1 Background and Motivation

Fig. 1. A350XWB First Flight (June 14, 2013)

With the first flight of the A350XWB a consequent evolution of the usage of CFRP for primary structures within Airbus has reaching the next milestone.

Fig. 2. Evolution of composite structural weight within the Airbus fleet.

After a long and excellent experience with CFRP (first on secondary structures and since 1983 also for major primary structural components of the vertical stabilizer) Airbus has reached the next step in the transition from a metallic to a composite aircraft with the first CFRP fuselage of an Airbus aircraft with the A350 XWB.

One key technology for the future development of composite aircraft structures is a suitable joining technology. Performing a weight, performance and cost tradeoff, bonding is one of the most promising joining technologies for composite structures.

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

2 State of the Art Bonding

2.1 Classification of Bonding Technologies

The following illustration shows the three main categories of joining of composites with thermoset matrices representing the different stages of integration.

Fig. 3. Classification of composite bonded joints
Co-Curing is the earliest stage of integration, representing a fully integrated component. The joining mechanism is chemical cross-linking.

**Typical Airbus application:**
Module-Shell of A300/310 Family

Secondary Bonding is the latest stage of integration. Two previously cured parts are joined by a film or paste adhesive. The joining mechanism between adhesive and adherent is adhesion.

**Typical Airbus application:**
Stiffeners on VTP-/HTP-Ribs of A380

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

**Typical Airbus Application:**
Co-Bonded Stringers at A350XWB Fuselage Shells

### 2.2 Surface preparation of bonded Joints

A proper surface preparation is mandatory to ensure the performance and process safety of a secondary- or co-bonded joint. The most common surface preparation / protection is the usage of peel ply for co-bonded and secondary bonded joints. Although this technology has some challenging aspects especially for the activation of the surface and remaining contaminations on the surface without further cleaning or activation processes as discussed in [3] the reproducibility and simple application are main arguments for its application as a baseline surface preparation. Additionally surface cleaning and activation technologies as Atmospheric Plasma are applied more and more in industrial applications [9].

Other novel Surface pretreatment technologies as Laser cleaning or vacuum blasting are under development and will be discussed in §6.2.2.

### 3 Definition of potential failure initiation modes

The following failure initiation modes are describing the most important origins of potential failures of bonded joints. The root cause for these initial failure modes is varying and only the major effects will be discussed in detail in this work.

#### 3.1 Disbond

A disbond is an initial area within a bonded joint without connection between adherent and adhesive. A typical root causes are a massive contamination of the adherent (e.g. with release agent) or failures within the adhesive application process of (e.g. gaps within the adhesive layer).

![Fig.4. failure initiation mode disbond](image)

A disbond is detectable with non destructive inspection technologies (NDI) as ultrasonic inspection within the individual limits of the detection threshold.

#### 3.2 Weak bond

A weak bond is a fully integer bonded joint with a reduced strength between adherent and adhesive. The root course is a not sufficient adhesion of the interface of adherent and adhesive due to small contamination of the surface.

![Fig.5. failure initiation mode weak bond](image)
A weak bond is not detectable by means of NDI due to the absence of a detectable interface layer. Research is addressed but results are not expected short- to mid-term for industrial usage.

### 3.3 Impact

Impact events within manufacturing and in service can lead to initial damages of the adherent and the adhesive.

![Impact](image)

**Fig.6. failure initiation mode impact**

Damages resulting from impact are detectable by NDI within the individual limits of the detection threshold.

### 4 Involved disciplines to ensure a reliable bonded joint and actual state of the art

#### 4.1 Process Safety

For any application of bonding technology a repeatable, robust and reliable process is mandatory and established within Airbus. Nevertheless a very low residual risk for the occurrence of weak bonds cannot be avoided today. In comparison to other industries, where structural bonding is well established, this residual risk is not acceptable within the aerospace industry. The sensitivity of the surface preparation / pre-treatment and contamination avoidance as the main driver for the process safety is well known and addressed within several R&D Projects.

#### 4.2 Material Qualification

Additional to the qualification of each material including the applied auxiliary materials within or prior to the bonding process is the qualification of the used material triple from adherent, adhesive and used auxiliary materials like peel ply is state of the art for all bonding processes at Airbus.

