Extended Evaluation of Test Data by Combining Strength and Fracture Mode Analysis

Thomas Koerwien

Airbus Defence and Space GmbH
Rechliner Str.
85077 Manching
GERMANY

thomas.koerwien@airbus.com

Thomas Meer

Airbus Central Research and Technology
Willy Messerschmitt Str.
82024 Taufkirchen
GERMANY

thomas.meer@airbus.com

ABSTRACT

The guidelines to certify bonded composite joints are outlined in the AC20-107B [1]. The means of compliance don't refer explicitly to process safety; instead it is a mandatory prerequisite. To determine process safety the knowledge of the influencing parameters associated to the bonding process is required.

This paper will give an insight into the research activities that have been conducted within the German LuFo project SCHACH [2]. One part of the project is focusing on robust composite bonding and the determination and assessment of bonding process influencing parameters. The main objective is to identify and tolerance parameters significant to the bonding process.

In particular the results of a 14 parameter screening Design of Experiment (DoE) will be discussed. Parameters under investigation are associated to surface pre-treatment, environment, curing, process timing, and loading. To determine the strength a new centrifuge has been used which resembles a head pull test. This test promises cost and time advantages and provides a remedy to lower the clamping force related scatter in regular head pull testing. However, the sensitivity is considered lower than standard DCB testing.

The DoE main effects analysis on strength data showed ambivalence parameter effects. Differences in the fracture mode did not necessarily trigger a significant different strength value, as a lower strength would be expected for adhesive failure mode. In order to take the failure mode into account a "complex bonding strength" is introduced. The strength is deprecated for adhesion failure and revalued for cohesive or laminate failure and thus the "complex value" contains additional information. The algorithm to determine the complex bonding strength was aligned with GIc data featuring different surface activation levels on the very material. With the combined data it is possible to identify parameters with significant influence to the bonding process using the new centrifuge test. Moreover the approach could be also adapted to other test methods to increase their sensitivity.

1. Introduction

The AC20-107B [1] provides clear guidelines for the certification of structural bonded CFRP joints such as:

….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;

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

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

(i) refers to the use of design features. In practice so called chicken rivets are used. In some cases they even work as a second load path if not designed properly. The actual intention is to use design features for crack growth limitation which require, to use the full potential, a new design and sizing approach.

Proof load testing (ii), beyond small AC and small series is forbiddingly expensive and not appropriate for military and commercial aircrafts.

Non-destructive testing methods with the ability to determine the joint strength in a repeatable fashion will not be available in the foreseeable future. Laser bond inspection [3][4] seems promising but actually belongs to proof load testing.

The implemented limitations of AC20-107B are consequences resulting from failures of bonded joints and associated near misses in the past. Not explicitly mentioned is process safety which is considered as a matter of course. An effective quality control requires the knowledge of which parameters are key for the manufacturing process. In addition to the process safety aspect, the knowledge around the consequences of process deviations will determine a possible keep, repair or scrap decision. Thus enabling significant cost savings in production as well as maintenance for both, military and civil aircrafts.

For a bonding process qualification strength data are produced by means of the building block approach. Cost drivers are the large number of parameters as well as the associated costs of the specimens. The goal is to assure high process capability while reducing the number of parameters or samples, respectively, to the vital few that actually go into a process qualification. To achieve that statistical methods are used.

DCB testing has become standard to determine bondline robustness and sensitivity to adhesion. The new LUMifrac headpull test offers significant economical advantages compared to standard DCB testing and shall be used for the determination of significant parameters. The sensitivities of both test methods will be discussed herein.

While the assessment of the strength is usually performed with a high resolution, the assessment of the fracture modes often remains at qualitative level. The approach presented aims at the quantitative assessment of failure modes in combination with strength data to identify key bonding process parameters. It will be demonstrated by means of LUMifrac but can be also adopted to other specimens types.

2. Process safety – mandatory for certification

The mid to long term vision is to open up an additional option based on process safety for bonding under “special conditions”. One of the prerequisites is the mastering and fundamental understanding of the bonding process. Based on the knowledge of critical process parameters and their interaction the individual process parameters will be toleranced to enable a robust bonding process and to increase the process capability (cpk), refer to Figure 2-1.

