanics, machine learning, digital image correlation, Lamb waves, laser bond inspection, etc. Clever methods for damage tolerance such as surface toughening and crack stoppers are presented. An innovative dummy proof testing method close to the repair is proposed. Probably the most important point is that since the detection of weak adhesion is still a challenge (even though laser inspection is a promising technique), damage tolerant design is essential to maintain safety.

AGENDA

AVT-361 Research Workshop on "Certification of Bonded Repair on Composite Aircraft Structures" workshop takes place in three days, as shown in Table 1.

Table 1 - Agenda of AVT-361 Research Workshop on "Certification of Bonded Repair on Composite Aircraft Structures" workshop

Location:		NLR, Amsterdam			
Date:		Tuesday 18 October 2022			
Time		Topic	Subjects	Presenter	
12:00	13:00	Registration			
13:00	14:00	Lunch			
14:00	14:10	Welcome	Welcome	Halm	
14:10	14:30	General	General NATO/AVT introduction	Thorvaldsen	
14:30	15:15	Key note speech	JSF structural repair development	Carl Rousseau	1
15:15	15:45	Ageing	Lap Shear Fatigue Life Effects from Moisture Conditioning During and After Specimen Production	Hart	2
15:45	16:05	Coffee break			
16:05	16:35	Ageing	Designing and validating high performance bonded joints for structural applications	Marques	3
16:35	17:05	Ageing	Ageing of adhesive bonded repairs and methods to monitor the bondline degradation	Nijhuis	4

Location:		NLR, Amsterdam			
Date:		Wednesday 19 October 2022			
Time		Topic	Subjects	Presenter	
09:00	09:30	Opening of the day	welcome / start-up	Halm	
09:30	10:00	Damage tolerance/Crack arresting	Towards the analysis of damage tolerance of bonded repairs	Jokinen	5
10:00	10:30	Damage tolerance/Crack arresting	Robust Bonded Joints with Surface Toughening design feature	Schollerer	6
10:30	11:00	Coffe break			
11:00	11:30	Damage tolerance/Crack arresting	Evaluation of crack growth as certification enabler for bonded repair applications	Kruse-Strack	7
11:30	12:00	Damage tolerance/Crack arresting	Evaluation of crack growth in scarfed bonded joints	Koerwien	8
12:00	13:00	Lunch			
13:00	13:30	NDE	Perspectives on Non-Destructive evaluation of bonded joints	Lindgren	9
13:30	13:50	Coffee break			
13:50	14:20	NDE	Structural Health Monitoring and Non-Destructive Evaluation	Mull	10
14:20	14:50	Bonding	Shock Resistant Bonding of Steel and Composite NATO AVT Research Workshop (RWS)	Schipperen, Verhaeghe	11
14:50	15:20	Certification	Bonded repairs to critical damage in primary composite – A proposed roadmap to certification	Li	12
15:20	15:50	Certification	Validation and Certification of Bonded Repair on F-18 Wing Root Step Lap Joint	Wallin	13
15:50	16:50	Spare			

Non Hosted Diner in the evening

Location:		NLR, Amsterdam			
Date:		Thurday 20 October 2022			
Time		Topic	Subjects	Presenter	
08:30	08:40	Opening of the day	welcome / start-up		
08:40	09:10	Simulation/Design	Multi-Scale Multi-Physics Bondline Strength Prediction Research	Hart, terMaath, Martinez, Merrett	14
09:10	09:40	Simulation/Design	NDE-Guided Compression After Impact simulation	Hoos, Mollenhauer, Flores, Iarve	15
09:40	10:10	Simulation/Design	Composite patch debonding monitoring based on surrogate modeling and particle filter	Oboe	16
10:10	10:30	Coffee break			
10:30	11:00	Simulation/Design	Abaqus Explicit Implementation of Regularized Extended Finite Element	Iarve	17
11:00	12:30	Technical Evaluation	Evaluation / Closing	da Silva	
12:30	13:30	Lunch			

There are 17 presentations covering all the aspects associated to the certification of bonded repairs. The presentations are organised in six sessions: Ageing, Damage tolerance/Crack arresting, Non-destructive evaluation, Bonding, Certification and Simulation/Design. The sequence could be done in several ways, but I would recommend to follow the steps usually involved in the adhesive bonding (production, design, ageing, non-destructive testing) or associated to the certification steps (design, validation, monitoring).

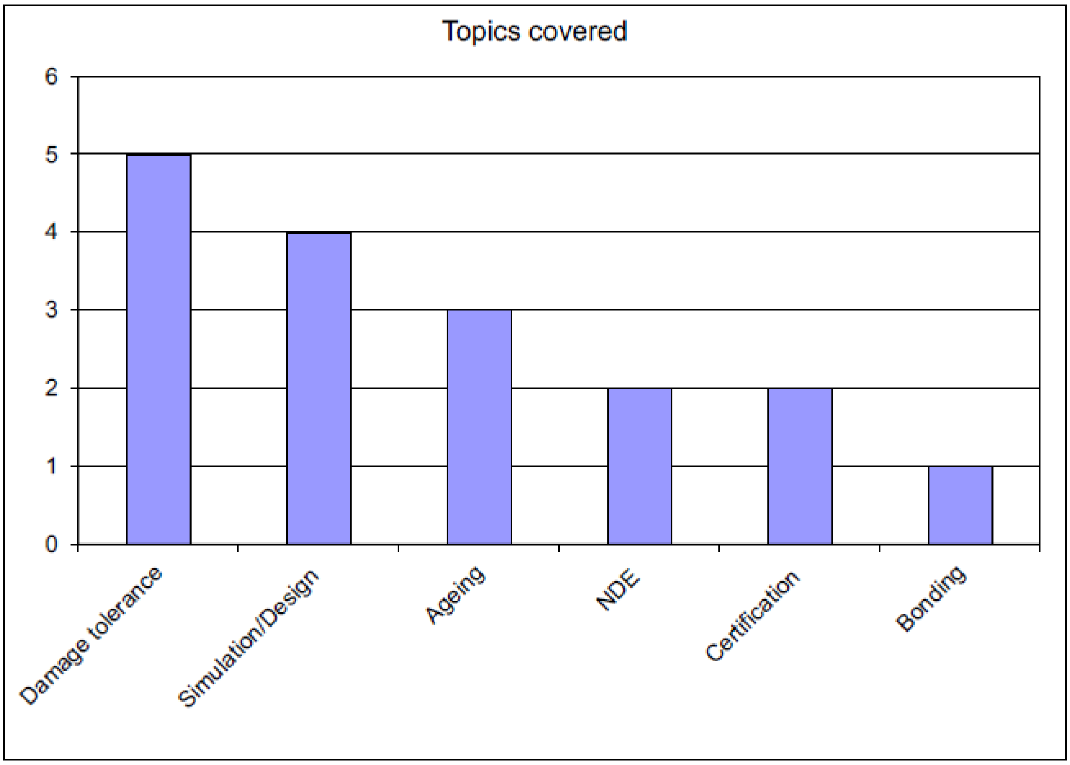


Figure 1 – Topics covered in the workshop.

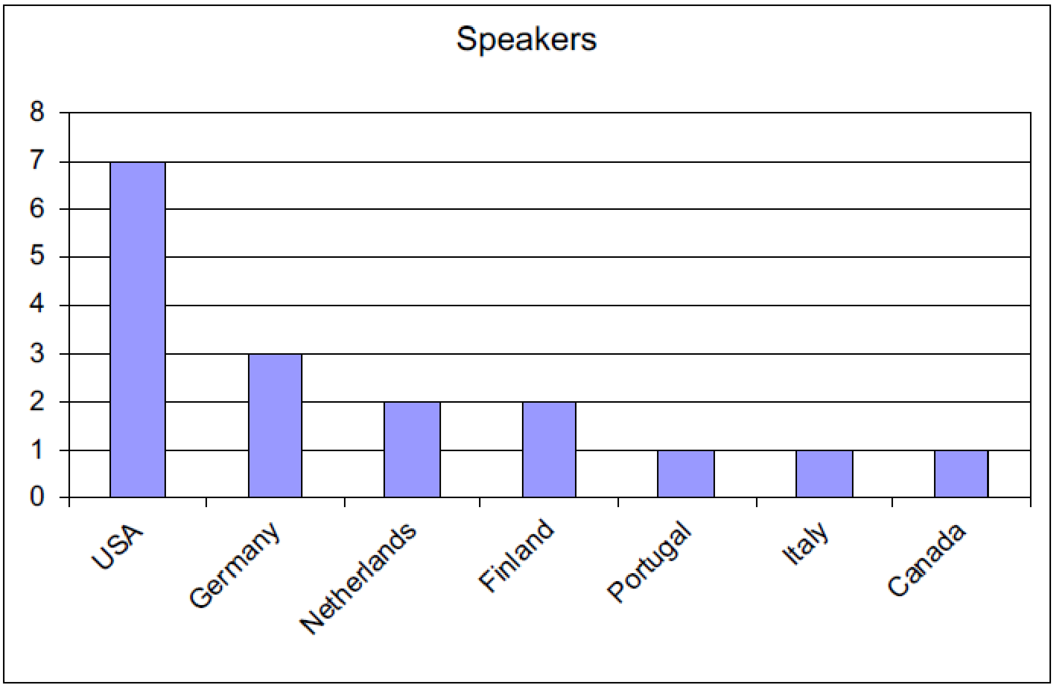


Figure 2 – Speakers in the workshop by country.

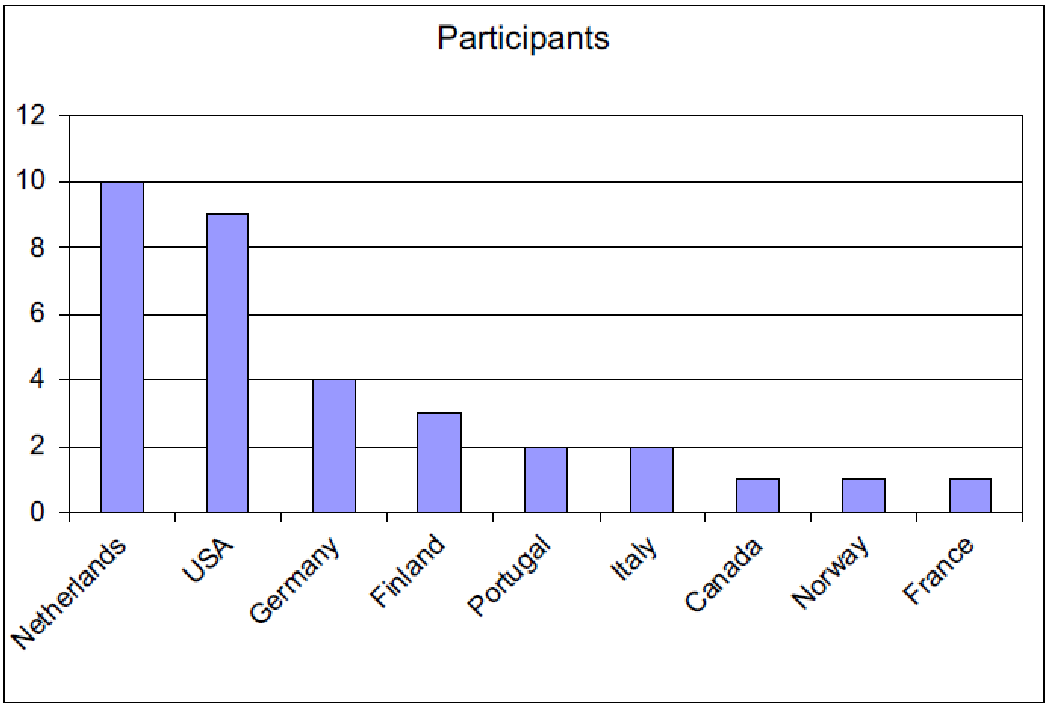


Figure 3 – Participants in the workshop by country.

The 17 presentations were evaluated concerning the scientific soundness and the technological significance for the repair certification. The global assessment of the presentations put in the right context and their impact in the scientific and industrial community is carried in the following section (Assessment of the meeting's impact).

Here, each presentation was commented and all questions and answers during discussions were captured and transcribed. However, since this is a detailed section that is more a complement to the technical evaluation report, the reader can consult Appendix – Evaluation of each presentation with comments, questions and answers. The questions and answers were transcribed based on notes taken during the meeting.

ASSESSMENT OF THE MEETING'S IMPACT

The overall technical-scientific situation related to adhesive bonding and repair in particular is presented. A comprehensive picture of the meeting presentations is given concerning their impact on the overall technical-scientific situation.

The assessment is carried out starting with an introduction to adhesive bonding (advantages, situation in aeronautical sector, defects in bondlines) and what involves repairs (advantages, certification). Then, the steps involved in certification are followed, i.e.:

- Design modelling,
- Damage tolerant design,
- Proof testing,
- Ageing,

- Structural health monitoring and non-destructive evaluation
- Certification.

Each section includes a reference to the presentations that deal with these steps with a critical assessment and impact.

Adhesive bonding was viewed a decade or two ago as an innovative technology with a very promising future [1]. There are many advantages associated to this joining method. The most relevant for the aeronautical and aerospace sectors is probably the weight gain and the durability, especially when it comes to fatigue. Adhesive joints are stronger than conventional rivet joints because the load is more evenly spread and more fatigue resistant because there are no stress peaks that occur next to holes when rivets are used (Figure 4).

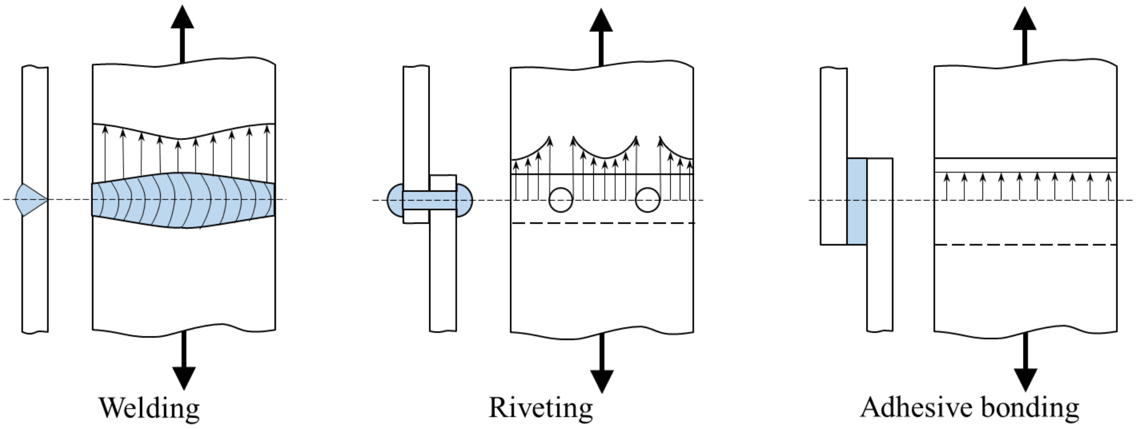
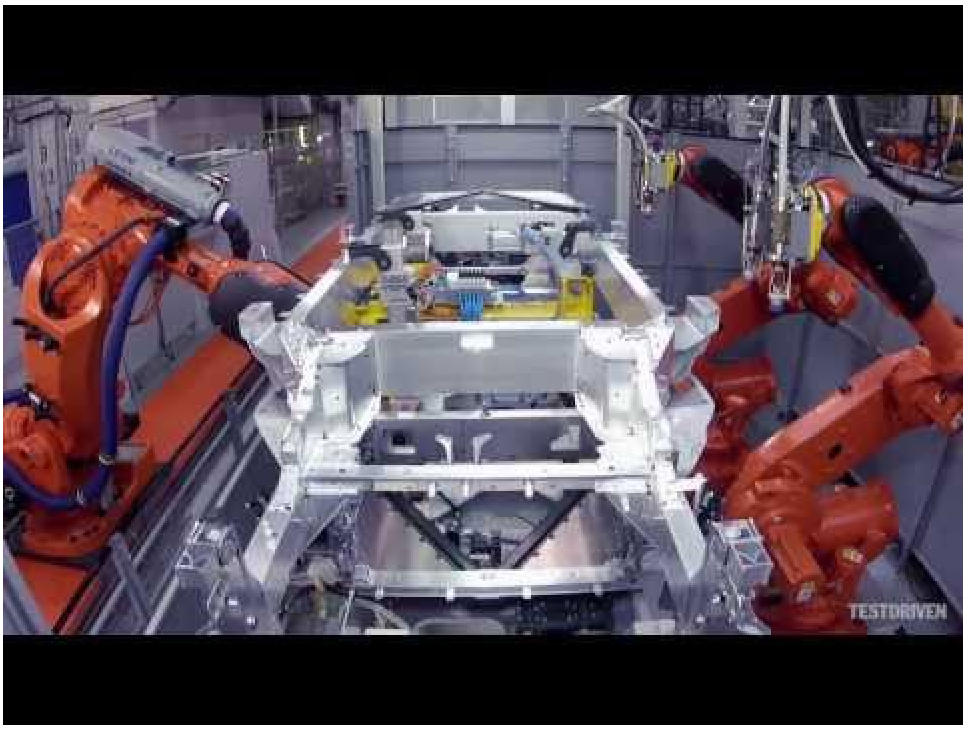


Figure 4 - Uniform distribution of load and no stress concentration.

Nowadays adhesive bonding can be considered a more mature technology and it is extensively used in many industries. The aeronautical sector was the pioneer in the use if the technology, but now the main driver for the further development of this technology is the automotive industry. That is because of electric and high performance car growth, both of which need light materials and structures to ensure efficiency and performance of the vehicle.

Light materials such as aluminium alloys and composites (fibre reinforced plastics) are best joined by adhesives. Aluminium is difficult to weld and sensitive to heat input, and composites are very sensitive to stress concentrations that occur next to holes. The traditional spot- welding production of the body is being replaced by adhesive application (Vídeo 1).



Vídeo 1 – Production process of a BMW i3 electric car.

Curiously, the aeronautical and aerospace sector that were the first to use adhesive bonding are reluctant to extensively apply the technology, especially when it comes to primary structures [2]. Even if it has been proved that adhesive bonding gives higher strength structures, primary structures still rely mainly on mechanical fastening. The main reason for the cautious use of adhesive bonding in aircraft and space structures is the difficulty in detecting weak adhesion (Figure 5). That jeopardizes the certification and prevents the use of adhesive bonding in places responsible for the full integrity of the structure.