The lack of knowledge of some specific ingredients or their individual production methods in last detail for adhesive, peel-ply or resin due to low needed volume within the Aerospace industry in comparison to other industries is leading to a residual uncertainty in the field of material qualification for changed properties of the certified products.

The strengthened involvement in material development is mandatory to ensure the needed maturity to reduce the influence of the material variation on the strength of the joint.

### 4.3 Non Destructive Inspection (NDI)

Detection of defects within the bond line is state of the art and well established as discussed in §3. The direct detection of properties like the remaining strength of a weak bond is not possible today.

The assistance for process safety as e.g. contamination detection is under development in different R&D Projects as the European Project ENCOMB [10].

#### 4.4 Design & Stress

Today’s design is not considering bonding without fasteners for primary aircraft structures. The sizing approach is based on the assumption of a full loss of the bonded joint. Therefore the fasteners have to be able to carry the full load of the joint. Also a no growth policy for cracks / disbonds is taken into account.
5 Bonded Aerospace structures within the context of certification boundary conditions

Resulting from the described State of the Art within the composite bonding technology today's certification rules according AC 20-107B [1] are limiting the certification of composite bonded joints to the following possible approaches:

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

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

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

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

[1]

Today no suitable NDI method to full fill the requirement [1](iii) of a secured measurement of the failure strength of a joint is in place. Also the affordability to establish a full single part testing of each bonded joint within an industrial environment of a commercial aircraft manufacturing according to requirement [1](ii) is not practical. Therefore the only requirement [1](i) is practically to be taken into account for the sizing & certification of bonded joints.

State of the art to certify a structural composite joint is to follow approach [1](i) by the usage of so called “chicken rivets” which have to be capable to carry the relevant loads taking into account a global failure of the bondline. This boundary condition and the corresponding technical concept of “chicken rivets” are limiting the benefits of the application of composite bonded joints in terms of weight, cost and performance.

6 Actual Developments on the route to certification of composite bonded joints

Different mechanism and strategies are addressed (at Airbus and the research community) to improve the sensitivity of bonded joints in terms of increased process safety and with regards to the certification.

6.1 Alternative joining mechanism

The most critical point for bonded joints is the sensitivity of the adhesion. Therefore alternative mechanisms to integrate two parts beside adhesion are under investigation. Following the fact, that integrated and co-cured parts joined within one curing cycle by chemical crosslinking, are not within the regulation framework for bonded joints acc. [1], chemical cross-linking as is one potential way to achieve a reliable and certifiable joint without the need for additional mechanical fastening.

6.1.1 Partially Curing / Semicuring

This technology approach is focussing on the consequent development of a co-cured joining mechanism relying on chemical crosslinking instead of adhesion. One technology approach is a partial cure of the adherent by local preventing of curing of the area to be joined in a second assembly-curing cycle.

[Fig.7. local curing prevention]

An alternative approach following the identical principle for the joining mechanism is the so called semicuring, where the adherents will be partially cured up to a defined degree of cure.
The glass transition temperature ($T_g$) of the semicured resin is above room temperature, therefore semicured parts are semi-solid at room temperature and easy to handle. Within a final assembly-curing cycle a co-cured chemically cross-linked interface is developed. Within a final assembly-curing cycle a co-cured chemically cross-linked interface is developed.

![Fig. 8. Semicuring principle](image)

The main advantage of these technologies in comparison to co-curing is the reduced tooling afford for the final assembly cure cycle. Also these technologies are suitable for today’s decentralised production scenarios.

### 6.1.2 Welding

Another alternative technology approach is Thermoset Composite Welding (TCW). The principle is to co-cure thermoplastic film at the surface of the joining area of the thermoset adherents. The joining is performed by welding of the thermoplastic surfaces.

![Step 1:](image)

The main motivation is the avoidance of an adhesive joining mechanism in the assembly process step and the simplified tooling needs in comparison to Co-Curing, Co-Bonding and the varying derivate technologies discussed in 6.1.1.

### 6.2 Increase of process safety

Process safety can be divided in the following main fields of research. One principle is the avoidance of process variation and potential contamination by means of automation. The other is dedicated to the detection and removal of potential contaminants from the surface. Additionally different approaches to increase the process safety by means of new design and joining principles are investigated. All approaches are mainly related to risk-elimination of the occurrence of weak bonds of secondary bonded or Co-Bonded Joints.

