# BONDING OF CFRP PRIMARY AEROSPACE STRUCTURES - DISCUSSION OF THE CERTIFICATION BOUNDARY CONDITIONS AND RELATED TECHNOLOGY FIELDS ADDRESSING THE NEEDS FOR DEVELOPMENT

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## Abstract

*Today, the application of bonding technology for primary aerospace structures is limited due to the certification regulations. State of the art is an additional application of fasteners which is limiting the benefits of the application of composite bonded joints.*

*This paper will give an overview of the current state of the art of certification compliance within the context of bonded CFRP primary structures. Also the role and interaction of different technology streams like surface preparation, process capability, material & adhesive development and design & sizing concepts to enable a secured roadmap to certification is discussed.*

*The resulting needs for current and future technology development and their interaction within the different disciplines is described. Also solution approaches to build a roadmap to certification of CFRP-bonded joints are highlighted.*

*Parts of this paper have been published previously at the ICCM19 proceedings [1].*

## 1. Introduction

With the first flight of the A350XWB a consequent evolution of the usage of CFRP for primary structures within Airbus Group has reached the next milestone. After a long and excellent experience with CFRP in civil and military applications, first applied on secondary structures and since 1983 for the vertical stabilizer as first major primary structural component for civil aircrafts, Airbus Group has now reached the next step in the transition from a metallic to a composite aircraft with the first CFRP fuselage of an Airbus aircraft on A350 XWB.

One key technology for the future development of composite aircraft structures is a suitable joining technology. Today’s state of the art joining method for primary airframe structures is mechanical fastening for metallic as also for composite structures. Performing a weight, performance and cost trade-off, bonding is one of the most promising alternative joining technologies especially for composite structures.

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

## 2. State of the Art Bonding Technology

### *2.1. Classification of Bonding Technologies*

Figure 1 shows the three main categories of joining of composites with thermoset matrices representing the different stages of integration.

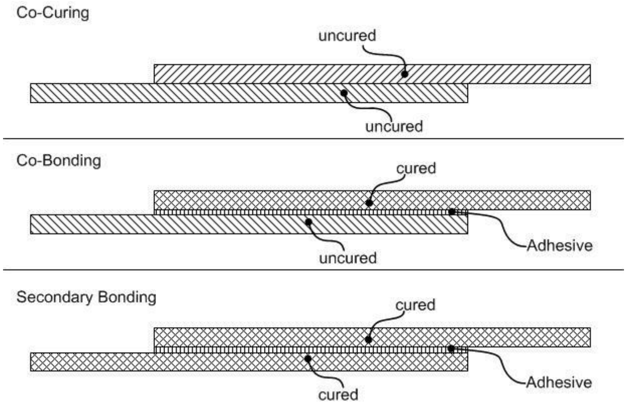

Figure 1. Classification of composite bonded joints

**Co-Curing** represents the earliest stage of integration, resulting in a fully integrated component. The joining mechanism is chemical cross-linking.

**Co-Bonding** represents 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.

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

### *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 application of peel ply for co-bonded and secondary bonded joints. This technology holds some challenging aspects, especially the activation of the surface and remaining contaminations on the surface without further cleaning or activation processes [4]. Main arguments for application of peel ply as the baseline surface preparation are the reproducibility and simple application as well as the protection aspect during handling and storage of the single part. Additionally surface cleaning and activation technologies as atmospheric plasma are applied more and more in industrial applications [10]. Other novel surface pre-treatment technologies such as laser cleaning or vacuum blasting are under development and discussed in §3.2.2.

### 2.3. Definition of potential failure initiation modes

The following failure initiation modes displayed in Figure 2 are describing the most important origins of potential failures of bonded joints. There are different root causes for these initial failure modes and only major effects will be discussed in this paper.

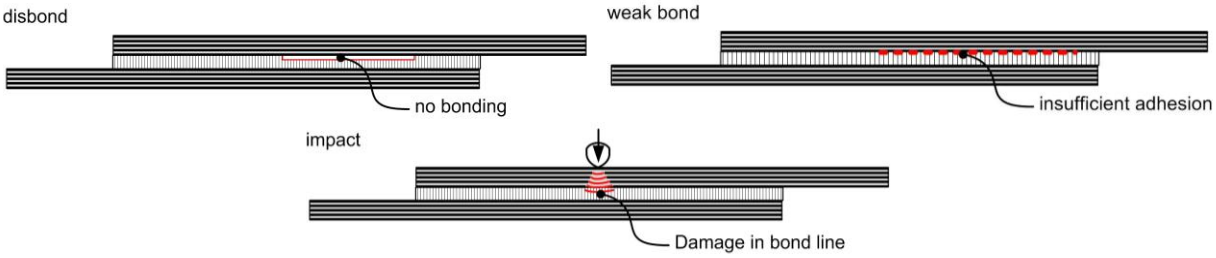

Figure 2. Typical failure initiation modes for bonded joints

A **disbond** is an initial area within a bonded joint without connection between adherend and adhesive. Typical root causes are massive contaminations of the adherend surface (e.g. with release agent) or failures within the adhesive application process (e.g. gaps within the adhesive layer). A disbond is detectable with nondestructive inspection technologies (NDI) as ultrasonic inspection within the individual limits of the detection threshold.