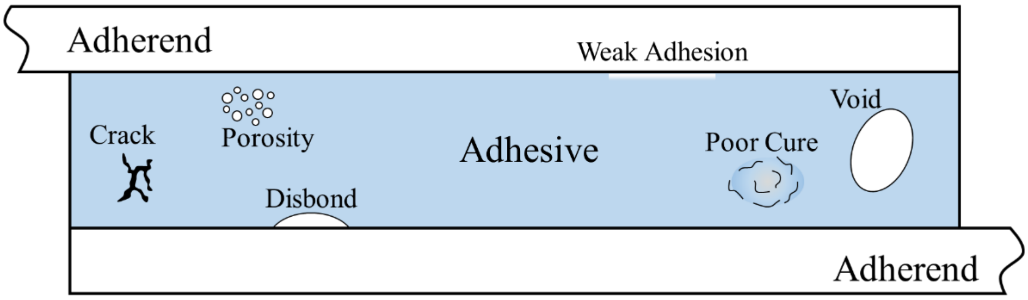


Figure 5 – Typical defects of the adhesive layer in an adhesive joint.

Adhesively bonded repairs are very attractive in aeronautical structures because of the ease of fabrication (Figure 6) and the load efficiency that enables an important life extension

(Figure 7). But again, if the repair is responsible for the integrity of a primary structure, then the certification is of paramount importance. If weak adhesion cannot be detected, then safe design, proof testing and structural health monitoring are the alternatives to ensure a safe repair (Figure 8). Typically, repairs are made of composite materials adhesively bonded to composite or metal. In addition to the bondline, composite damage such as delamination needs also to be considered (Figure 9) [3]. The bondline and the composite are subjected to a variety of loading during service such as static loads, fatigue, impact, temperature cycling, and water ingress. All these loading cases can be degraded by ageing, which must be accounted for as well. These are the main issues to tackle when it comes to repair certification.

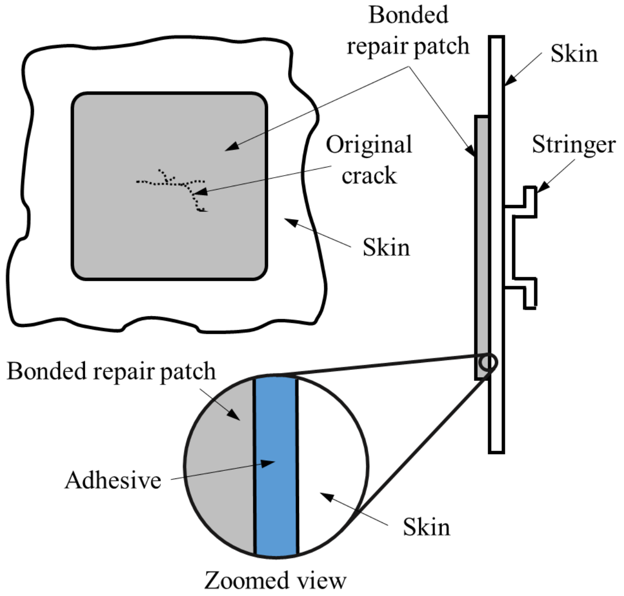


Figure 6 - Schematic representation of an adhesively bonded repair patch.

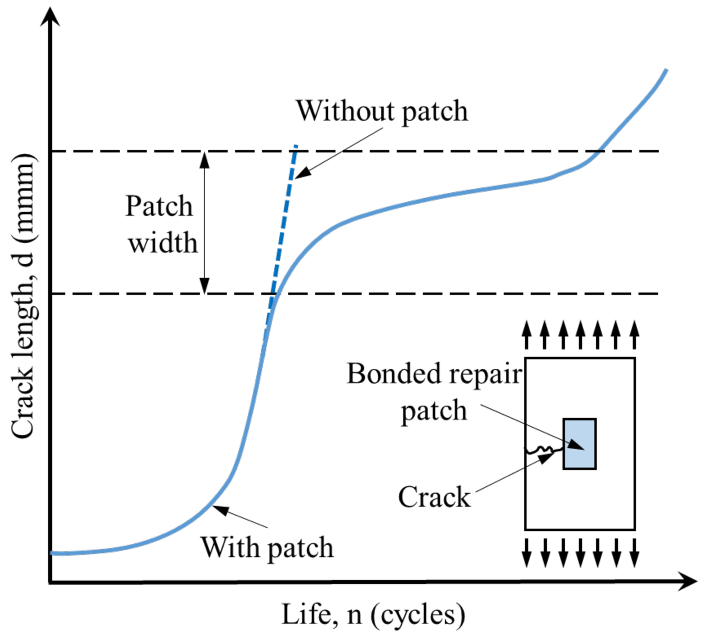


Figure 7 - Extension of the service life gained with the use of bonded crack stoppers.

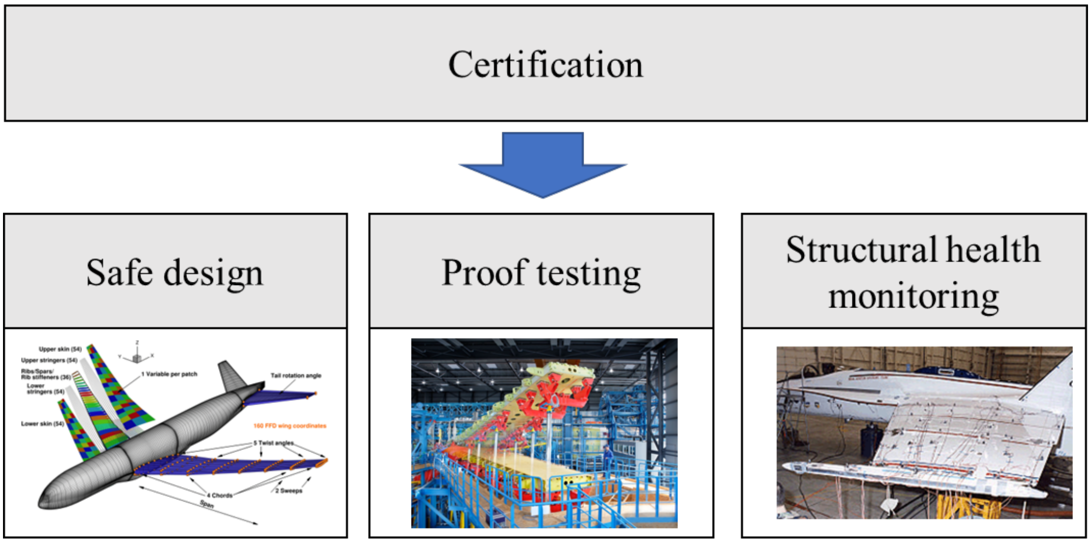


Figure 8 - Certification process of an aircraft structure based on the principles of safe design, proof testing and structural health monitoring.

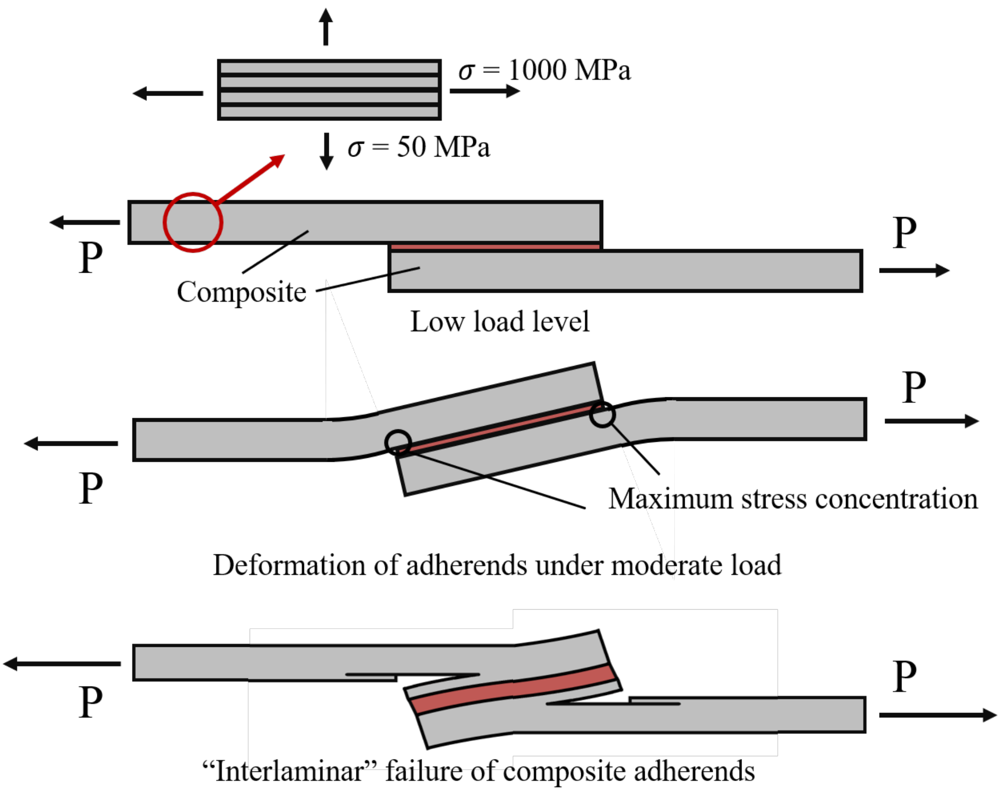


Figure 9 – Failure in a single lap joint due to delamination.

Adhesive bonding has been the subject of extensive research, especially driven by the automotive industry. The main issue being investigated now is the durability or ageing. It is very simple to design for tomorrow but much more difficult for a longer period and to consider all the types of loadings and environments. The main tool used to design adhesive joints is damage mechanics which combines continuum mechanics and fracture mechanics (Figure 10). The interface consisting of the adhesive or the interface between two laminates can be modelled by a single layer of cohesive element that degrades as a limit load is reached [4]. It is presently the most complete and reliable tool to design adhesive joints. It also includes composite delamination which is therefore perfect for designing repairs with composite materials. This tool is referred to and used in three presentations (Presentation 3

- Designing and validating high performance bonded joints for structural applications, Presentation 5 - Towards the analysis of damage tolerance of bonded repairs and Presentation 17 - Abaqus explicit implementation of regularized extended finite element). The work in 17 is even more advanced and uses Regularized eXtended Finite Element Method (Rx-FEM), a variant of the extended finite element method. Rx-FEM allows maintaining regular element integration scheme. A beam under impact being is considered. It is not clear if cohesive zone elements are used between the skin and the core. Rx-FEM does not need the pre-definition of the crack path. It is used for an impact situation which to my knowledge has never been done before. The problem associated to XFEM is the crack propagation between interfaces [5]. When there is mode I loading, the crack will follow the right path, but when loaded in mode II the crack tends to the interface and then the substrate, perpendicularly to

the principal stress. In practice the crack will stay at the interface and will not go into the interface (Figure 11).

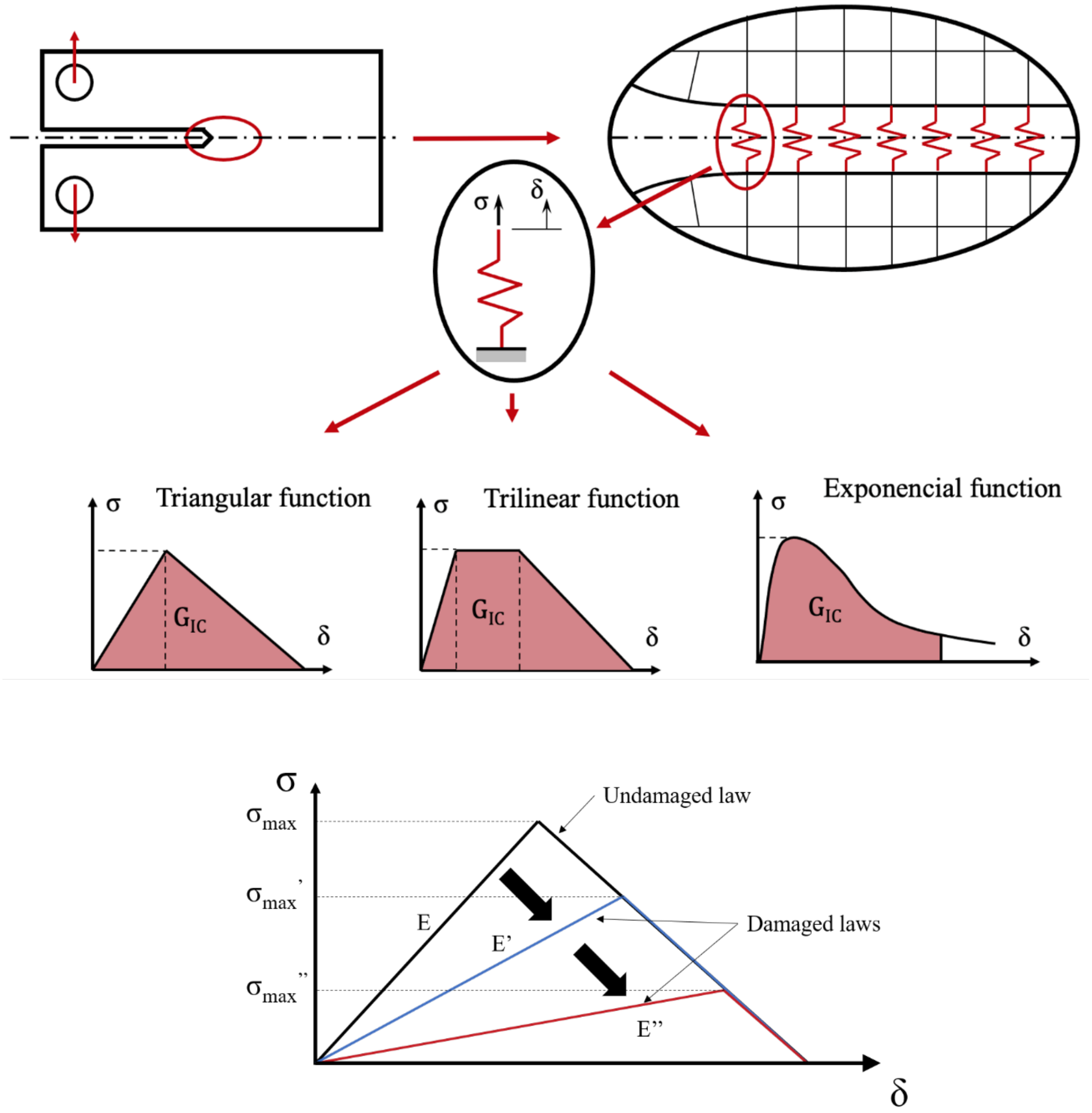


Figure 10 - Principle of a cohesive zone model and different cohesive law shapes.

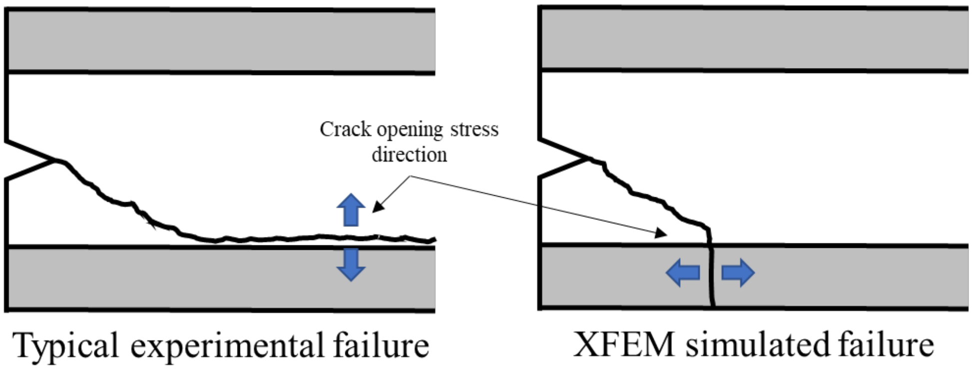


Figure 11 – Incorrect crack deviation towards the substrate typically found when using XFEM

Multiphysics and multiscale modelling is being applied to a variety of technologies to understand more deeply what governs the physics behind it. Joining processes have also invested in this approach and adhesive bonding is no exception [6]. The modelling starts with the adhesive in the liquid state, then considers the application of the adhesive on the substrate, then the spreading of the adhesive on the surface of the substrate and the hardening or curing of the adhesive (Figure 12). At the end the exact shape of the adhesive and the stress state are known. These obviously influence the mechanical behaviour of the joint and give a more realistic joint strength prediction. This process also enables more informed control during the production stage. The adhesive-adherend interaction is a microscale or even nanoscale phenomenon that is difficult to model in a macro approach. Local modelling can be used [7] or even molecular dynamics [8] (Figure 13). This integrated approach is followed in Presentation 14 - Multi-scale multi-physics bondline strength prediction research but the authors recognise that a common physical model gets too complex. To bridge different scales is a major technical challenge. Machine learning is used in a 4-point bending test to identify the most influential parameters on the macroscopic response. Machine learning has been applied in many fields with success, especially when the data treatment gets too complex. The viscoelastic behaviour of the adhesive is also considered. The work presented in Presentation 16 - Composite patch debonding monitoring based on surrogate modelling and particle filter also makes use of these advanced data treatment techniques to interpret data from optical fibres. The discussion here is about modelling techniques. The work presented in Presentation 16 - Composite patch debonding monitoring based on surrogate modelling and particle filter is about non-destructive testing and structural health monitoring. This subject is discussed in more detail below. Presentation 15 - NDE-guided compression after impact simulation is also a case of a work that deals with simulation and non-destructive testing. Image analysis has made a lot of advances in recent years, and it is possible to get a very good 3d definition of the defects present in a structure [9]. This helps the design engineer to assess the exact impact that a defect can have in the strength of the repair (Figure 14). A study about the impact of the damage fidelity on the numerical results is carried out. Reducing the fidelity of damage has an impact of the strength prediction (predicted load is lower). However, a lower fidelity damage approximation provides a conservative prediction which is adequate for strength prediction

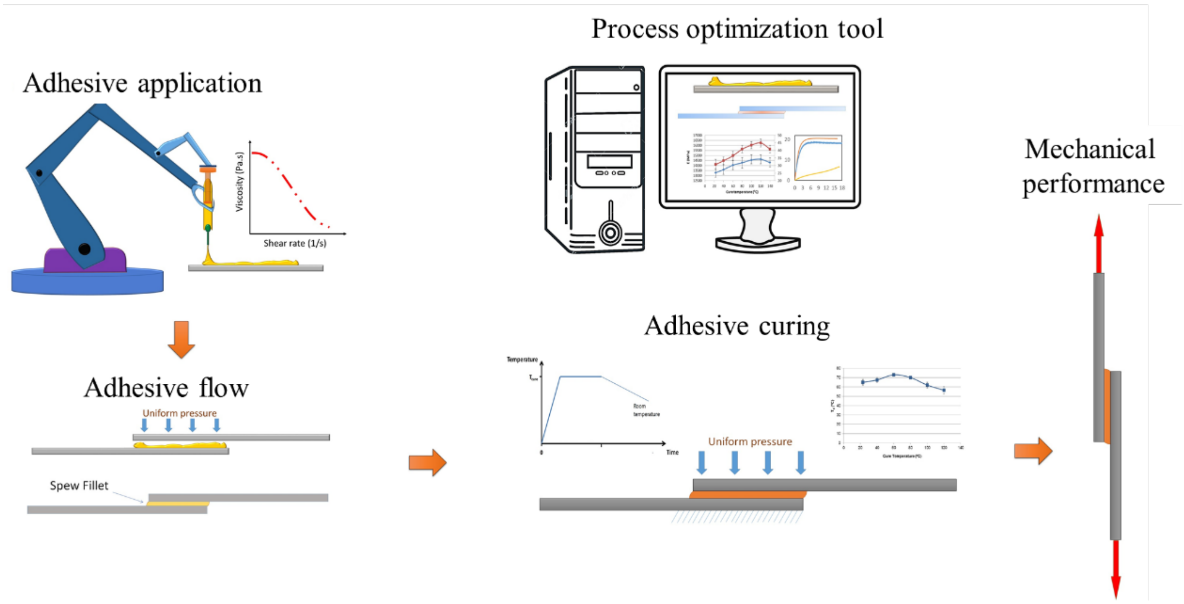


Figure 12 – Workflow for a project seeking to correlate adhesive application, flow and curing with the final mechanical performance of a joint.