#### 6.2.1 Automation

One major risk for contamination or process variation is the human factor. The actual development is therefore more and more focussing on a repeatable and documented process chain. The European Project ABiTAS (Advanced Bonding Technologies for Aircraft Structures) - led by Airbus – has been focussed on this topic. The following figure gives an overview on the scope and the process chain taken into account for ABiTAS.

![Fig. 10. ABiTAS Process Chain](image)
research for industrial aerospace application. But focusing on the certification requirements as discussed in §5 process safety in not one of the building blocks of [1] that are mandatory for composite bonded joints.

6.2.2 Detection and removal of contaminants

Within ABiTAS as well as in the European Project ENCOMB also the topic of contamination detection has been addressed by new NDT technologies. In comparison to classical NDT to detect physical damages and failures the so called “Extended NDT” is focusing on the determination of physio-chemical properties of the adherent surface in the interface region [5]. These properties are mainly influencing and defining the performance of the final bonded joint as well as the remaining risk for a weak bond.

Target is an industrial reliable detection method for critical contaminations and surface states that lead to weak bonds. Actual results (e.g. for the aerosol wetting test [9]) are promising, but nevertheless not yet leading to a step change for the certification boundary conditions.

Another approach to increase the process safety is the secured removal of any kind of contamination with the potential to ease a weak bond. Beside the approaches discussed in § 2.2 there is a high need for reproducible and quick surface cleaning and activation technologies. Also the influence of individual human factors (e.g. as for traditional grinding) must be reduced.

Promising work has been done in the field of laser pre-treatment. Typically a selective removal of resin incl. potential contamination is performed by a suitable laser source as UV or CO₂ laser. Studies from University of Braunschweig, Germany [2] have shown very promising results. Also no degradation of the remaining resin has been observed.

An alternative technology is vacuum blasting were the blasting medium is accelerated by a vacuum applied in a special blasting cover. As discussed in [6] this Technology shows good potential for a clean and reproducible surface preparation of CFRP.

Fig.11. Surface states for different pre-treatment technologies [2]

Fig.11. shows the different surface states resulting from the different pre-treatment approaches as discussed in [2].

a) Contaminated Surface as the not acceptable baseline without application of pre-treatment or cleaning procedures. Not acceptable for stable bonding process.

b) Peel ply surface with relatively thick resin layer in the top. The rough surface topology as mirror of the used peel ply surface is not resulting in highly activated surfaces for bonding [3]. Also a risk for contaminations from residuals of the used peel ply has been observed.

c) Grinding or blasting is securely removing the full first resin layer incl. potential contaminations. A damage of fibres in the first layer is often not avoidable.

d) Laser pre-treatment can remove the full resin layer without harming the fibres. Due to variations in the thickness of the resin layer and the typically subtracting mechanism of a laser treatment the final geometrical state in of the surface has to be evaluated carefully.
Following §5 also surface pre-treatment and the secured removal of contaminants is not part of the potential certification scenarios acc. [1]. Nevertheless this field of technology has the potential to be contributing to future development eliminating the risk for the occurrence of weak bonds.

6.2.3 New design & joining principles

With the motivation of designing composite joints not relying on secondary bonding, therefore taking into account questions that link to tolerance adapting and process safety, Modular Joints have been developed and investigated within European Project MoJo [7]. The main principle is the usage of an uncured (textile) joining element that is co-bonded with both adherents.

![Fig.12. Principle of modular joints](image)

Following this new approaches consequently it can be an enabler for novel build concepts beyond state of the art build sequences and architectures.

Regarding certification technology approach of modular joints is similar to the traditional co-bonding concepts. Following [1] there is still the need for design features to limit potential failures within the co-bonded joints.

6.3 Damage limitation and detection

This technology principle is directly derived from the certification requirements acc. [1]:i. The main principle is to securely limit a potential local damage of the joint acc. the discussed initiation modes in §3. Depending on the applied damage scenario for the sizing philosophy there will be also a need for special damage detection capabilities.

State of the art is the usage of fasteners to limit a potential failure of the joint and to secure the limit load capability based on the assumption of a full loss of the bonded joint by a global weak bond.