A **weak bond** is a bonded joint with a reduced strength between adherend and adhesive. It is characterized by an adhesive failure mode. The root cause is an insufficient adhesion of the adherend interfaces due to small contamination of the surface or unfavorable process conditions. A weak bond is not detectable by means of NDI due to the absence of a detectable interface layer. Research addresses the problem but results are not expected short- to mid-term for industrial usage.

**Impact** events within manufacturing and in service can lead to initial damages of the adherend and the adhesive. Damages resulting from impact are detectable by NDI within the individual limits of the detection threshold.

### 2.4. Involved disciplines to ensure a reliable bonded joint and current state of the art

#### 2.4.1. Process Capability

For any application of bonding technology a repeatable, robust and reliable process is mandatory and established within Airbus Group. Nevertheless, a very low residual risk for the occurrence of weak bonds cannot be ruled out today. In comparison to other industries, where structural bonding is well established, this residual risk is not acceptable within the aerospace industry.

#### 2.4.2. Material Qualification

The material qualification covers the adherend material, adhesive, and the applied auxiliary materials within or prior to the bonding process. Additionally, the qualification of the applied material combination of adherend, adhesive and used auxiliary materials like peel ply is state of the art for all bonding processes. The lack of detailed knowledge of some specific ingredients or their individual production methods for adhesive, peel-ply or resin 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.

### *2.4.3. Non-destructive Inspection (NDI)*

Detection of defects within the bond line is state of the art and well established. The direct determination of properties like the remaining strength of a weak bond is not possible yet.

The assistance for process safety as e.g. contamination detection is under development in different R&D projects as ENCOMB [11] and RAPID REPAIR [14].

### *2.4.4. 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 and the surrounding structure of the joint have to be able to provide a second loadpath to carry the full load of the joint. Furthermore a no growth policy for cracks / disbonds is taken into account.

## 3. Certification Compliance

### *3.1. 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 [2] 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." [2]*

Today, no suitable NDI method to full fill the requirement [2];*(iii)* of a secured measurement of the failure strength of a joint is in place. Moreover, it is not affordable to establish a full single part testing of each bonded joint within an industrial environment of a commercial aircraft manufacturing according to requirement [2];*(ii)*. Therefore only requirement [2];*(i)* is practically to be taken into account for the sizing and certification of bonded joints.

State of the art to certify a structural composite joint according [2] is the usage of additional fasteners 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 additional fasteners are limiting the benefits of the application of composite bonded joints in terms of weight, cost and performance.

### 3.2. Current developments on the route to certification of composite bonded joints

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

#### 3.2.1. Alternative joining mechanism

The most critical point for bonded joints is the sensitivity of adhesion. Therefore, alternative mechanisms to integrate two parts besides adhesive bonding 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 according [2], chemical cross-linking is one potential way to achieve a reliable and certifiable joint without the need for additional mechanical fastening.

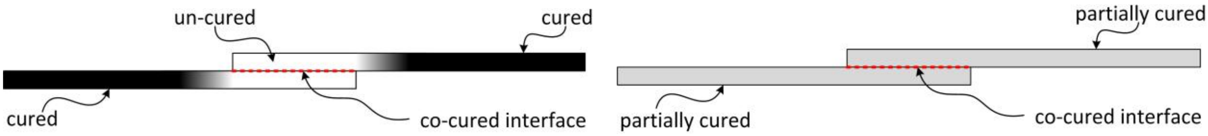

Figure 3. Local uncured zones and B-Staging principle

**Local uncured Zones:** One technology approach is a cure of the adherend with local prevention of curing of the area to be joined in a second assembly-curing cycle, as shown on the left side of Figure 3.

**B-Staging:** Another approach shown on the right side of Figure 3 also targeting on a co-cured interface is B-Staging, where the adherends will be partially cured up to a defined degree of cure. B-Staged 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.

The main advantage of these technologies in comparison to Co-Curing is the reduced tooling effort for the final assembly cure cycle. Furthermore these technologies are suitable for today’s decentralized production scenarios.

#### 3.2.2. Increased process safety and process capability

Beside the profound knowledge of the Material involved the improvement of process safety can be divided in the main fields of research discussed in this paragraph.
All discussed approaches are mainly related to risk-elimination of the occurrence of weak bonds of secondary bonded or co-bonded joints.
A sufficient process capability and therefore process safety is a mandatory prerequisite for any application of bonding technology but nevertheless it will not lead directly to a secured certification of bonded joints. It is not part of the building blocks of the currently valid certification requirements [2] as discussed in §2.1 that are mandatory for composite bonded joints.

### Automation:

One major risk for contamination or process variation is the human factor. The current development is therefore more and more focussing on a repeatable and documented process chain. The European Project ABiTAS (Advanced Bonding Technologies for Aircraft Structures) [5] - led by Airbus Operations – was focussed on this topic.

Stable, controlled and reproducible processes are mandatory and prerequisite for any application of bonding technology. Therefore, automation is one major field of needed research for industrial aerospace application.