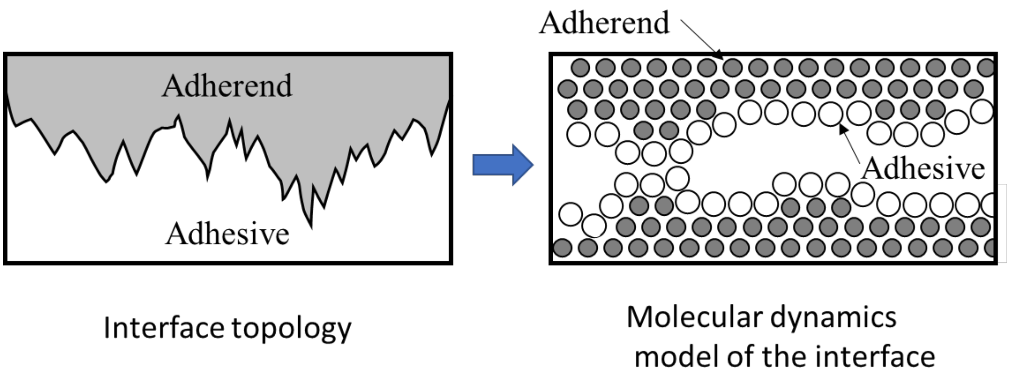


Figure 13 - Local modelling of the adherend-adhesive interface and its molecular dynamics.

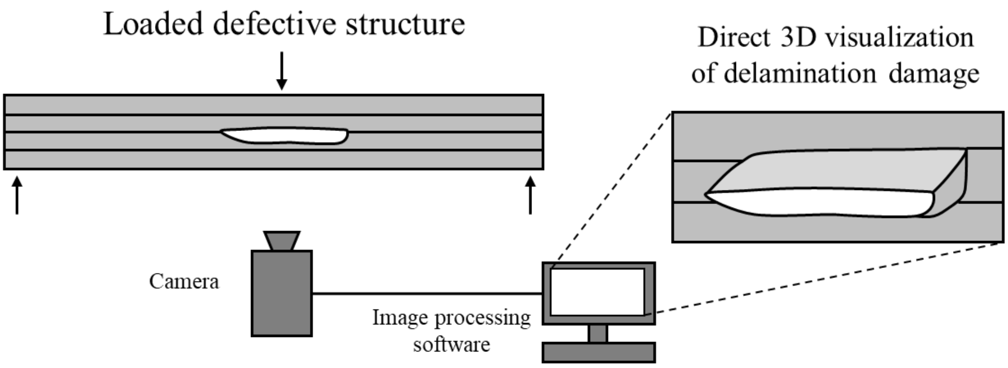


Figure 14 – Detection of 3d defect with high resolution camaras and image processing software

Damage tolerant design in automotive structures consists often of combining adhesive bonding with another method of joining such as spot weld, fastener or rivet. This facilitates production and is an additional safety measure in case the adhesive fails. There is a two-stage failure mode that enables a progressive failure (Figure 15) [10]. This aspect of failsafe is extremely important in aeronautical structures. The same principle as that used in the automotive industry is used in aeronautical structures with the 'chicken rivets' or something similar. But damage tolerant design is not about hybrid joining where the rivets take a major part of the load. Damage tolerant design is dealt with in four presentations and is really one of the key points to deal with weak adhesion.

In one case a surface toughening method is presented (Presentation 6 - Robust bonded joints with surface toughening design feature). The composite is reinforced at the ends of the overlap where there are stress concentrations to prevent composite delamination (Figure 16). Currently, a film of polyvinyl diene fluoride is used (PVDF). The method is compared with other methods to reinforce the joint strength with good results. This technique has also been developed in another group with similar results (Presentation 3 - Designing and validating high performance bonded joints for structural applications) [11]. This surface toughening technique can make a repair more tolerant and reduces the risk of delamination when using composites due to their low interlaminar strength. This is very well shown with the help of advanced monitoring techniques such as digital image correlation in Presentation 5 - Towards the analysis of damage tolerance of bonded repairs.

Presentation 7 - Evaluation of crack growth as certification enabler for bonded repair applications presents results obtained in several European projects related to crack arresting, damage tolerant sizing and simulation methods. A large single lap joint with composite adherends is studied containing weak adhesion and disbond arrest features consisting of pins and surface toughening (treated in Presentation 3 - Designing and validating high performance bonded joints for structural applications and Presentation 8 - Evaluation of crack growth in scarfed bonded joints). In addition to fatigue, impact damage is also included. The results are compared with a case where there are no arrest features, and the improvement is considerable (Figure 18). The experimental campaign is also complemented with a finite element simulation and a very good agreement is obtained.

Another approach for damage tolerance is to take advantage of the joint configuration such as that offered by a scarf angle and strategic laminates orientation to create several load paths for crack retardation or arrest (Presentation 8 - Evaluation of crack growth in scarfed bonded joints) (Figure 17). The staking orientation as well as the slope of the layers were modified to create an intricate crack path to increase energy dissipation during crack growth. These two techniques could be combined for additional strength and damage tolerance.

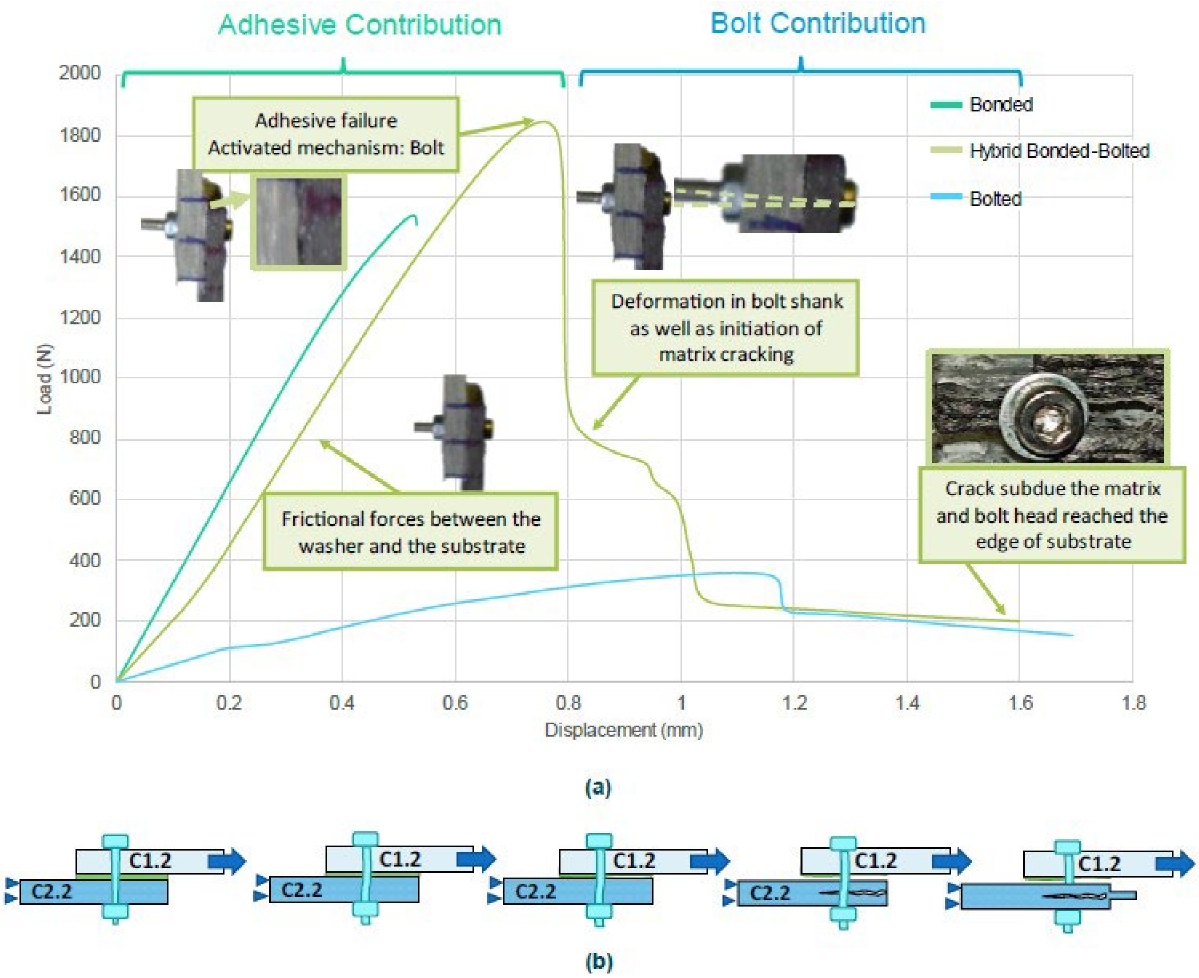


Figure 15 – Contribution of adhesive and bolt in the mechanical performance of hybrid joint(a)and schematic representation of the failure process (b).

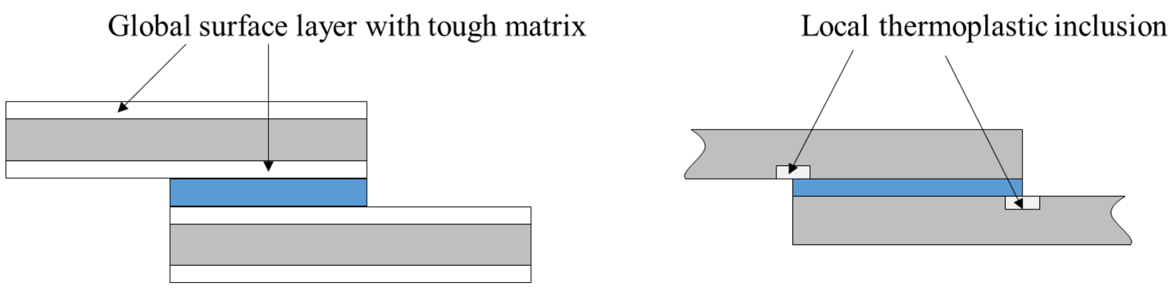


Figure 16 – Surface toughening concept

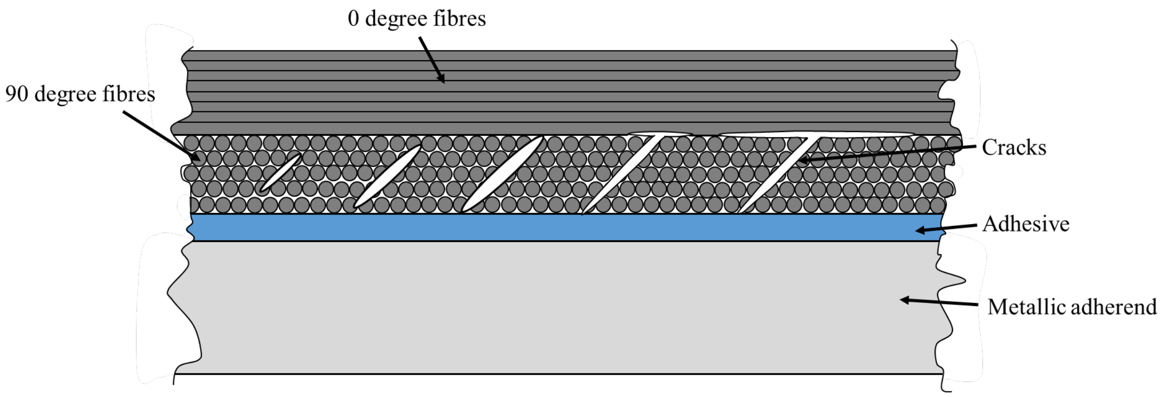


Figure 17 – A change in the laminate orientation makes the crack growth more difficult.

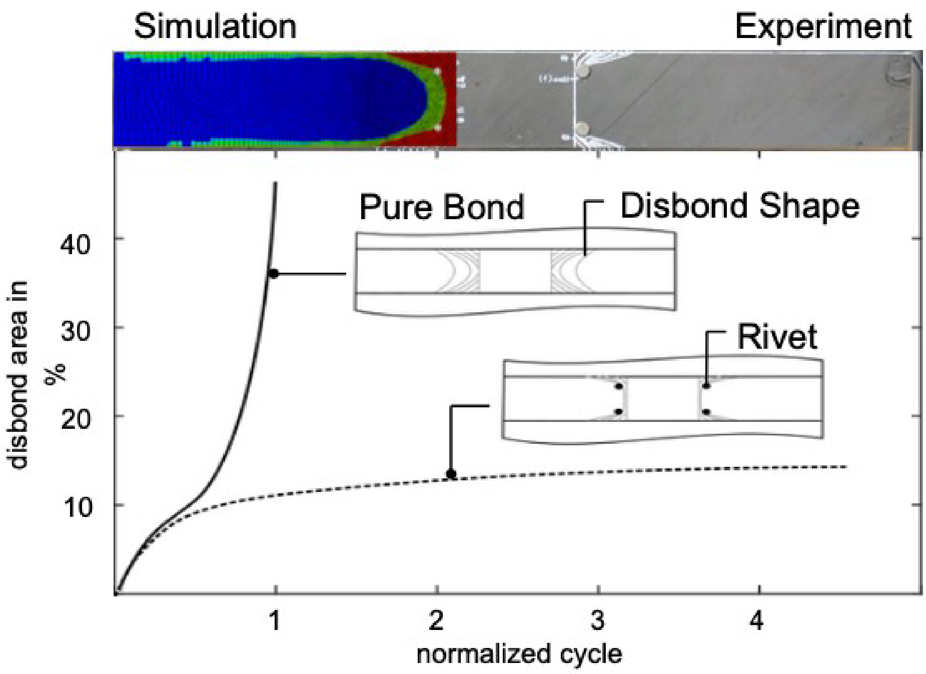


Figure 18 – Effect of crack arrest features in the crack growth of a single joint (from Presentation 7 - Evaluation of crack growth as certification enabler for bonded repair applications)

Other methods documented in the literature consist of thread stitching and z-pinning (Figure19) [12-14]. Functionally graded joints where the gradation is done in the adhesive (Figure 20) [15] or in the adherend [16] can provide a joint that avoids stress concentrations at the ends of the overlap or the repair (Presentation 3 - Designing and validating high performance bonded joints for structural applications). The graded functionality can also enhance the temperature resistance of the joint with the use of low and high temperature adhesives (Figure 21) (Presentation 3 - Designing and validating high performance bonded joints for structural applications). There is still another possibility to design smart repairs that would take advantage of the recent advances in 3d printing [17, 18]. There are nowadays 3D printing machines that include fibres as well so that the fibres could be placed in strategic places of the repair to produce an optimised damage tolerant structure (Figure 22).

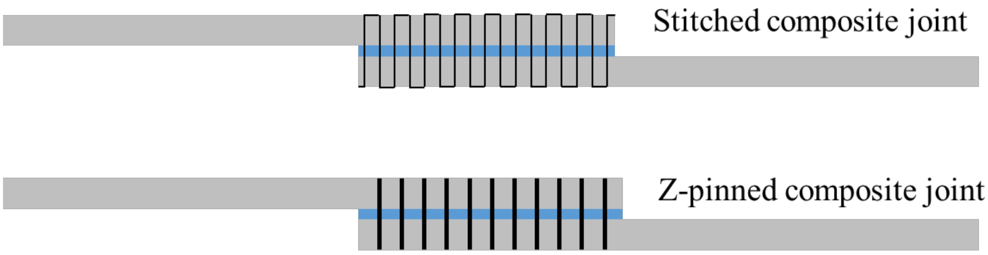


Figure 19 - Thru-the-thickness reinforcement methods for composites using thread stitching and z-pinning

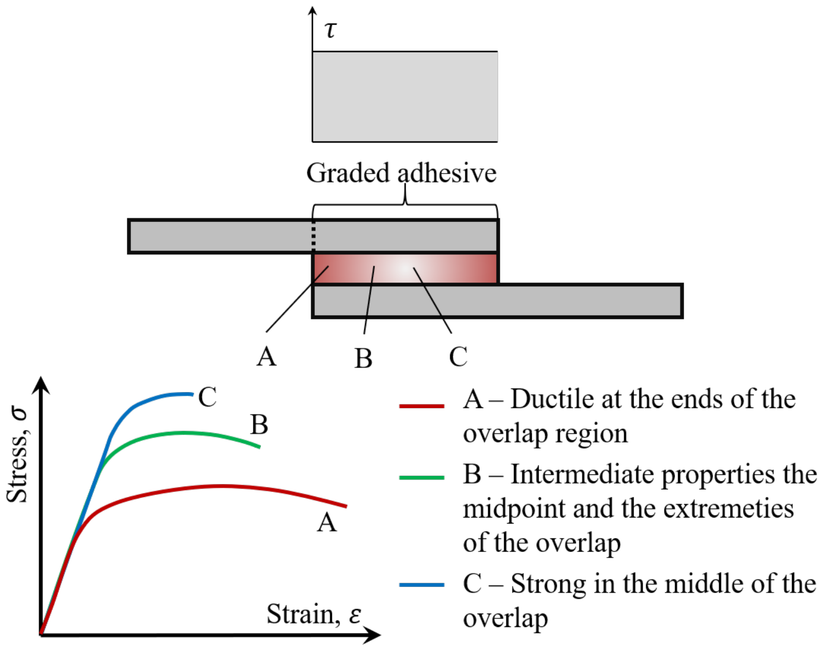


Figure 20 – Functionally graded joint for improved joint strength.