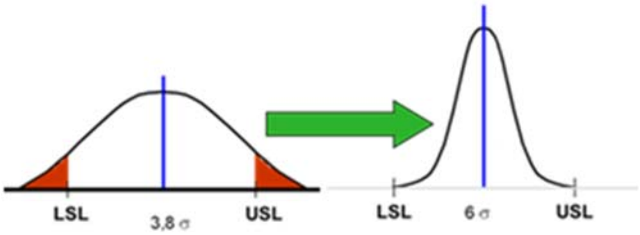


Figure 2-1: Targeted process capability

The approach described here is using Six Sigma methodologies. Basically, it is a systematic way to tackle multiparameter challenges. The bonding process is associated with a vast set of parameters. A study performed in a previous project Azimut [5] mapped more than 100 parameters associated with the bonding process. These parameters can be clustered in controllable and non-controllable or hard to change parameters. The latter parameters referring for example to the composition of the shop atmosphere, the chemistry of the adherent resin and ingredients of the adhesive, to name a few. These parameters have to be fixed and measured as far as possible. For the controllable parameters, the assignment is to split up the parameters in to independent measurable properties. Quite often they are highly interlinked. E.g. changing the topology using an abrasive process is associated with a change of the surface chemistry. This leaves it hard to determine if the topology has an influence on bonding strength. However, within LuFo Azimut [5] a number of parameters such as pressure, roughness, surface tension of adhesive, resin layer thickness and others have been investigated and their influence determined. In order to enlarge the picture of parameter influences a wider range of parameters has been subjected to investigation within the project LuFo Schach [2] which shall be discussed subsequently in section 5.

Besides the mastering of the bonding process the qualification and awareness training of the bonding personnel is absolutely key. Although such measures will not be discussed here it is essential to mention that process safety cannot be guaranteed without proper trained staff.

3. Description of test methods – Double cantilever beam test and LUMifrac adhesion analyser

In the following sections the used test methods will be introduced. The Double Cantilever Beam (DCB) test is serving as the reference test, while the LUMifrac adhesion analyser is a relatively new testing device which is not standardised yet at Airbus to determine the adhesion strength.

3.1 Double cantilever beam test

The Double Cantilever Beam tests (DCB) were performed according an internal Airbus test standard, which based on DIN EN 6033 [6]. Two strips of CFRP (25x300mm) with a unidirectional fibre orientation, are bonded together by an adhesive including an initial crack on one edge. This crack is realized by a piece of release foil. The clamps of the test-machine were mounted to the free cantilever beams with a specified distance to the crack position. The pre-cracked specimen, is loaded continuously by opening forces until a defined propagated crack length has been achieved (see Figure 3-1).

Figure 3-1: DCB sample while crack propagation

During the crack propagation, the loads and crosshead displacement of the test machine will be continuously recorded. The bonded joint fracture energy GIc is calculated from the propagated crack length and the applied energy determined from the load vs. crosshead displacement diagram (see Figure 3-2). Additional the failure mode has to be determined. In principal, the failure mode can differ between adhesion failure (AF), cohesive failure (CF) and / or delamination (DF).

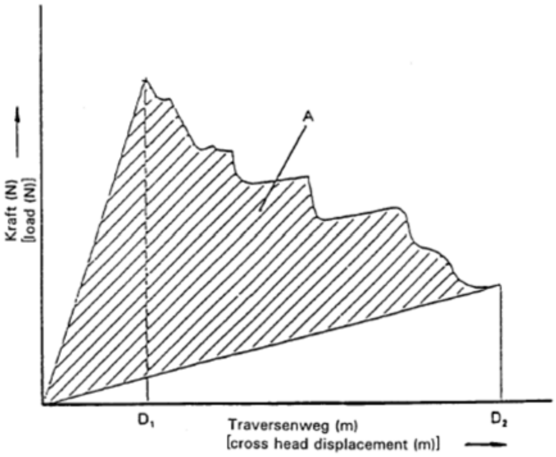


Figure 3-2: Load-crosshead displacement diagram and calculation of the GIc value (area A) [6]

3.2 LUMifrac adhesion analyser

The LUMifrac adhesion test complies with the headpull test according to DIN EN ISO 4624. The specimen has dimensions of approx. 25 mm x 25 mm with a thickness of 5 mm. The thickness must be kept constant within a test series to avoid side effects from specimen bending. Onto the specimen surface an aluminium adaptor with a diameter of 10 mm is bonded. The adaptor is attached to a copper weight. The adhesive is applied on the adaptor using a pipette. Before bonding the bush is placed on the substrate. For bonding the weight is inserted in the bush and gently squeezed down. The surface of the adaptor is usually laser or Phosphoric Sulfur Anodising (PSA) treated to ensure failure on the CFRP side.

For testing the specimen is inserted into a sensor casing. The sensor casing is located in a rotor. During test the rotational speed of the rotor is increased up to the rupture point of the bondline. With the bondline rupture the weight is hitting the sensor that triggers the reading of the rotational speed. With actual rotational speed the centrifugal force and the bonding strength, respectively, can be calculated. The principal sketch is given in Figure 3-3.