6.3.1 Disbond Stopping Features

Following the discussed work within the previous paragraphs all dedicated to the avoidance or detection of weak bonds the following assumption is enabling a new field of research:
A global weak bond is detectable or can be avoided securely by dedicated technologies to be developed mid to long term.

This gives the opportunity to take into account only local initial damages for the development of new design features – so called disbond stopping features.

The development of those Features is addressed in the European Project BOPACS started in September 2012 with duration of 42 month.

Target of BOPACS is the proposal of a road map to certification and the development of Means of Comply based on:

- Research beyond the state of the art into crack growth and disbond extension mechanisms in adhesively bonded joints.
- Design, analysis and testing of crack stopping features, capable of preventing cracks or disbonds from growing above a critical size, with a joint still capable of carrying the predefined load.

The following categories of disbond stopping features have been identified and will be investigated with different technology approaches:

- **Surface interfering features**, interfacing only with the top layers of the adherent material, not influencing the outer shape and global architecture of the part
- **Surface Modification** by mechanical or chemical means without additional elements applied in the joint.
- **Geometry Modification** by variation of the global geometry of the adherents in the area of the joint.
- **Through thickness features** penetrating through the full thickness of the joined components
- **Adhesive bondline architecturing**, applied only within bondline without change of adherents.

Proposed technical solutions beside the benchmark of conventional fasteners are e.g. rivetless nutplates or small diameter pins or staples as proposed by [8].

### 6.3.2 Damage detection

Damage detection can be distinguished in two major fields. One is the scheduled inspection interval per Aircraft and the other is the short term in field detection. For scheduled inspections there is no special need of research for the detection of failures in the bondline identified beside the already addressed topics for delamination and damage detection for CFRP.

To enable the discussed disbond stopping approach acc. § 6.3.1 for some technology approaches new in service detection capabilities will be needed to detect potential defects within a few flight cycles. Therefore also technologies from the field of structural health monitoring (SHM) are contributing on to potential certification scenarios as also investigated e.g. in ENCOMB.

### 5 Conclusion and outlook

Today there is no feasible way to implement a structural bonded joint without additional features as for example fasteners on aircraft primary structures within the near future, therefore that the needed technologies to enable a secured certification are not in place today.

Intense research has been done in the last years to increase process safety and to eliminate the risk for the occurrence of a weak bond. Major Fields of development are process automation, extended NDT and surface pre-treatment for bonding.

Even if significant progress has been made in these technology fields that enable the secured implementation of secondary bonding in many industries, a direct adaption of these solutions for aerospace application is not feasible due to the higher requirements for reliability, safety
and design service goal. To achieve a fully bonded structure without the requirement of additional fasteners is not possible within today’s certification boundaries acc. [1].

Following the possible technological paths stated within [1] the following two solutions are not feasible to contribute from today’s point of view to a certification of composite bonded joints:

Full single Part testing of bonded composite joints is not practicable from cost and lead time point of view for an industrial application on large aircrafts.

NDI to test the strength of a bonded joint is as technology not available on mid to long term perspective.

Therefore the only one feasible option remaining:

Limiting of maximum disbonds to uncritical size by design features is the only feasible way to achieve certification on the next generation of bonded composite joints. Utilizing new approaching technologies as for the detection of global weak bonds enable new sizing approaches relying on secured stopping of local defects.

An alternative potential way to certify bonded structures for aircraft primary structures is to utilize alternative chemical / physical mechanism instead of adhesion. Co-curing has shown a good reliability and technology variants to integrate the co-curing mechanism for assembly purpose without the need of fully integrated manufacturing concepts as e.g. semicuring are mandatory to develop further to clearly demonstrate the equivalence in terms of strength and process safety to co-cured structures.

Additionally there is still a need for new technology approaches combining the benefits of a bonded joint with the reliability of a bolted joint in a competitive cost and lead time framework.

A new technology solution to enable the fully bonded aircraft will only be established within a strong cooperation of industry and academics pushing on the one hand to a stable process with the needed performance within the right cost and lead time framework.

On the other hand to perform the needed science to be able to clearly understand the utilized physical or chemical mechanisms and potential influencing factors and environmental conditions.

References