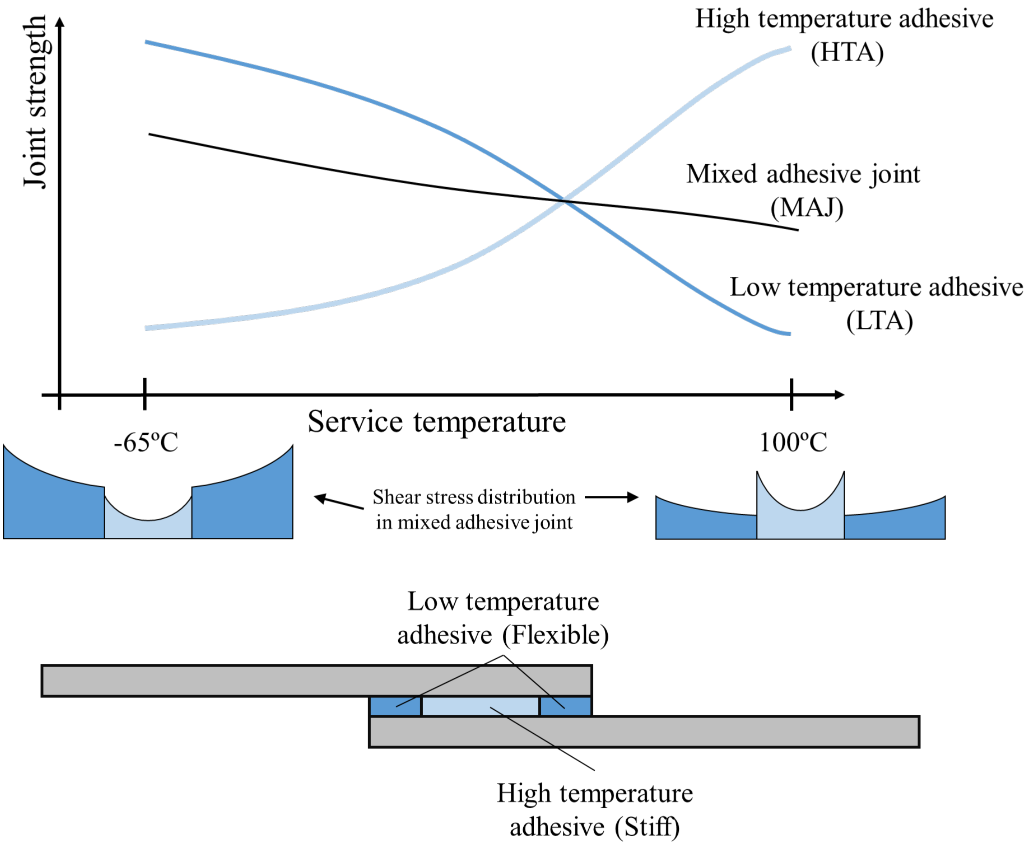


Figure 21 - Functionally graded joint for improved temperature resistance.

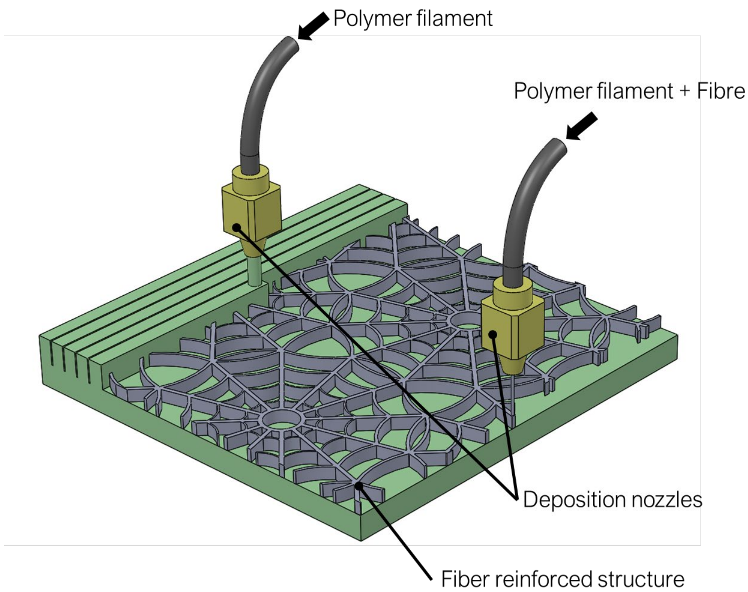


Figure 22 – 3d printing of a fibre reinforced plastic with unconventional fibre orientation.

Proof testing is the most convincing step for certification purposes. Aircraft wings are an example of a component where a proof test (typically equal to 150% of the expected service load) is employed (Figure 23). Proof testing is particularly expensive even at laboratory scale specimens. To reduce the cost as much as possible, small scale coupons representative of the real repair are used in Presentation 4 - Ageing of adhesive bonded repairs and methods to monitor the bondline degradation. This work uses a clever dummy joint close to a repair to assess the quality of the repair. The effects of time dependent damage such as ageing degradation or fatigue cracks are not captured in regular proof tests. But in this work, the proof test is carried out after moisture ingress and temperature cycling. The results present an important dispersion. But the question is to know if the stress state in the bonded repair coupon is the same as in the repair. Also, moisture ingress and temperature cycling in the coupon might not represent properly what is happening in the actual repair. The issue of ageing is discussed below

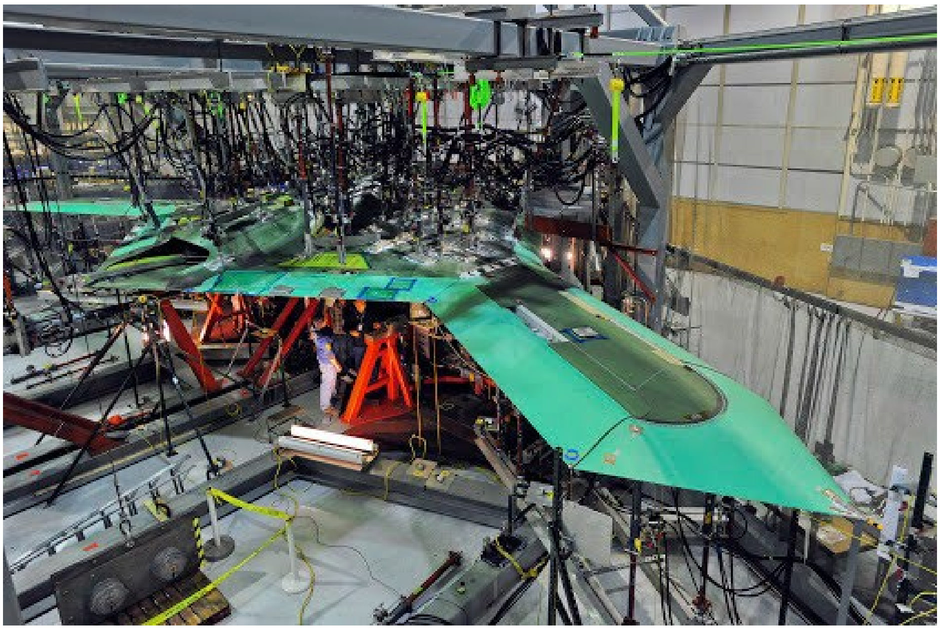


Figure 23 - Proof test of the X-47B unmanned aerial vehicle (Northrop-Grumman).

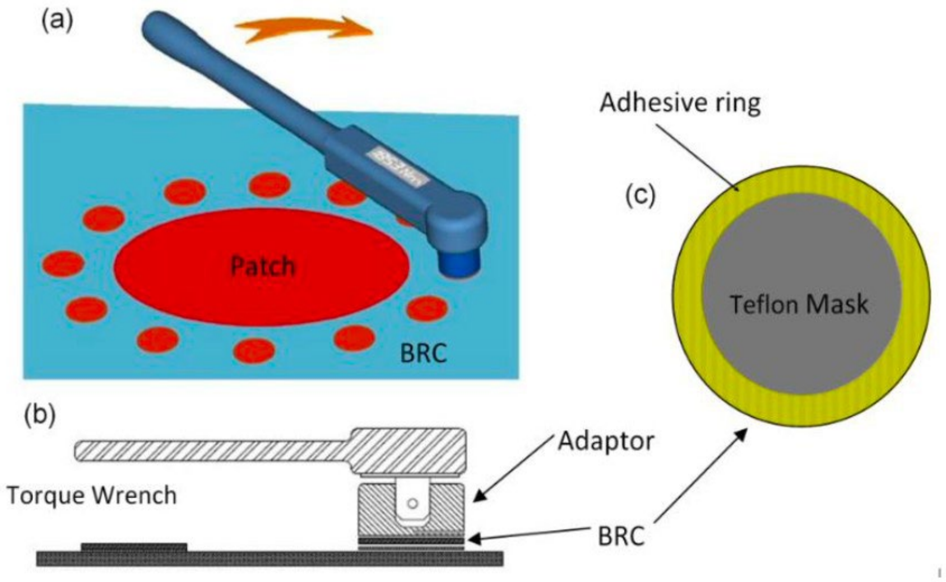


Figure 24 – Dummy repair for proof testing the repair (taken from Presentation 4 - Ageing ofadhesive bonded repairs and methods to monitor the bondline degradation

Ageing is probably the main issue in adhesive bonding [19]. Ageing can occur due to several types of degradation caused by fatigue, impact, water, temperature, and radiation. It is a big challenge to ensure integrity of the repair under these ageing conditions. Also, the phenomena involved are very complex and cannot be understood purely from a mechanical design perspective. The adhesive itself suffers chemical changes but the major issue is the interface [20]. This the main enemy of the adhesive bonding, especially when durability is involved. An interface might initially after a repair is produced sound but with time it will degrade and might lead to debonding at the bondline or between laminates (Figure 25). Water ingress changes the adhesive and resin properties, but this change is well understood and can be controlled. The problem is to understand what happens to the substrate surface during service [21]. This is especially relevant when metals are involved. Composites are less sensitive to this issue (Presentation 2 - Lap shear fatigue life effects from moisture conditioning during and after specimen production, Presentation 3 - Designing and validating high performance bonded joints for structural applications). The detection of water at the interface can be done for example by fibre Bragg gratings. This device is also used for structural health monitoring (see discussion about monitoring below). A multiphysics approach is required to capture properly all the phenomena involved. Design criteria that consider all these variables become very complex but cohesive zone modelling (Figure 10) is a very promising approach. It is used to design for static loading, fatigue, impact, creep and water ingress [22-24]. The degradation can occur as a function of the number of cycles (fatigue), strain rate (impact), temperature (creep) or water content. A cohesive law can integrate all the degradation possibilities (Figure 26). This approach has also the advantage to integrate possible interactions that cannot be included when each ageing condition is considered separately. A cohesive law can be defined for the adhesive or resin as well as for the interface. But a lot of data is needed to define the right material or interface properties.

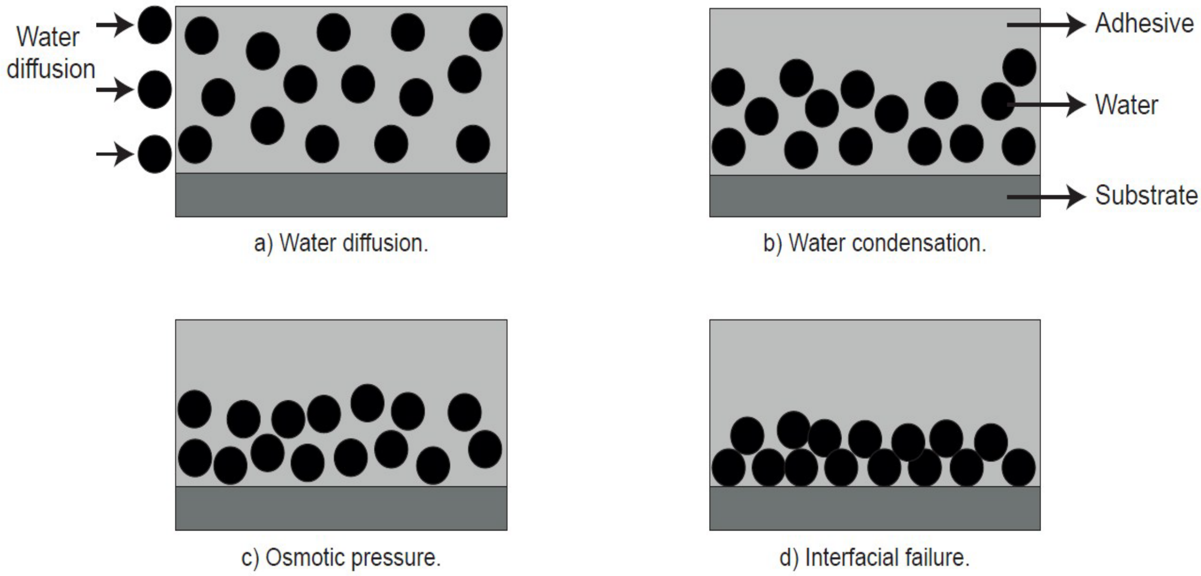


Figure 25 – Interfacial failure due to water diffusion.

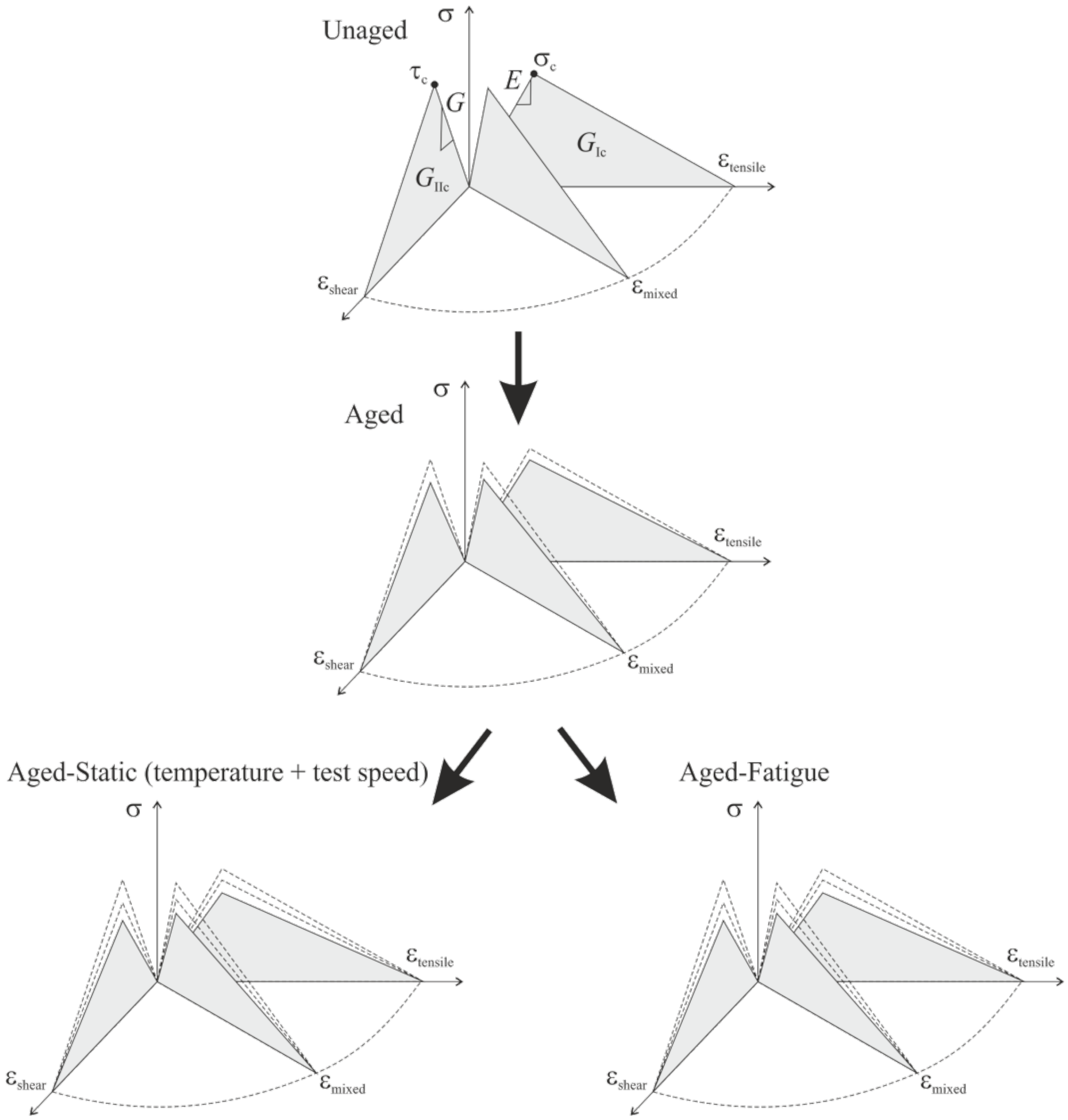


Figure 26 - Degradation in cohesive zone modelling as a function of number of cycles (fatigue), strain rate (impact), temperature (creep) or water content.

Alternatively to the cohesive zone modelling approach, a total fatigue life (S-N) approach might be used (Presentation 3 - Designing and validating high performance bonded joints for structural applications). It is computationally less demanding and still can include all the environmental effects such as temperature and water (Figure 27) [25]. The S-N method usually requires a simple linear elastic analysis to be conducted on the joint geometry under analysis and the defined equivalent stress should be measured within the bondline. By knowing the effective stress value, the corresponding life can be estimated using the previously determined master curve (Figure 28) [26].

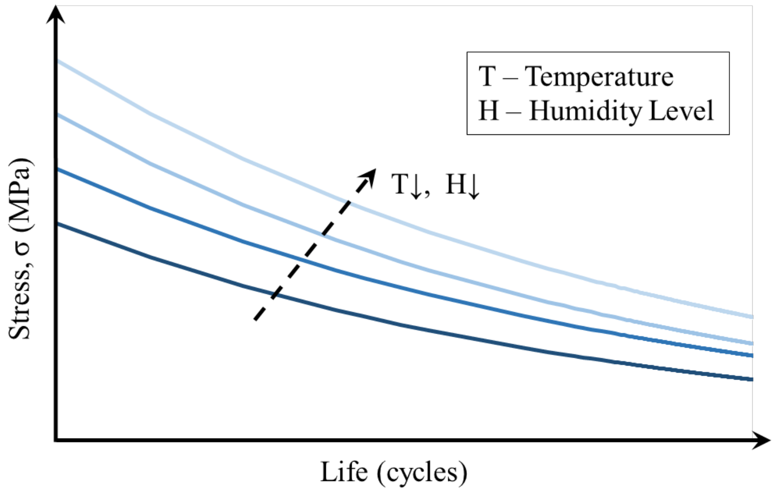


Figure 27 - Effect of temperature and ageing on the S-N curve.