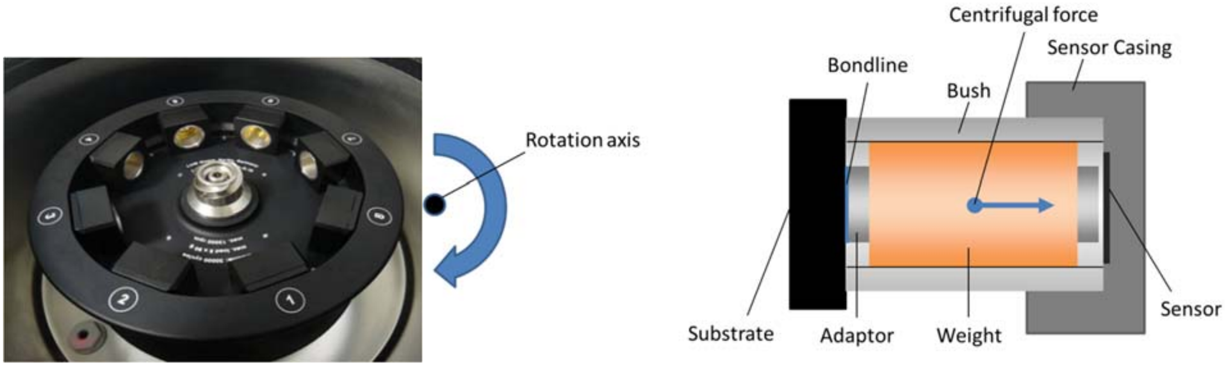


Figure 3-3: Schematics of the LUMifrac test method and actual rotor in centrifuge

Regular head pull tests are prone to misalignments during bonding. This can lead to premature failure and high scatter. The advantage of this test method is that misalignments are avoided once the bush sits fully aligned on the surface. Furthermore, material consumption is very low and a high number of specimens can be manufactured at once and tested within hours. In theory up to eight specimens can be tested during one test run. At higher speeds single part testing is preferred to avoid chain triggering effects.

4. Determining of bonding strength

4.1 Materials used

For the experimental studies in sections 4 and 5 the following materials have been used:

- CFRP parent material: Hexcel Prepreg 8552/IM7
- Auxiliary materials → results surface properties:
    - Peel Ply: Fibre Precision Group Super Release Blue (SRB) → siloxane residues
    - Or release foil: Wrightlon WL 5200 → fluorine residues
- Film adhesive: Henkel EA9695NW.035
- Paste adhesive: “MoJo Mix”; Mixture of Henkel EA9395/EA9396 (80:20)

The paste adhesive served as a coupling adhesive to bond the LUMifrac adaptor onto the film adhesive.

4.2 Sensitivity benchmark of testing methods to determine weak bonds

For common manufacturing of Carbon Fibre Reinforced Plastic (CFRP) parts different types of auxiliary materials can be used for demoulding. Whatever materials were used (liquid release agents, release foils, peel ply), all of them leave residues on the surface and / or a non-polar surface. An additional surface pre-treatment is recommended. In this study, an atmospheric pressure plasma (APP) treatment was chosen to realize reliable and reproducible surface conditions. Therefore, the CFRP surfaces were treated with a various nozzle distance to realize a variation of plasma intensity over the adherents (Figure 4-1). The other plasma parameters, e.g. power, velocity, line spacing etc. were fixed.

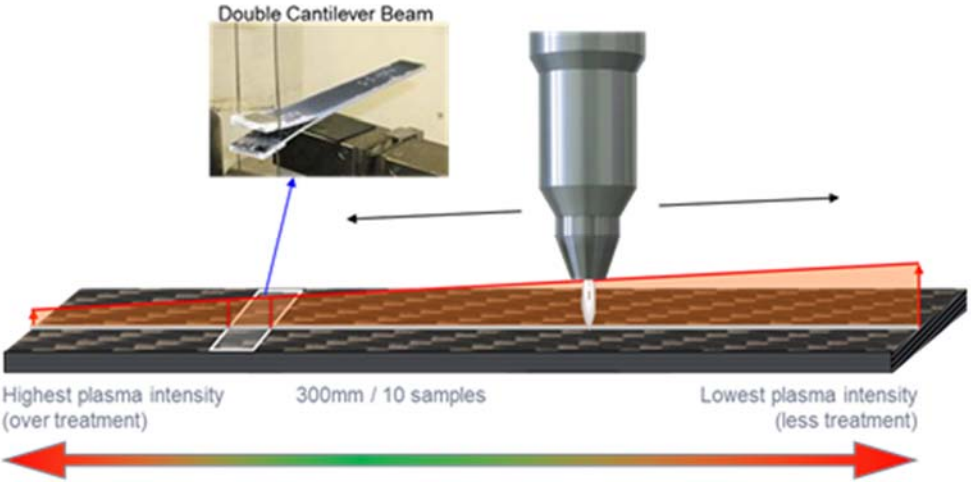


Figure 4-1: APP treatment with various plasma intensity, adjusted by various nozzle distance

To identify the influence of the APP parameters a characterisation method is necessary, which is sensitive enough to note insufficient treatment reliability. Therefore, a siloxane based peel ply (SRB) was used, which is usually not suitable for adhesive bonding, but would cause an adhesion failure without any pre-treatment and after APP treatment a cohesive failure. This allows to determine the process limits for plasma treatment, which are valid for suitable peel ply too [9]. Different mechanical tests were chosen i.e. single lap shear, floating roller peel and double cantilever beam test to characterize the ability detecting weak bonds respective determine the process limit for plasma treatment.