### Detection and removal of contaminants:

Within ABiTAS, as well as in the projects ENCOMB and RAPID REPAIR, 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 adherend surface in the interface region [6]. These properties are mainly influencing and defining the performance of the final bonded joint as well as the remaining risk for a weak bond.

The target is an industrial reliable detection method for critical contaminations and surface states that lead to weak bonds.

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

Promising work has been done in the field of laser pre-treatment. Typically, a selective removal of resin including potential contaminations is performed by a suitable laser source as UV or CO2 laser. Studies from University of Braunschweig, Germany [3] have shown very promising results and 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 [7] this technology shows good potential for a clean and reproducible surface preparation of CFRP.

### Influence of process- and environmental-parameters on bond quality:

For the process itself the associated parameters need to be determined. In order to keep process variations as low as possible the vital few parameters must be identified.

Apart from the discussed contaminants, there are dozens of parameters with a potential to influence the strength of the bond. These parameters can be roughly clustered into materials, manufacturing process, loads, and environment. The profound knowledge of these parameters and their interaction will allow to set parameter tolerances right. This will drive up the process capability.

Subsequently, monitoring systems for the vital parameters can be developed and installed along the process line to identify and assess variations. This approach will contribute to certify structural bonding based on process safety in the long run and would imply a change of the current certification philosophy. For the time being, process safety is essential but not sufficient.

### *3.2.3. New design & joining principles*

With the motivation of designing composite joints that do not rely 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 [8]. The main principle is the usage of an uncured (textile) joining element that is co-bonded with both adherends. Regarding certification, the technology approach of modular joints is similar to the state of the art Co-Bonding concepts. Following [2] there is still the need for design features to limit potential failures within the co-bonded joints.

Nevertheless new joining technologies are enabler for structural integration concepts addressing not only joining aspect as shown in Figure 4. There are also advantages from new industrial build sequences and system integration concepts which can be exploited.

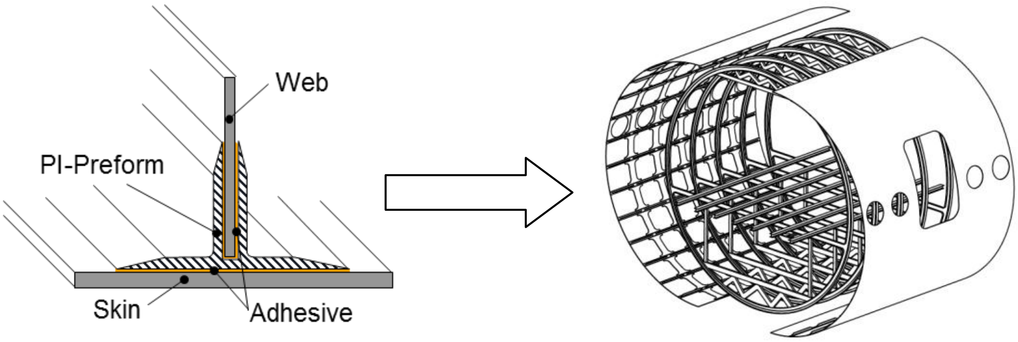

Figure 4. Fuselage integration concept enabled by novel joining technologies

### *3.2.4. Damage limitation and detection*

This technology principle is directly derived from the certification requirements according [2];*(i)*. The main principle is to securely limit a potential local damage of the joint resulting from the initiation modes discussed in §1.2.

Depending on the applied damage scenario for the sizing philosophy there will be also needs for special damage detection capabilities.

State of the art to guarantee a damage tolerant joint 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.

**<u>Disbond stopping features:</u>**

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:

<u>A global weak bond is detectable or can be avoided securely by dedicated technologies to be developed mid to long term.</u>

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 [12].

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.

Proposed technical solutions beside the benchmark of conventional fasteners are e.g. rivetless nutplates or small diameter pins or staples as proposed by [9].

**Damage detection:**

Damage detection can be distinguished in two major fields: the scheduled inspection interval per Aircraft and 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 according § 2.2.4.1. for some technology approaches, new in service detection capabilities will be needed to detect potential defects within a few flight cycles. Therefore, technologies from the field of structural health monitoring (SHM) are contributing to potential certification scenarios as investigated e.g. in the European project SARISTU (Smart Intelligent Aircraft Structures).

## 4. Conclusions

At present and in the near future, there is no feasible way to implement a structural bonded joint on aircraft primary structures without additional features such as fasteners. The reason is that the needed technologies to enable a secured certification are not in place today.

Intense research has been performed in recent 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, understanding of bonding parameter influence, and surface pre-treatment for bonding. Even if significant progress has been made in these technology fields enabling the secured implementation of secondary bonding in many industries, a direct adaption of these solutions for aerospace primary structures is not feasible due to the higher requirements for reliability, safety and design service goal.

Limiting of the maximum disbonds to an uncritical size by design features is the currently only feasible way to achieve certification in accordance with the regulations [2] for the next generation of bonded composite structures.

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. B-staging 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 research to be able to clearly understand the utilized physical or chemical mechanisms and potential influencing factors and environmental conditions.

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