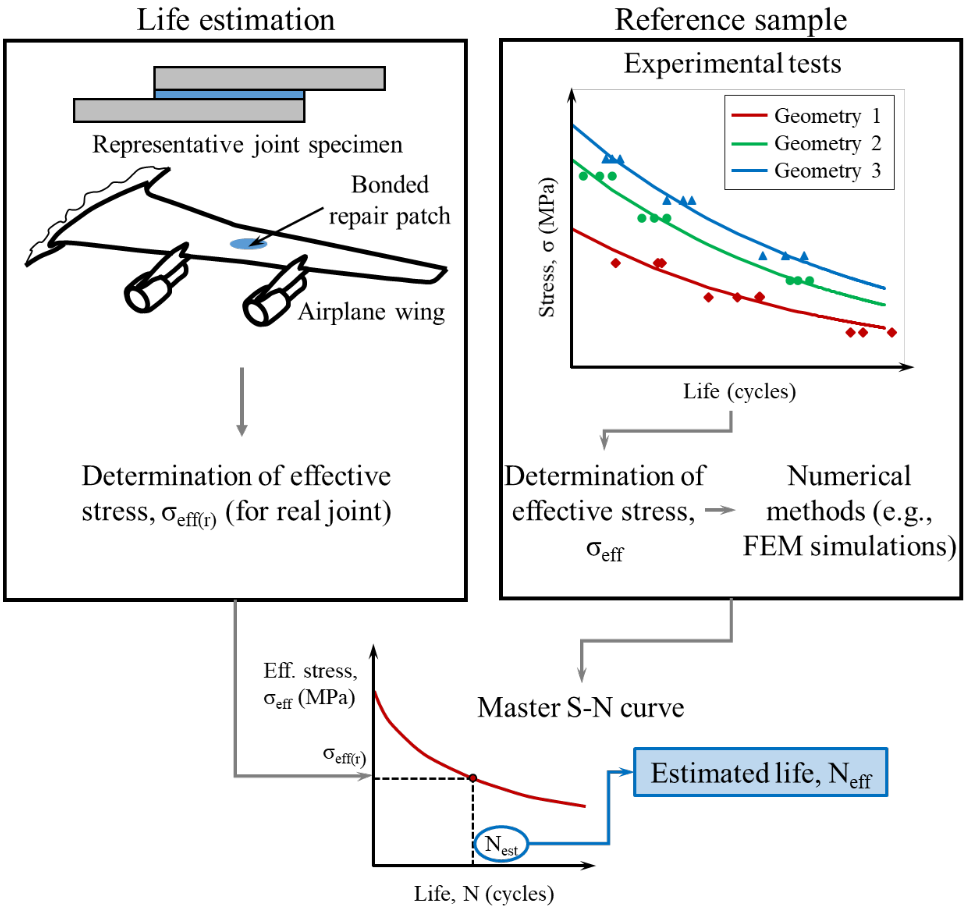


Figure 28 - Schematic view of the S-N procedure for fatigue life estimation of bonded joints.

Fortunately, impact is not so frequent in aeronautical structures, but when it occurs it can seriously put at risk the integrity of the structure. Damage can be very clear visually, but it might be disguised and present internally at the bondline, between lamina, or within each

ply. The non-destructive evaluation and structural health monitoring should take that into account. Presentation 11 - Shock resistant bonding of steel and composite deals with this issue in marine structures. The question is to know if these results can be easily extrapolated to aeronautical cases.

There is still another aspect to consider which is the effect of water at the surface prior to bonding (Figure 29). In general, the documented studies about the effect of water assume that the production is done under pristine conditions. However, in practice in the workshop this might not be the case. Presentation 2 - Lap shear fatigue life effects from moisture conditioning during and after specimen production deals precisely with this issue. This is very important and very little documented in the literature. Fortunately, the work shows that of a chemical treatment is followed for aluminium, the effect of water prior to bonding is not so detrimental. It is important to protect the bondline from moisture and test the process in the installation environment.

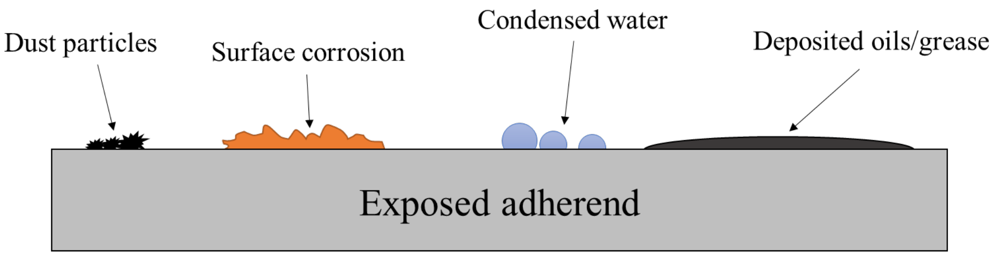


Figure 29 – Typical contamination sources of exposed adherends before bonding

Non-destructive evaluation (NDE) and **structural health monitoring (SHM)** is the last step of the certification and one of the trickiest. As shown in Figure 5, defects are varied and abundant in bondlines, as explained in Presentation 10 - Structural Health Monitoring and Non-Destructive Evaluation. However, 'while SHM systems are capable of assessing the location of damage, it is the NDE techniques that aim to identify the size of the damage'. Ultrasound is the most common NDE and can detect most defects. Other common techniques include tap test, radiography and thermal infrared method. The only defect that is still not possible to detect is weak adhesion. This is the holy grail of NDE and SHM. Acoustic emission can to some extent, but the joint needs to be loaded close to failure for a proper detection [27]. However, progress has been made and of the most promising method is Laser Bond Inspection (LBI) introduced in Presentation 9 - Perspectives on Non-Destructive evaluation of bonded joints. The laser induces tension at the interface that will cause a debond if there is weak adhesion (Figure 30). This can be a truly disruptive technique as it is the only one currently that is capable of detecting weak adhesion and relate it to the strength of the bond or delamination. The risk associated to this technique is that if too much energy is used in the laser, sound joints might be actually destroyed. However, it can be a game changer if it can solve this issue and others related to the system dimension, durability and calibration.

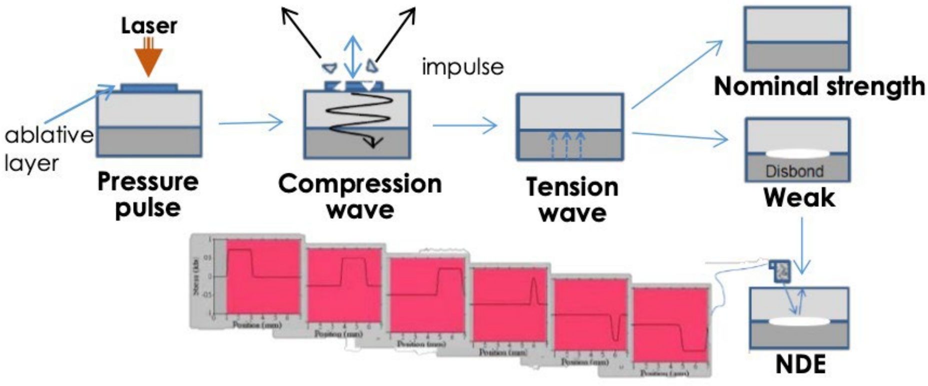


Figure 30 - Laser Bond Inspection (LBI) concept (from Presentation 9 - Perspectives on Non-Destructive evaluation of bonded joints).

Several techniques are available for SHM such as those that rely on the vibration response of the structure to piezoelectric actuator as shown in Figure 31 (e.g. Lamb waves or EMIS) or on fibre strain sensors (e.g. fibre Bragg gratings or optical backscatter reflectometry fibre used in Presentation 16 - Composite patch debonding monitoring based on surrogate modelling and particle filter). Similar to the Lamb waves method, EMIS also employs piezoelectric sensors which can act both as an actuator and as a signal receiver (sensor). However, in contrast with the Lamb wave technique, where a set of waves is generated only for a given excitation frequency, EMIS excites the joint in a much wider range of frequencies. Lamb waves are used in Presentation 10 - Structural Health Monitoring and Non-Destructive Evaluation in a single lap joint with aluminium and composite substrates. Encouraging results are obtained but the authors recognise that there are still many issues to solve, especially signal noise which gets worse when composite materials are used. Indeed, the results generated by the piezoelectric sensor are very difficult to interpret. To tackle this issue complex signal processing tools and algorithms can be used as shown in Presentation 3 - Designing and validating high performance bonded joints for structural applications. Data- driven algorithms (i.e., rely mainly on experimental data) and model-driven approaches (i.e., rely mainly on simulation data) with focus on deep learning are being developed (Figure 32) [28]. Weak adhesion is one of the defects that this machine learning exercise might detect.

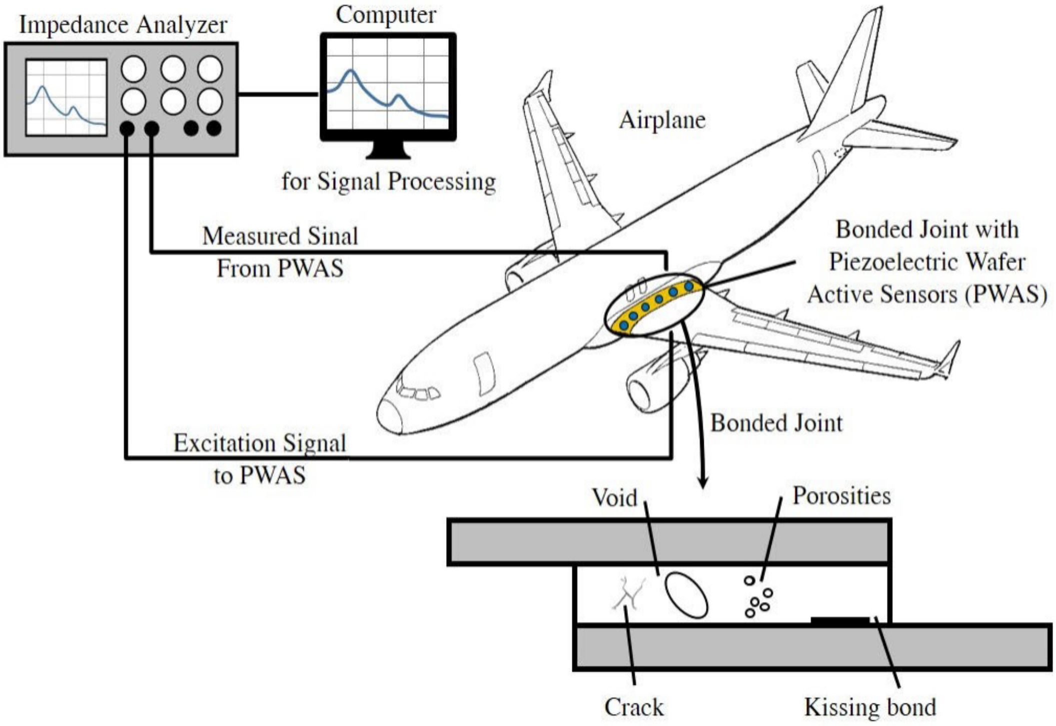


Figure 31 - Schematic representation of the electromechanical impedance spectroscopy method and its operation principle.

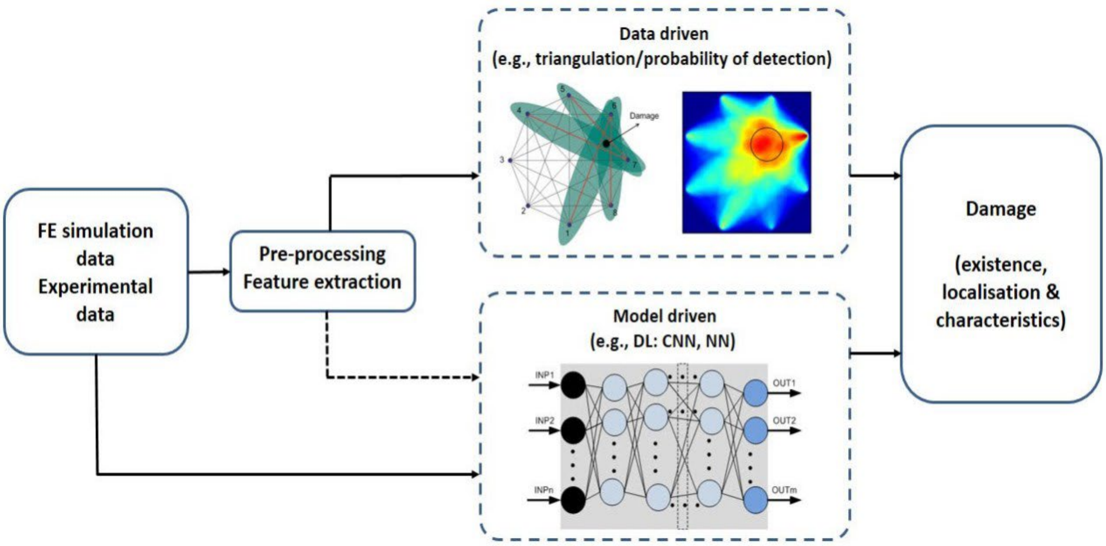


Figure 32 - Data- driven algorithms and model-driven approaches with focus on deep learning.

The final step is to integrate all of the above and define a clear roadmap for certification. This is very clearly shown in Presentation 12 - Bonded repairs to critical damage in primary composite – A proposed roadmap to certification. Many aspects treated in other presentations are introduced here. This is an excellent guideline for certification standards. A three-step roadmap is proposed:

1. Repair design that ensures damage tolerance and/or fail-safe capability;

2. Validation of the repair processes based on high level quality control of pre-bond processing and patch implementation; and

3. Proven and reliable technology for non-destructive detection of in-service unanticipated bond degradation.

The steps are well defined but there are still many gaps to fill in relation to design procedures, realistic proof testing and reliable methods for non-destructive detection and structural health monitoring. One of the authors of this presentation published a paper on this subject [29]. It is shown that proof testing of bonded repair coupons is a promising approach for validating bond strength and structural health monitoring of repairs based on a strain-transfer approach is a good possibility.

A general overview of the F-35 structural design, development and verification is first given in Presentation 1 – Joint Strike Fighter (JSF) structural repair development. Methods of repair for different situations are given in solid laminate structures, core-stiffened structures, solid laminate structures (Figure 33) and core-stiffened structures. This is a kind of recipe for each situation that can facilitate greatly the certification. But the F35 aircraft structure does not get damaged a lot and does not get repaired a lot. Bonded structural repairs are used only on core-stiffened sandwich structure. For solid composite parts other methods of repair are preferred such as bolted repairs. The limit load is not a problem. A 3d printed repair with the exact shape of cavity and smartly designed to take better the stresses is something to consider.

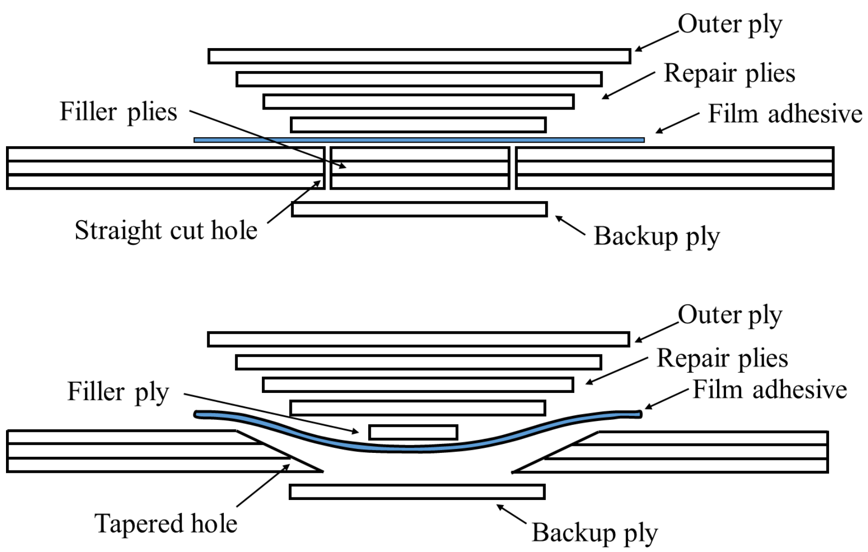


Figure 33 - Repair process of a laminate panel.

A case study is given in Presentation 13 - Validation and certification of bonded repair on F- 18 wing root step lap joint. The joint is between titanium and CFRP. The repair procedure followed was certified with static and fatigue tests. It was shown that the repair can restore the strength of the bondline. However, the root cause for the weak bondline is not known. This closes nicely the loop of the workshop on 'Certification of Bonded Repair on Composite Aircraft Structures' with a real perspective of what is involved in a certification procedure.

Figure 34 – Bonded repair certification on F-18 wing root (taken from Presentation 13 - Validation and certification of bonded repair on F-18 wing root step lap joint).

CONCLUSIONS AND RECOMMENDATIONS

Nearly 20 works were presented at this AVT-361 Research Workshop on "Certification of Bonded Repair on Composite Aircraft Structures". Certification is a very serious matter in the aeronautical industry, and nothing should be left unsecure. The main steps involved in the process according to Presentation 12 - Bonded repairs to critical damage in primary composite – A proposed roadmap to certification:

1. Repair design that ensures damage tolerance and/or fail-safe capability;

2. Validation of the repair processes based on high level quality control of pre-bond processing and patch implementation; and

3. Proven and reliable technology for non-destructive detection of in-service unanticipated bond degradation.

The presentations focussed on different aspects of these three steps using the most up to date tools available or even in some cases techniques that are not yet well documented in the literature. The major findings can be summarised as follows:

- For designing in terms of strength and fail safe, advanced numerical tools are used such as cohesive zone modelling and extended finite element method.

- Methods to arrest or retard crack growth include surface toughening of the composite, crack arrest features and ply orientation. This is essential to deal with weak bonds.

- For a complete understanding of the repair behaviour, all the steps involved in the production, i.e. adhesive application, adhesive hardening and adhesive/adherend interaction, should also be taken into account. Multiphysics and multiscale approaches are being considered and applied.

- The validation of the repair should be ensured with very careful quality control and ultimately by proof testing. Proof testing should also consider the ageing process. Dummy proof tests are sought to reduce the cost.

- Ageing is a major issue and data concerning fatigue, water ingress, impact and temperature effect should be generated as much as possible. The design stage should also consider these aspects.

- Structural health monitoring should be implemented and complemented with non- destructive techniques. Promising techniques such as Lamb waves and laser inspection were presented. Machine learning can be used to treat the complex data generated by these devices.

The works presented are very impressive in terms of innovation and the first recommendation would be to prepare full length papers and publish the findings in a special issue of the journal related to adhesion and/or composites or a NATO journal.

Even though the level is very high, there are some aspects that are currently being studied and published in the literature that could be applied to the certification of repairs:

- For the design stage, the ageing prediction could be done in a more integrated way using a cohesive zone model that would incorporate all the degradation processes such as fatigue, water, temperature and strain rate.

- The manufacturing process is currently being modelled in the automotive industry with great success. This should also be done and would give much more confidence to the strength and ageing predictions.

- Fatigue ageing is probably the main degradation process. The cohesive zone modelling approach might be too complex to implement. An alternative is a SN approach that also combines the effect of temperature and water.

- The temperature variations in the aeronautical sector are very severe. The presentations do not treat in detail this aspect. This is particularly relevant at low temperatures (-55ºC) where the adhesive is extremely brittle. Thermal cycling is also known to accelerate ageing and degradation.

- There is also no discussion about the best adhesive and surface treatment to use. This might be because these aspects are already sorted but they will certainly have a big impact in the final result.

- Additive manufacturing is being used intensively in many industrial sectors. This technology could also be used in the design and application of repairs. Recent advances in fibre reinforced plastics should be explored and experimented.

- Another hot topic that has been studied intensively in adhesive joints and that could be applied to repairs is the concept of functionally graded materials.

Machine learning is also a big thin now. The physical phenomena tend to be disguised and omitted but it is very useful when the data is just too complex to interpret. One aspect that is particularly difficult to analyse is the data signal generated in vibratory systems such as Lamb waves. It is worth investing in the data treatment of these signals as weak adhesion might be possible to detect with the right algorithm.

Finally, I recommend that a consortium of partners of this workshop be formed and funded by any measn to work on what is missing for a sound certification of bonded repairs.

REFERENCES

[1] da Silva, L. F. M., Öchsner, A., and Adams, R. D., Eds., Handbook of adhesion technology, 2nd Edition. Berlin: Springer Science & Business Media, 2018.

[2] Marques, E. A. S., Akhavan-Safar, A., Tenreiro, A. F. G., da Silva, L. F. M., and Carbas,

R. J. C., Structural Adhesive Bonding in Aerospace Applications, (Engebook, Porto, 2022).

[3] Camanho, P. P., Davila, C. G., and De Moura, M., Journal of Composite Materials, 37, 1415-1438 (2003)

[4] Li, S., Thouless, M., Waas, A., Schroeder, J., and Zavattieri, P., Engineering Fracture Mechanics, 73, 64-78 (2006)

[5] Campilho, R., Banea, M., Chaves, F., and da Silva, L. F. M., Computational Materials Science, 50, 1543-1549 (2011)

[6] Burka, P., Liu, X., Thompson, M. C., and Sheridan, J., Composites Part B: Engineering,

50, 247-252 (2013)

[7] Teixeira, F. G. and da Silva, L. F. M., The Journal of Adhesion, 87, 671-687 (2011)

[8] Zhao, Y.-P., Wang, F.-C., and Chi, M., Handbook of Adhesion Technology, 2nd Edition,

2018).

[9] Durão, L. M. P., Tavares, J. M. R., De Albuquerque, V. H. C., and Gonçalves, D. J., Composite Structures, 96, 576-583 (2013)

[10] da Silva, L. F. M., Pirondi, A., and Öchsner, A., Hybrid adhesive joints, (Springer Science

& Business Media, 2011).

[11] Shang, X., Marques, E. A. S., Machado, J. J. M., Carbas, R. J. C., Jiang, D., and da Silva,

L. F. M., Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design Applications, 233, 521-530 (2019)

[12] Mattheij, P., Gliesche, K., and Feltin, D., Journal of Reinforced Plastics and Composites,

17, 774-786 (1998)

[13] Partridge, I., Cartie, D. D., and Bonnington, T., Advanced Polymeric Composites, (2003)

[14] Mouritz, A. P., Composites Part A: Applied Science and Manufacturing, 38, 2383-2397

(2007)

[15] Marques, J., Barbosa, A., Da Silva, C., Carbas, R. J. C., and da Silva, L. F. M., The Journal of Adhesion, 97, 172-206 (2021)

[16] Dos Reis, M., Marques, E., Carbas, R., and da Silva, L. F. M., Journal of Advanced Joining Processes, 2, 100033 (2020)

[17] Merklein, M., Schulte, R., and Papke, T., Journal of Materials Processing Technology,

291, 117032 (2021)

[18] Ganguly, A., Shankar, S., Das, A., Shukla, M., Swaroop, C., and Bhardwaj, T., Materials Today: Proceedings, (2022)

[19] da Silva, L. F. M. and Sato, C., Design of adhesive joints under humid conditions, (Springer, 2013).

[20] Borges, C., Marques, E., Carbas, R., Ueffing, C., Weißgraeber, P., and da Silva, L. F. M., Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 235, 527-549 (2021)

[21] Grangeat, R., Girard, M., Lupi, C., and Jacquemin, F., The Journal of Adhesion, 1-17 (2022)

[22] da Costa, J., Akhavan-Safar, A., Marques, E., Carbas, R., and da Silva, L. F. M., International Journal of Fatigue, 161, 106939 (2022)

[23] Borges, C. S. P., Nunes, P. D. P., Akhavan-Safar, A., Marques, E. A. S., Carbas, R. J. C., Alfonso, L., et al., Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, (2020)

[24] Neto, R. C., Akhavan-Safar, A., Sampaio, E., Assis, J., and da Silva, L. F. M., Theoretical and Applied Fracture Mechanics, 119, 103336 (2022)

[25] Da Costa, J. A., Akhavan-Safar, A., Marques, E. A. S., Carbas, R. J. C., and da Silva, L. F. M., Journal of Applied Polymer Science, 139, 51991 (2022)

[26] Castro Sousa, F., Akhavan-Safar, A., Rakesh, G., and da Silva, L. F. M., The Journal of Adhesion, 98, 1-23 (2022)

[27] Chen, Z., Adams, R., and da Silva, L. F. M., Engineering Fracture Mechanics, 78, 990- 1007 (2011)

[28] Tenreiro, A. F. G., Lopes, A. M., da Silva, L. F.M., and Amorim, J. D., Mechanics of Advanced Materials and Structures, 1-16 (2022)

[29] Baker, A., Gunnion, A. J., and Wang, J., The Journal of Adhesion, 91, 4-38 (2015)

APPENDIX – EVALUATION OF EACH PRESENTATION WITH COMMENTS, QUESTIONS AND ANSWERS

Keynote speech (related to Damage tolerance/Crack arresting)

Presentation 1 – Joint Strike Fighter (JSF) structural repair development

Carl Rousseau (Lockheed Martin Aeronautics, USA)

Comments:

A general overview of the F-35 structural design, development and verification is first given. The typical pyramidal building block is presented with the material and coupon level at the base. Materials optimised for weight, cost and performance. Aluminium, composites and titanium are used. Finite element models of the whole structure are given from raw to high fidelity models. The development of the design is a worldwide enterprise with the participation of countries from Europe and Australia. Several static testes are given on the whole aircraft. Durability tests are also presented from 2010 to 2019. Post durability tests were carried out.

The aircraft structure does not get damaged a lot and does not get repaired a lot. The composite damage types are scratch, dent, edge damage, hole damage, delamination, and penetration. Bonded structural repairs use only on core-stiffened sandwich structure. For solid composite parts other methods of repair are preferred such as bolted repairs. The limit load is not a problem. Methods of repair for different situations are given: solid laminate structure, core-stiffened structure, solid laminate structure and core-stiffened structure.

Questions:

How detailed is the modelling of a repair in the whole structure of the aircraft? What kind of defects are found in the F-35 inspections?

Why not use 3d printing to generate the repair?

Discussion after the presentation:

#Q1: What is considered a thick composite?

#A1: 1 and1/4 inch which is a solid laminate for skins and fuselage.

#Q2: Are there any load enhancement factors?

#A2: Mainly with metals. There is no need for composites.

#Q3: Why 3 lifetimes are required?

#A3: This is a customer request for UK. For USAF and US navy, only 2 lifetimes are required.

#Q4: Is there barely visible impact damage in thick composites?

#A4: Damage tolerance is not important. 1.85 limit load (not ultimate) is applied. There is no velocity requirements for F16. Air force has quite relaxed requirements. Durability is only required for honeycomb composites. Skins are all right.

#Q5: Do the technicians that do the repairs need to be certified?

#A5: Air force has courses for maintenance personnel. But the personnel is cycled quickly. The training id done internally. There are only standard trainings for civil aviation.

#Q6: The repair is dedicated to bonding or composites?

#A6: More for composites. But there should also be for bonding.

#Q7: Why don't you use bonded/scarf repairs?

#A7: It is faster to use bolted repairs. The use of limit loads allows for a large repair. Thin repairs are used.

#Q8: Comment on the requirement of battle damage.

#A8: Only a few parts need.

#Q9: Is the repair of honeycomb durability limited? Should it be demonstrated?

#A9: There is no need of full-scale tests with impact. The probability is low.

#Q10: How do you ensure you are not passing the stress to other areas in case of damage such as delamination?

#A10: A stress analysis is carried out to make sure this does not happen. Metals are problematic with cracks. No repair is adhesively bonded. Rivets and bolts are used. Composites are no issue.

#Q11: How do you repair bismaleimide (BMI) composites that need to withstand 250ºF?

#A11: Bolted titanium is used. There is no good bonding repair for BMI.

Ageing (3 presentations)

Presentation 2 - Lap shear fatigue life effects from moisture conditioning during and after specimen production

Daniel C. Hart (Naval Surface Warfare Center Carderock Division, USA)

Comments:

This study is about the effect of temperature and moisture during fabrication and in-service on the fatigue behaviour of single lap joints with different surface treatments and a rubber toughened epoxy (Pro-Set M1002-M2046). Lap shear specimens with 5456 aluminium alloy are tested after the surface is left for at least 60 minutes exposed to the environment. A phosphoric acid treatment is applied and compared to the case where there is no treatment (solvent only). It is shown that an elaborate surface treatment such as etching have a big impact when moisture is present during fabrication and will reduce the effect of the initial exposure to the environment. It would be good to have a quantification of the level of moisture on the specimens prior to bonding.

Questions:

Low and high modulus bonded repairs are relative to the adhesive used or the substrates? Why use such a thick substrate of 6.35 mm?

What do you expect in the case of aeronautical aluminium alloys such as 2000 and 7000 series?

How much water ingressed in the joint? Was it quantified? Was the joint saturated?

Discussion after the presentation:

#Q1: Why do you use both phosphoric and AC-130 treatment?

#A1: To establish if AC-130 alone is sufficient.

#Q2: Why don't you follow the order clean, sandblast and primer?

#A2: Sandblasting is not easily available. High pressure water is an alternative. For epoxy we can use an abrasive disc followed by AC-130.

#Q3: Is AC-130 a corrosion inhibiter?

#A3: No, it requires a primer. For durability, primer is essential.

#Q4: Do you have problems of durability with salt fog?

#A4: No problem with patch durability using a polysulfide seal around the patch.

#Q5: What about the use of other tests than the single lap joint used such as peel or wedge tests?

#A5: Yes, these tests would be more informative for assessing the quality of the surface treatment.

#Q6: Is there an effect related to repair seizing?

#A6: For low stress areas, a low modulus patch is used to avoid crack growth.

#Q7: But high stiffness patches should work better to protect against damage.

#A7: It is enough to use low modulus composites in the patch. The stress concentrations are low and the repair is durable for a few years.

#Q8: What is the adhesive thickness?

#A8: from 0.3 to 0.5 mm. but it can up to 1 mm.

#Q9: What about training and care?

#A9: It is very challenging to follow the procedure. The manufacturer recommends 3 mm but often only

0.5 mm are obtained in practice.

#Q10: Is etching and rising possible on flat surfaces?

#A10: It is possible to tilt the ship and wipe the rest.

#Q11: Did you get wet conditioning failure?

#A11: Yes, the plastic edges failed and moisture penetrated to the aluminum.

#Q12: Do you have any issue concerning the edge protection?

#A12: No issue. And the polysulfide layer can be repaired if needed.

Presentation 3 - Designing and validating high performance bonded joints for structural applications

Eduardo Marques (Institute of Science and Innovation in Mechanical and Industrial Engineering (INEGI), Portugal)

Comments:

This presentation is a global overview of the advanced joining processes group of INEGI. It covers a wide range of topics but recently the focus is on durability and non-destructive techniques. Moisture and fatigue effects are treated either with crack growth concepts or a simpler SN approach. It is shown that water diffusion in the adhesion is not constant over successive wet and dry exposures. The problem of the interface is also discussed and it is demonstrated that it is particular important for metals, contrarily to composites. High frequency vibratory health monitoring (Lamb waves and EMIS) combined with machine learning are used to detect conventional defects and possibly weak adhesion. Innovative techniques for damage tolerance of composite joints are also presented such as surface toughening and graded joints. It would be nice to have more aerospace and aeronautical partners to transfer the knowledge for this industrial sector.

Questions:

How the graded joints could be applied in repairs?

How can the non-destructive techniques be applied in large aeronautical structures?

Discussion after the presentation:

#Q1: How can you apply the SN master curve data to complex specimens other than single lap joints?

#A1: This has already been applied to complex real joints in the tractor industry.

#Q2: How do you apply tailored bondlines?

#A2: Film adhesives can be used. Or a physical barrier when paste adhesives are used such as rubber or nylon. A multiple nozzle can also be used to apply multiple adhesive beads ate the same time with the right amount and space.

#Q3: The SN data shows that moisture has not a big effect on mode II. Why bother about mode I and design to avoid mode I?

#A3: there are always situations where mode I might be present.

#Q4: Do you test Arcan with composite substrates

#A4: No, only metal. But composites can be used without any problem.

#Q5: You can't measure crack length in Arcan specimens.

#A5: That's right. The stiffness degradation us used to monitor damage. For crack propagation, another specimen is used such as the double cantilever beam test.

#Q6: The impact of the gradation in the joint depends on the overlap.

#A6: Yes. Graded joints make sense only for 15-20% of the overlap.

#Q7: The cohesive zone model degradation is very intuitive but difficult to a physical meaning.

#A7: That's right. But a practical approach is followed where the experimental tests are used to measure the degree of damage in the strength and fracture energy of the cohesive law.

#Q8: The training use in the structural health monitoring technique used is very dependent on the geometry and material used.

#A8: that's right. A training might be needed for each situation.

#Q9: What is the excitation used in the Lamb waves, echo or pulsed?

#A9: Na actuator is used a tone end of a single lap joint, and a sensor is applied is used at the other end.

#Q10: Can you determine the bondline thickness with Lamb waves or EMIS?

#A10: This has not been tried yet.

#Q11: How can you monitor the degradation of a weak bond?

#A11: Detecting a weak bond is already a challenge let alone how it damages with time.

Presentation 4 - Ageing of adhesive bonded repairs and methods to monitor the bondline degradation

Peter Nijhuis (NLR-Structural Technology department, Netherlands)

Comments:

This work proposes a clever dummy joint close to a repair to assess the quality of the repair in service. Ageing is considered in terms of humidity, fatigue and thermal cycles. This would be an alternative to a non-destructive testing of the repair. The problem is that the dummy joints might not properly represent the situation of the repair and the dispersion obtained is considerable. However, the results show that it is possible to have a good idea about the quality of the repair but not up to failure. Also, an adapter is required to load the dummy joint which needs to be removed when the structure to repair is in service. Parallel tests on the actual repair, scarfed, bonded repair coupons, lap joints and wedge tests are also carried out.

Questions:

Is the stress state in the Bonded Repair Coupon (BRC) the same as in the repair?

The moisture ingress and temperature cycling will be different in the BRC from the repair. The two cases might not directly comparable, and you might have a wrong information from the BRC.

Discussion after the presentation:

#Q1: The failure mode is more important than the load level. But you have damage in the substrate.

#A1: The pair of material needs to be changed. The scatter observed is from the material. There are stress concentrations in the weave.

#Q2: This is a good pass or fail test. But it is difficult to detect adhesive or cohesive failure.

#A2: Perfectly correct.

#Q3: Do you have lightening protection?

#A3: Needs to be verified.

#Q4: The surface state should be the same in the dummy specimen as in the repair. That means that a non-damaged area should be surface prepared which is a king of forced degradation. This is difficult to accept for an aircraft maker.

#A4: Totally agree.

#Q5: Did you apply fatigue in the dummy specimens?

#A5: Yes, all specimens were tested with and without fatigue.

#Q6: The wedge test was developed for metals. It is quite strange to see it apply to composites.

#A6: This test is indeed controversial and might not be needed.

#Q7: Did you carry out a full test on an equivalent circular repair to the dummy specimen?

#A7: Some tests were made but just for static strength.

#Q8: Where is the failure location in the scarf joints? In the scarf in the overply?

#A8: It varies. In some cases, in the scarf and in others it failed everywhere.

#Q9: Did you analyse the percentages of failure mode?

#A9: This will be analysed.

Damage tolerance/Crack arresting (4 presentations)

Presentation 5 - Towards the analysis of damage tolerance of bonded repairs

Jarno Jokinen (Materials Science and Environmental Engineering, Tampere University, Finland)

Comments:

A design methodology based on damage mechanics and failure monitorization with digital image correlation is presented. It includes composite material and the delamination phenomenon. Virtual Crack-Closure Technique (VCCT) is considered but it has the limitation of requiring the existence of an pre-crack. Cohesive zone modelling is used to design a double strap joint. The authors stress that reliable data are necessary to define the cohesive law, in particular the mixed mode failure envelope. This is still fundamental knowledge and practical aeronautical cases should be considered. Also, dynamic loads (fatigue and impact) should be studied.

Questions:

How do you determine the critical strain energy release rate?

How can the knowledge of this fundamental work based on small coupons can be transferred to large structures with repairs?

Discussion after the presentation:

#Q1: Simulation of bonded joint under mode I conditions is shown. But mixed failure mode is often present. How does the VCCT approach work with mixed failure modes? Can VCCT approach be captured?

#A1: This model only analyses what the user wants. It requires a predefined path. In some cases, CZM is needed to predict the crack path more accurately. The behaviour can be simulated, but it depends on the properties. VCCT only plays with the fracture properties. If this is defined accurately, the total behaviour of the system can be simulated unless there is a large change of properties in the material.

If you know what you are doing you can use the same technique for everything, but you need to have test results data to back-calculate. Using the lowest values of fracture toughness at the interface, laminate or bondline should be enough for the real application. Mostly, what is sought is the onset of crack propagation, not the propagation. The risk of cracking is not so critical in mode II but it is in mode I.

#Q2: How was the fracture energy measured in mode II?

#A2: For mode II, ENF was used. It is really complicated to test.

#Q3: The fracture envelope as a function of the loading mode is below the linear evolution. But it is known that it can be above the linear evolution in other cases.

#A3: In many works it is above the linear case above for mixed mode. But in this case, it was below.

#Q4: In the way the patch is simulated, a fillet is present at the end. Where was the CZM located in the fillet? Was XFEM considered?

#A4: Yes, it makes sense to use XFEM. Now VCCT is being used at the release film location and CZM is for the first ply (delamination). The rest of the adhesive is a continuum model.

#Q5: What about the surface of the substrate?

#A5: It was a challenge using the release film since it was not tight enough and it had some curvature. But this did not affect the bonded area. Failure started as a cohesive failure and then delamination occurred. The fracture surface includes a release film and we need to know the criticality of this defect. We want to know the load limit for criticality. Once we know what's happening, we can build the model.

#Q6: Crack starts in the fillet and then goes into the composite. The predictions are close to the experimental loads?

#A6: Yes, we are getting quite a good response. VCCT defines well the damage onset point.

#Q7: Is DIC used during all of the fatigue test?

#A7: Yes, it is very complex, but we did use it. However, it is difficult to see anything for mode II.

Presentation 6 - Robust bonded joints with surface toughening design feature

Martin Schollerer (German Aerospace Center – Institute of Composite Structures and Adaptive Systems, Germany)

Comments:

Hybrid bondlines are first presented where a pre-bond patch is located in the middle of the bondline to stop the crack. But it does not solve the problem of delamination in the composite. An innovative method is presented where in the single lap joint the composite surface is toughened to avoid delamination. Several options are available for the material to use to surface toughen the substrate. Currently, a film of polyvinyl diene fluoride is used (PVDF). The method is compared with other methods to reinforce the joint strength and it is clear that it has a huge potential and could be applied in repairs without the need to apply a scarf. This surface toughening technique is in line with other works in the literature that use other materials to reinforce the surface of the composite. The method should be also verified under other loading modes and make sure it is durable.

Questions:

What is the impact of the surface toughening in the manufacture of the composite? What kind of material is recommended for surface toughening?

Instead of surface toughening, why not use a flexible adhesive at the ends of the overlap? What do you expect for fatigue loading?

Discussion after the presentation:

#Q1: What is your fatigue testing frequency? Is there any temperature issue?

#A1: 8Hz, but heat only starts at 10 Hz. We tried with DIC and it determined the crack initiation location well but not it is not very precise for propagation. The adhesive cures at 180°C so it is safe with regards to temperature.

#Q2: When you change the localized surface toughness at the surface, does it affect the life of the adherend? What happens around the toughened area? Do you transfer the problem elsewhere?

#A2: We did not test specifically but from testing data, we see that in front of the toughened material there is a small area where the crack growth accelerates.

#Q3: What are the criteria for success of this project before implementation in practice is possible?

#A3: At this stage we did not define it.

#Q4: The available thermoplastic materials are limited for aerospace certification and compatibility between the thermoset and thermoplastic is an issue.

#A4: We tried a lot of materials, depending on stiffness. Aircraft manufacturers say that water ingress and chemical stability are the main requirements, but at this stage we are just concerned with the effect and the design and size of the solution. We are not concerned with certification at this stage.

#Q5: The term ‘crack stopper’, is highly specific for a certification procedure (your solution does not stop cracks, it slows growth). So, we are talking about rivets, fasteners, proven solutions. But in this case, we have variability of the process (surface treatment, design etc), which is still not solid for certification.

#A5: Agreed. In principle we can go for arrested growth-based designs as long as we show that the time for a slow growth is large enough. We have the message that if we can prove that we do not go into critical condition we might be all right. This needs to be discussed case by case, but the door is not closed for a slow growth certification and it’s not a completely new process (similar to what is done for metal). In fact, we compared this with the standard crack stopper in the project.

#Q6: What about global weak bond design?

#A6: It is a material qualification issue. A local weak bond might happen, but if you have a large bondline you can have a maximum disbond limit in the design. Still, you need to ensure that the process is all right and properly certified, even if a disbond limit is allowed for. This in principle can be taken as an assumption, but when we have this case, often there are issues with the production such as wrong and unqualified materials and processes.

#Q7: I have never seen this samples with local weak bonds.

#A7: There are mostly local processes escapes. You first have to make it step by step more critical (no fasteners) until we reach a bondline that is fully loaded and that it would fail but have a second line of defense. Nowadays we have too many “chicken fasteners” and we can’t see the issues.

#Q8: We could use this technique to size the bondline to have a sacrificial area outside the bonded area. Regular NDI on the joint in the sacrificial area (safe zone) where we can find the crack.

#A8: I agree with the proposed technique.

#Q9: Why do you put the ductile material in the middle of the overlap since the edges are the critical area?

#A9: We want to allow the crack to start and then stop it, so we place it in the middle. If you put the ductile material at the edges, the crack will not progress. But the project aim was to have a stable crack initiation and then progress with a typical crack speed. Then we want to influence the crack and eventually stop it. Furthermore, there is a mixed mode condition in the CLS specimen, it is more challenging and realistic.

#Q10: The fracture energy G_{IC} increases and then reduces during the double cantilever beam test (DCB). So why did you not apply it for all of the surface?

#A10: If you do it for the whole surface, we only push the material through the thickness of the material. Crack travels always through the adhesive, with no delamination, but with visible plasticity on the thermoplastic material.

#Q11: The fatigue test is in displacement control. Why not load control?

#A11: We had a certain strain level, but the load was in fact controlled. We always use load control.

#Q12: Crack growth must also consider residual stresses, linear elastic, crack formation and plastic deformation. It is difficult and computationally expensive.

#A12: To model all this is quite challenging. It is being worked on by a PhD. The characteristics of the thermoplastic are crucial for this simulation.

Presentation 7 - Evaluation of crack growth as certification enabler for bonded repair applications

Thomas Kruse-Strack (Airbus Operations, Germany)

Comments:

This work is focused on composite aeronautical structures concerning crack arresting and damage tolerance under fatigue. That’s because Airbus recognises that when weak bonds are present that is the unique alternative. Full testing and non-destructive testing are not possible. Designing with composite materials is a bigger challenge than with metals because of the sudden failure presented by composites. Therefore, the idea is to develop an approach to retard or arrest crack growth. In case of slow growth, a proper structural health monitoring is needed. A very comprehensive slide is given about all the parameters involved in the full bonding process technology that comprise design, material properties, bonding production (e.g. surface preparation), repair and health monitoring. Each of these subjects has been treated in several European projects (BOPACS, JOINDT, FACTOR). The JOINDT project is about the certification of repairs to address acc. AC20-107B. It follows the pyramidal approach typical of aeronautical design with coupon level, element level, structural level and application. What is treated is the element level with the single lap joint containing weak adhesion and disbond arrest features consisting of pins and surface toughening (treated in Presentation 3 - Designing and validating high performance bonded joints for structural applications and Presentation 6 - Robust bonded joints with surface toughening design feature). In addition to fatigue, impact damage is also included. The results are compared with a case where there are no arrest features and the improvement is considerable. Surface toughening is also shown to retard fatigue crack growth. The experimental campaign is also complemented with a finite element simulation. The idea is develop a design tool to reduce the amount of tests. Now the project is at the stage of transfer to the industrial design.

Questions:

How is the application of the crack arrester done?

Is the application of the crack arrest features practical in industrial applications? The crack arrest feature introduces a hole in the composite. Is that reliable?

Can you detect the weak bond beforehand? Which health monitoring systems are considered?

Discussion after the presentation:

#Q1: For the fatigue testing, how many coupons are fatigue tested usually?

#A1: The curves shown are for a single coupon. Right now, we have about 15-20 coupons tested, but this is a huge effort and very expensive.

#Q2: You are saying that if you can relate the detection of a weak bond to the strength of the material this is a breakthrough. But what about laser testing detection?

#A2: Yes but you can destroy a weak bond using this case, so it is not exactly what we want (we want a number for the joint strength).

#Q3: How to make the weak bond?

#A3: We just use a thin foil, but we admit that it is not a truly weak bond. We want to have the extreme cases, full damage or full strength and everything in between.

#Q4: You want to study the location of crack stoper, but you do not know where the weak bond is.

#A4: We want to know what the maximum pitch is used in a bolted connection to secure a weak bond, assuming that the crack will be near one of the fasteners and then travel towards the other. Furthermore, we are targeting additional crack arresting features such as a toughened material or a scarf shape. Detectability through NDI is again the issue, we want to show how large the damage can be and that it would be difficult to miss such significant damage at this stage. Generally, we don't know where damage is occurring, but we design to account for any damage location.

#Q5: Limit load capability without a patch or with a failed patch is maintained but there is a limited amount of time because we are violating rules for limit amount of load for 3 seconds. How large a repair you can make is a function of the capability to observe the damage.

#A5: If we lose a repair patch it should be found quickly, because we have issues such as rapid decompression. Overall, the idea is to decouple the static strength from fatigue behaviour. We are following some rules, but we do not exactly know the durability. So, we need to do some finite element analysis (FEA) and testing to check if the predicted life is ahead of the aircraft life, but this is still being discussed at this stage. In fact, repair is almost never done with FEA support, everything is calculated by hand in the repair process. FEA is only possible for large repairs where we have time available.

#Q6: How about shear load and position of fasteners for shear load? Torsional loads?

#A6: It is in the to-do list. We have other ideas, and this might work differently. We have to test it out in a bi-axial machine, and it is not straightforward. We don't know ratios of modes and load vectors. All simple joint geometries are easy and affordable to test. But mixed-mode and complex testing is hugely expensive and could be solved by working in parallel with different entities/manufacturers working together.

Presentation 8 - Evaluation of crack growth in scarfed bonded joints

Thomas Koerwien (Airbus Defence and Space, Germany)

Comments:

Design features in scarf laminated joints are presented to understand how to prevent crack growth and maintain limit load capability of the structure. This was obtained in the FACTOR European project. Modified Crack Lap Shear (MCLS) specimen is used where an inclined layer staking is used to make crack propagation more difficult is used, and it clearly shows different crack speeds as the different laminates with different staking orientations are cracking. A thorough scanning electron microscopy analysis is carried out to understand clearly the mechanisms of failure.

Questions:

Is the MCLS specimen a good representation of the real repairs?

What do you propose in light of these results to prevent or slow crack propagation? Is the inclined staking difficult to produce? Can it be easily implemented?

Discussion after the presentation:

#Q1: What input properties are needed for these models to assess adhesive failure vs cohesive failure? You have some influence of the surface preparation and the difference in crack propagation speed for different ply orientations. To simulate we need to introduce different fracture toughnesses. How do we populate the model?

#A1: The initial purpose was to determine process robustness. But now we can have a high- resolution model of what will happen as the crack progresses. But this is complex, and we are not there yet and we need more hard experimental data. In many cases we are getting crack directly to the laminate and not in the adhesive, which is incorrect. In the stepped scarf we are also progressing but we have a lot of uncertainties and scatter from experimental data, so it will be very difficult to model. Step-wise it is all right, but continuously it is still a problem.

#Q2: I think the point is to see where the crack growth is stable. How do you put this in a big picture regarding the crack growth rates for composites (as we do for metals, where we know our rates quite well)? Can we show that the crack progression is slow enough?

#A2: We think so because we had to provoke this. Standard specimens are not prone to crack propagation. We have seen that crack growth in scarf joints is very low.

#Q3: How to convert the bundle of experimental curves in a single one?

#A3: These cracks initiate in different locations of the laminate, from manufacturing uncertainties. These were removed from the analysis and all the curves were joined together.

#Q4: Did you measure the E-modulus of scarf joints?

#A4: No, we just want the crack variability and do not correlate this with the stiffness.

#Q5: Are you sure it was not adhesive failure?

#A5: Yes, it was not. Once we start damaging the surface and expose fibres, we are all right. But cutting fibres is very bad.

#Q6: What strain levels were used (because the crack growth was slow)?

#A6: 50% of static strength led to quick failure. We ended up at around 2500 microstrain.

#Q7: What is the zig-zag behaviour found in a previous project?

#A7: In the early days of the project, we explored different coupon shape options, and we started static test of CLS. If you have release foil you will have a radius that will hamper crack growth. The zig-zag creates a smooth transition of the crack in the interface without any overshoot and thus it was adopted for fatigue.

#Q8: Plasma is more difficult to implement in practice than sanding, for example. Why was it not considered?

#A8: We can't make sure that the path/distance/speed is constant for manual application. A robot is feasible but it is expensive/hard to get approval. A chemical treatment works well as an alternative.

NDE (2 presentations)

Presentation 9 - Perspectives on Non-Destructive evaluation of bonded joints

Eric Lindgren (US Air Force Research Laboratory, USA)

Comments:

An innovative technique called Laser Bond Inspection (LBI) is proposed here to measure weak adhesion. The common ultrasonic and thermal methods are unable to detect weak adhesion. The laser induces tension at the interface that will cause a debond if there is weak adhesion. This is a technique that can detect weak adhesion and relate it to strength. That is a remarkable result. However, there is the risk to cause further damage in the structure. In this case, this method would be destructive and not non-destructive as it is supposed to be. Other challenges include the application to a wide range of geometries, dimensions and the post non-destructive evaluation.

Questions:

Repairs are referred as bonds to be inspected. But can it be applied to primary bonds? What to do when the laser induces damage in the repair?

Does it work with any substrate?

What do you mean by the durability of the system? Can it be used to dismantle joints?

Discussion after the presentation:

#Q1: Would this technique work for thick dissimilar bonds? Metals with composites, etc?

#A1: I think so, but with limitations because of the wave propagation. The energy absorbed would be very different and would require new calculations.

#Q2: Energy is critical and for large ship parts there is primer, paint. How important is the surface state in the process to calibrate actual forces?

#A2: It depends on the thickness of the coating. Wavelengths can interact with the coatings, and elastic coatings which absorb ultrasound energy would require deeper analysis. Reflections and total thickness need more study.

#Q3: What information you need of the structure? Thickness, backing structures etc. Stacking sequences?

#A3: Thickness is critical. A lot of our work is between 1-3 mm (aerospace). Fluence vs thickness is critical or else we need to have very high laser power. Stacking sequences are not that critical. Unless you have very complex material construction this should not be an issue. Maybe near the bond, where there is the risk of opening the stacking sequence and not the adhesive.

#Q4: From a simulation perspective, your laser generates what wave type? For the disbond and delamination how do you quantify this?

#A4: Th technique sends a mechanical wave impulse in the part. We are not doing simulation just yet and there is a lot of discussion on how to do this with such a high energy level.

#Q5: You are trying to disbond a weak bond, but in some cases we are interested in full debonding/self-dismantling. Would laser be a practical solution for correcting repairs?

#A5: This would be an expensive way to do so. It should be possible (for 2 to 3 cm^2 of area) but if we know that the joint and patch would be weak, otherwise it would need large energy that would damage the material. The strength of the composite laminate might be very low compared with the undamaged adhesive. For metallic structures the dynamics would be very different especially at the composite/adhesive/metal interfaces, but this has not been studied yet.

#Q6: Laser energy will hit not the bondline but also the back face. The nature of the material, the presence of stiffeners, all can change the response. It is far away from a true proof test since it does not work for very complex structures.

#A6: The pulse goes down as a compression wave and then flips in its phase and reflects back up. This is mostly for the panel level. We have done gently curvatures and it is all right. Complex geometries is still an open issue in this regard. We don't know the acceptance criteria.

#Q7: You might have a good bond, but the energy level can damage it just by seeking the defect. How this correlate to the accept/reject criteria?

#A7: The laser power will depend on the acceptance criteria, so you dial the laser power to open the desired level of joint strength. You can open stronger joints if you wish to do so.

#Q8: If we differentiate between proof test and NDE we need to have multiple loading conditions. Is this the same here? You just do tension test at this stage.

#A8: The intent is to show bond strength, not to replace a full proof test. We call it a localized proof test. Once we open a sample, we have destructed the structure. It might not ready for civil certification but from the military perspective they are satisfied with the performance. There are different types of proof testing (component, vehicles, etc). This is equivalent to proofing a part to a single condition load case, avoiding gross flaws. It has been done with other process qualification steps. Traveller coupon level proof tests are often done.

#Q9: What's stopping from doing an interpretation of the laser return wave? It is possible to use two lasers, one for inspection and the other for data reception.

#A9: We do not do it. We do an ultrasound analysis just after the laser is fired. To directly acquire the response of the laser pulse requires a different domain of power.

#Q10: How often did you perform the same test on the same location? One of the thresholds is the out of plane strength of the laminate, can you quantify this margin before you "fall of the cliff''.

#A10: We did this several times in the same location, but the question is how often we needed to do that. If you have an acceptable bond strength you need to define what parameters need to be controlled to assume that the bond strength was degraded during the life of the system. It is like looking for cracks using other methods. We are trying to dial the acceptance of the strength of the bond.

Presentation 10 - Structural Health Monitoring and Non-Destructive Evaluation

Todd C. Mull (Clarkson University, USA)

Comments:

This work is related to the use of ultrasounds to detect defects in aluminium single lap joints, carbon fibre panels and E-glass single lap joints. Defects are simulated with glass beads and tapes. A finite element analysis is also carried out with very good results. But the model is very heavy for wave propagation simulation. For structural health monitoring, Lamb waves are being considered. A single lap joint is used with aluminium and composite substrates. Two sensors are applied at each end of the overlap. This is thorough research that is looking to use the structure vibration for detecting damage. Encouraging results are obtained but the authors recognise that there are still many issues to solve, especially the noise which gets worse when composite materials are used.

Questions:

Ultrasounds are effective with dissimilar joints composite-metal?

Can Lamb waves detect weak adhesion?

Can it be applied in a practical way to a big structure such as an airplane?

Discussion after the presentation:

#Q1: Can you give more details about the use of the ductile damage model?

#A1: Ductile damage works for metal structures but also for the adhesive in this case. We are not sure if it would work in fatigue and loading unloading scenarios. It works well for a constant type of load, both in failure load and the morphology. You just need the elastic- plastic data, but you have to apply the fracture energy to a single element and then match the stress strain behaviour at the element level to isolate the geometrical effects, with good results. Is it proper? Maybe not but it works.

#Q2: Do you have plastic deformation of substrates?

#A2: Yes, in the aluminium we do have plastic deformation.

#Q3: What kind of defects are you detecting with the Lamb waves?

#A3: We are trying to look at it from a numerical perspective. Our correlations are better with damaged specimens than with those which are not. But we are not sure of the reason and thus we do not have the results so far.

Bonding (1 presentation)

Presentation 11 - Shock resistant bonding of steel and composite

Ingrid Schipperen (TNO, Department of Structural Dynamics, Netherlands)

Comments:

The term ‘bonding’ used to describe this work is not the most appropriate. It should be in the simulation/design or ageing sessions.

This paper is about the impact strength of composite-steel joints used in marine vehicle structures. Epoxy and methacrylate adhesives were used with thick bondlines. Several specimen configurations were tested and numerically simulated, and it was concluded that the star shape is the strongest joint. Thick substrates and thick bondlines are used. The shocks were applied to the joints in a tensile mode which applies shear in the adhesive. The joint withstood quite well the shock load.

Questions:

What is the star shape joint?

What about the use of elastic adhesives instead of rigid adheives?

Can the knowledge gained in this work be transferred to aeronautical structures?

Discussion after the presentation:

#Q1: Did you consider the performance of in-plane vs out of plane test. Are there specific requirements?

#A1: We did not do it. We did coupon level test in peel and sheer. In peel it fails but there is no requirement for it since it does not match the shock we are replicating.

#Q2: Do you have a blast requirement?

#A2: Yes.

#Q3: For this last test, the crack occurs after the explosive loading and then there is no further growth. What is the consequence in a real ship? Do you repair it or leave it like that for the rest of life?

#A3: It should last as long as the fight lasts and then its immediately repaired. In theory all the systems are working but repairs are necessary. During your safe return home there might a second explosion.

#Q4: This is a fine example of engineering method using a building block approach to validate method using analytical methods on small coupons.

#A4: Yes but there is an additional point, which are strain rate effects. This must be accounted for in the material testing.

#Q5: After the shock you did not see damage in the steel composite structure. Did you inspect with NDT?

#A5: We did not inspect since we do not have this capability in-house and were limited by the available time at the shock table.

#Q6: Did you measure residual strength after the second shock?

#A6: Yes, we tested the same sample twice and only then we did the residual strength measurement.

#Q7: The considered adhesive types (epoxy and methyl methacrylate) might not be good for thick adhesive layers. Did you try more elastic adhesives?

#A7: Initially we did go as low as 200 MPa of elastic modulus in the adhesive, but that adhesive led to issues in the manufacture of a thick bondline without cracks.

#Q8: What is the test speed for the shock test?

#A8: We know that strain rates up to 300-400 s^{-1} were present in these tests.

#Q9: In the final video for the steel composite what adhesive was tested?

#A9: We used methyl methacrylate in the final tests. The use of epoxy was stopped at the coupon level as it was too rigid.

#Q10: Did you consider the use of any inspection methods for that application?

#A10: No, we did not consider NDT.

Certification (2 presentations)

Presentation 12 - Bonded repairs to critical damage in primary composite – A proposed roadmap to certification

Lucy Li (Aerospace Research Centre, National Research Council Canada, Canada)

Comments:

This work gives a very good general perspective of the whole subject of the workshop. Many aspects treated in other presentations are introduced here. This is an excellent guideline and a good basis for certification standards. Certification is especially important for the repair of primary structures with a low residual strength prior to the repair. To avoid certification by conducting proof testing on each repair, a three-step roadmap is proposed:

- Repair design that ensures damage tolerance and/or fail-safe capability and/or alternative load path. Methods without mechanical joints are considered with novel adhesive joint design, to prevent fast or unstable damage growth;
- Validation of the repair processes based on high level quality control of pre-bond processing and patch implementation followed by post bond inspections, including bond poof test; and
- Proven and reliable technology for detection of in-service unanticipated bond degradation or damage growth in the parent structure, including periodic non-destructive testing, bond proof test or/and structural health monitoring.

The steps are well defined but there are still many gaps to fill in relation to design procedures (a slow crack growth approach is recommended), realistic proof testing and reliable methods for non-destructive detection and structural health monitoring. Several hints and possibilities studied in the literature are given. Also, what is present in the literature is at coupon level but what is needed is to scale up the specimens so that they represent better real repairs.

Questions:

Which novel adhesive joint is proposed for fail safe? Which non-destructive testing method is recommended? What about the type of adhesive to be used?

Discussion after the presentation:

#Q1: I do not exactly understand this idea of sharing the load. For example, we had some works using a very ductile adhesive to balance the load sharing between the joint and the adhesive, but this might not work for large temperature variations. Eventually, if you optimize a crack arresting feature for bondlines, this will be very different from fasteners.

#A1: Indeed, if you can have some novel bondline features that provide a significant fatigue life the use of fasteners might not be necessary. Ultimately, it comes down to the certification bodies, which might not be convinced that the joint/process is sound.

#Q2: For the slow growth approach, we have not discussed the loads. Typically, we are seeing constant amplitude tests to demonstrate the crack propagation. In reality, we have variability amplitude load. I think not all load cycles propagate the crack. We need to know where the thresholds are to use the slow growth approach.

#A2: For CLS you have to select a load level above the level which grows the crack. This is more for learning about the mechanisms. We try to be as conservative as possible, to consider a limit load case from the internal case

We have to consider the type of aircraft. Helicopters are high cycle fatigue and fixed wing is different. If we have all data on fatigue crack growth, then it opens new doors for the design. There are some projects working in this field to obtain more data on fatigue in the next two years.

#Q3: In the beginning you stated that maybe bolting is easier. Maybe there is a difference between military and civil areas. There is a major paradigm change in civil aviation. Then the aircraft was bought used and disposed. Now, the aircraft is leased or bought by low-cost airlines for very low prices and then resell the aircraft in an almost new condition at a good price to profit. A cosmetically perfect repair is now more appealing in this regard to sell.

#A3: Agreed. But for military purposes bolting is still in use.

Presentation 13 - Validation and certification of bonded repair on F-18 wing root step lap joint

Markus Wallin (Patria, Finland)

Comments:

A real case study is presented here about the repair of a F-18 wing root step lap joint. The joint is between titanium and CFRP. Disbonds are found from lower wing skin close to the wing root. Repairs were carried out on scrap wing to validate the repair process. The damaged area was machined, a composite patch was bonded to facilitate non-destructive evaluation and cured with a blanket. Specimens were cut and tested with static and fatigue tests. Good results were obtained in the static and fatigue tests in the sense that the repair can restore the strength of the bondline. However, the root cause for the weak bondline is not known.

Questions:

What was the surface treatment applied? Did the certification include a NDE evaluation?

What is effect of water and temperature on the repair?

What do you suspect concerning the cause of the weak bondline?

Discussion after the presentation:

#Q1: During a repair for the shear buttons, do you mill out the composite and then test?

#A1: Yes, we did a test by taking the aluminium button, milling down to the original bondline and then used a paste adhesive. Failure was mainly in the paste adhesive, so the bondline was sound and strong. Having a failure at the bondline is a difficult task due to the high adhesive strength. I think we can succeed by using pressure and a film adhesive to bond the button for the test. It’s a work that should progress.

#Q2: Is there data that shows stronger performance in equivalent specimens from other users? Does this show that the strength can vary? Does Boeing have original test data for certification, what is the original procedure for certification? We argue that FM300 does not degrade.

#A2: We think that there is some variability unfortunately. There has been a lot of work seeking for the cause of failure. It might be the combination of several things.

#Q3: The root cause should be an issue in the bonding, ageing or an impact?

#A3: I mostly suspect of the surface preparation or the curing of the adhesive. If we look at the fracture surfaces, these are way too shiny. I think there are indications in other results (NIR) but this did not give me a good basis, since we only have the nominal dimensions of the specimens and it is difficult to scale.

#Q4: What about the Australians, they had problems in wings and ended scrapping wings. Did they do similar testing?

#A4: Not sure what they did. They have concentrated on testing wider specimens with double the width, but we do not now right now.

#Q5: On the FEA side, you said it was off from experimental result. By how much?

#A5: Not much, it was still with then scatter. About 5% off. But I expected a bit more.

#Q6: You did close-form analysis on the lap? How did you predict failure? I wonder if the composite initiates damage at a step.

#A6: With maximum shear on the bondline. How we built the model is different from Boeing and Navy process. When you take the specimen out of the in-service wing, we found that the configuration was a bit different from the original design. The steps are not aligned with the specimen.

#Q7: Do you know which surface preparation is done on the titanium? We are working on long term durability of civilian aircraft. Bonding of titanium of titanium of CFRP does not have a good long-term procedure. Maybe our idea of long-term durability is different from yours.

#A7: We use Sol-gel. If we make titanium repairs, we use sol-gel and primer.

#Q8: The possibility of weak bonding is concerning. For the static and fatigue, they all failed in the lower half, was there some adhesion failure? Did you do any chemical analysis on the titanium?

#A8: All of them failed at the outer mould line. Inner looks good. But failure is not equal in all specimens. We did some chemical analysis, but all look all right and no contamination could be clearly identified.

#Q9: For the repair itself, was it co-bonded?

#A9: Precured pre-preg patch of original material, plus secondary bonding. This type of repair is what we do in a regular basis.

Simulation/Design (4 presentations)

Presentation 14 - Multi-scale multi-physics bondline strength prediction research

Daniel C. Hart (Naval Surface Warfare Center, Carderock Division, USA)

Comments:

A multi-scale and multi-physics approach is presented in this work to design and monitor adhesive joints. A c model is used to incorporate surface roughness and voids in the bondline behaviour. A composite patch on aluminium is tested in 4-point bending. Machine learning is used to determine the relationship between the most influential parameters and the macroscale response. The viscoelastic nature of the adhesive is also considered in the numerical analysis. Monitoring is ensured by Lamb waves and ultrasounds. The study is still at early stages and want to understand how to link interactions of atomic to macro-scale behaviours in the future. This is a big technical challenge that can have a big impact in the way adhesive joints are designed.

Questions:

Has this approach been compared with other simpler one scale solid mechanics analyses? What kind of defects can be detected with Lamb waves?

Can this approach provide a more reliable certification?

Discussion after the presentation:

#Q1: What is the methodology for the surface roughness modelling. Stochastic roughness model, etc?

#A1: You are feeding the information directly to a cohesive model. We are trying to figure if we can measure the roughness in the field. We do profilometer measurements and use this data to feed the reduced order model. We will then use the model to determine data to feed the cohesive model with a high-fidelity peridynamics model.

#Q2: How do you simulate the interface between the adhesive and the substrate.

#A2: Peridynamics modelling is used at the interface. The molecular dynamics is used in this case, but we haven't started at this moment. We can then add the influence of other things, such as primers, water and then obtain factors that can be used to adjust the peridynamics model. We use the reduced order model to simplify the process. We also want to know what to measure (profilometer data, voids in the adhesive)

#Q3: Curious of the application of the peridynamics which is non-local and a very sensitive and computationally intensive process. How does the mesh and surface roughness is handled?

#A3: We have access to the DOD clusters. We also have colleagues available that have experience in this field. Its computationally demanding and thus we are seeking a reduced order model. We are finding the model suitable to handle the cracks and voids.

#Q4: Is it not easier to follow a build and break approach?

#A4: For the cheap applications it's all right but in the long term we want to know exactly what the bond state is exactly where we are taking into account a limit state. Maybe ultimately, we go to maximum stress but we want to have this procedure available.

#Q5: Does you creep model account for the 3rd phase (failure) of creep?

#A5: In this stage we are doing DMA, stress relaxation and creep. We have to do 7 tests for different intervals. Testing this material is very challenging, in order to create a Prony series.

It is non-linear visco-elastic and it takes 2 weeks to settle down before testing is carried out. The end goal is a non-linear model for the adhesive and linear model for the resin, include it a UMAT to use cohesive zone model and try to predict joint strength. Composites are not really visco-elastic, but the adhesive itself is the problem, especially for very thick bondlines.

Presentation 15 - NDE-guided compression after impact simulation

David Mollenhauer (University of Texas at Arlington Research Institute, USA)

Comments:

This work makes the bridge between defects detected by x-ray computed tomography in composites due to impact damage and the resulting residual strength using finite element simulation. The impact is applied with a drop weight on a plate of composite and the residual strength is measured afterwards under compression. The extended finite element analysis is very complete and includes delamination growth, matrix crack growth, fibre fracture and buckling. Thermal stresses are also considered. It is shown that impact damage can cause local buckling of the structure. A study about the impact of the damage fidelity on the numerical results is carried out. Reducing the fidelity of damage approximation reduced the predicted peak load significantly but a lower fidelity damage approximation provides a conservative prediction which may be useful for life prediction/residual strength prediction.

Questions:

Did you consider only the composite behaviour or the composite in a bonded joint? Is the composite plate studied a good representation of the actual cases?

How did you decide about the impact loading and compression test afterwards? Is this connected to reality?

Discussion after the presentation:

#Q1: I am curious about tap test simulation. Was the same size of damage considered through all interfaces? Did you find a conical shape?

#A1: Yes, the same size was used. The goal of this was to try the crudest assumption, the largest damage that you see and then project it all the way through and the results are pretty good. This is all enhanced CT. I would never propose CT as a practical method for aircraft assessment, this was just ground truth.

#Q2: You show how the accuracy changes by not including something. For cracks, how did you do this assessment?

#A2: We can allow or disallow the cracks to form on their own and propagate on their own. Basically, it is a simple switch in our code. We don't directly include any measured crack, but we let these cracks form.

#Q3: You mention a two-step procedure to get the cracks, can you explain?

#A3: If you use an X-ray procedure you need two sets of x-rays. We must actually insert a crack that travels between the two delamination and then apply some side pressure to bend the specimen and the crack will form in the right place. This is our two-step procedure.

Presentation 16 - Composite patch debonding monitoring based on surrogate modelling and particle filter

Daniele Oboe (Politecnico di Milano, Mechanical Engineering Dept, Italy)

Comments:

Machine learning (surrogate model) is used in this work for structural health monitoring of a laboratory repair specimen. The objective is to development a structural health monitoring system for bonded repair patches on the NH90 helicopter. The model is fed with finite element models (model driven) that represent typical cases and the data from optical fibres is used to diagnose and predict when the structure needs maintenance. This approach is more efficient than the classical interval defined maintenance.

Questions:

How many optical fibres are needed to properly monitor the structure? How can this approach be implemented in a real airplane?

How much time is gained with this approach in relation to the regular internal maintenance approach?

Discussion after the presentation:

#Q1: This is being tested at constant amplitude? How do you think your model will behave under variable amplitude load.

#A1: We measure the temperature to compensate its effect on the strain field. Our model was developed for constant load. In a normal application we need to normalize the load. We can use the sensors to determine the load and add load to the model.

#Q2: Using the load and adding load to the model is a huge assumption since you need to calibrate the effect of the strain field changes and how it is causing damage. But it opens new avenues for research. Maybe you can tailor the model for this, but you have to account for the additional parameters that influence the strain field. You should define your assumptions upfront. You have a good approach but please consider different scenarios and how to include them in the model.

#A2: We agree there is a lot to be done. We are also using a load independent algorithm that can auto adapt to the variations in load level.

#Q3: Consider these parameters and try to quantify them well, otherwise we are trying to manage many uncertainties.

#Q4: We need to collaborate more. The academic approach is different from that of the Airforce approach. The role of the academics is to quantify the different parameters and the fidelity does not need to be as high.

#Q5: There is a significant difference between the military and civilian world. SHM is not very desired by civilian aircraft users. For example, hard-landing sensors are often not desired because they might affect the availability of the commercial aircraft

#Q6: In America maintenance is guided by economics, and how you use these sensors is related to how we make money. In the military, when they are in the air, they are spending money. Flight hours are very different. There is a different case of using SHM between civil and military application.

#A(3-6): It depends on what you want to get. More complex data or simple damage detection. We can use this technique to obtain a simple idea of we had debonding or we want the strain fields.

#Q7: These types of sensors are very fragile. When you try to place them in a military aircraft it is hard. They actually want a cheap, reliable and transparent sensor, with a well-defined procedure.

#Q8: You need to quantify the load variability of the sensor and then we need to go to a certification process. This is a major research challenge for the future.

#Q9: We have local areas where want to make sure a repair is still in place. The other is the scheduled maintenance, to get information about some fatigue and then we open the question regarding repairability. As soon as we go in this direction, we can only establish something that make sense for maintenance. You can also have detection of corrosion which is a huge issue for airlines. The takeaway is that as long as you adjusted for all aspects of maintenance it makes sense to also include other types of maintenance at the same time (including electronic systems).

#A(7-8-9): We agree that uncertainties are a major challenge. This is just to show how the framework can accommodate for different problems. We did not consider the load variability at this stage, but we have successfully demonstrated the validity of the process.

Presentation 17 - Abaqus explicit implementation of regularized extended finite element

Endel Iarve (University of Texas at Arlington Research Institute, USA)

Comments:

The relatively recent extended finite element method is used here to simulated composite delamination in impact situations. A variant of the extended finite element method is used, the Regularized eXtended Finite Element Method (Rx-FEM), that allows maintaining regular element integration scheme. A beam under impact being is considered. It is not clear if cohesive zone elements are used between the skin and the core. This advanced tool has been used in several situations in the past such as static loading but never in the case of impacts.

Questions:

How did you simulate the interface between the core and the skin? Did you include cohesive zone elements?

How does it compare with a common damage mechanics analysis such as cohesive zone modelling?

The pre-processing and processing efforts are similar to conventional tools? What about its use in adhesive bondlines?

Discussion after the presentation:

#Q1: Do you have duplicate elements at the start of the process? And what about 3D models, are they possible?

#A1: Yes, we need to do so. Yes, 3D is perfectly possible to do but we started with 2D because it is much easier for the student to start with.

#Q2: In our work we have used XFEM in adhesive joints. It works very well with mode I (DCB). But in single lap joints, with mixed mode loading conditions, it tends to go into the substrate and does not travel near the adherend. What's your feedback on this approach?

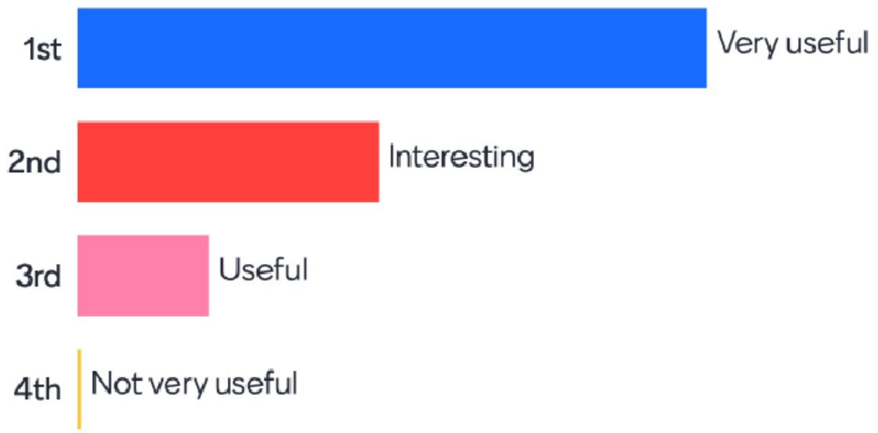
#A2: In fact, we are doing the same thing. The interfaces include the cohesive elements placed already at the interfaces. The crack will travel from an interface towards the other and then progress through the cohesive elements.

#Q3: Your three-ply laminate looks like a sandwich panel and the initial damage modes are exactly the same as found a sandwich panel.

#A3: Yes, and this Abaqus explicit model is very efficient, so we can run these models easily.

ANNEX – QUERY AT THE OF THE MEETING

How do you rate the usefullness of the meeting



Would you be interested in a follow up? In one year? Two tears? Let us know.

Mentimeter

one year	Definitely	yes. 2 years.
Yes, in two years.	yes, in two years	Yes. In 2 years
Yes	Definitly yes - in 2-3 Years to give chance for progress....	Yes 1 year
yes, 2 years	1 year	yes, two years
3-4	2 years	Yes, two years.
yes, 2 years	I mam retired by then	Two years