Figure 4-2 shows the comparison of the three different test standards with different loading modes. The abscissa represents the nozzle distance of the plasma jet to the CFRP surface, correspondingly the intensity of plasma increases in the opposite direction. At the ordinate the specific strength is plotted, related to the optimal treatment with maximal strength. The single lap shear [10] samples do not initiate any insufficient treatment. The shear strength is always in the same range, only influenced by the failure mode. High values of the deviation are caused by cohesive failure (CF), lower values by a delamination failure (DF) of one CFRP adherent. No adhesion failure (AF) can be detected by shear loads. Otherwise the floating roller peel test [11] indicates a decrease of the peel strength with lower plasma intensity. Additionally, the failure mode transferred from CF to AF continuously. In order to use a thin (0,5mm) aluminium sheet as peel plate the maximal stress did not occur at the analysed CFRP adherent, assumed for worse weak bond indication. Because the most sensitive way in this study to detect weak treated areas was the double cantilever beam test (DCB) [6]. Again, the failure mode corresponds with the energy release rate (GIc). But insufficient adhesion can be detected very early. Summarised, for detecting any defects in surface treatment for adhesive bonding, a peel load should be preferred to a shear load.

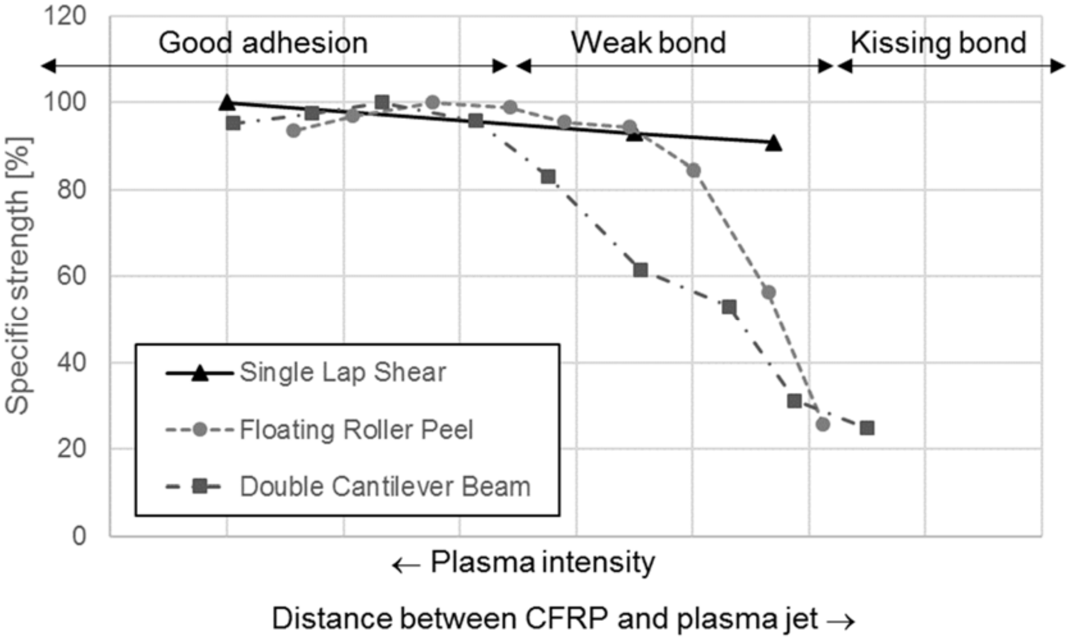


Figure 4-2: Comparison of different mechanical tests concerning sensitivity to weak bonds

4.3 Comparative study of DCB vs. LUMifrac

Now the most sensitive method to detect insufficient adhesion is compared to the LUMifrac tensile analyser. Therefore samples were prepared for DCB and LUMifrac tensile tests. Again, different intensities of plasma were used for CFRP treatment to provide different levels of adhesion. For DCB and LUMifrac the same intensities of plasma, type of adhesive and way of curing was used.

Regarding the DCB, both the GIc value and the failure modes indicate the different states of surface treatment very well (Figure 4-3). Good adhesion results with a high GIc value in combination with cohesive failure (CF). On the other hand, bad adhesion is indicated by neat adhesion failure (AF) and a very low GIc value but not zero. Last joints are defined as a “kissing bond” here and indicate interfacial defects without spontaneous separation of the interface. “Kissing bonds” are not detectable be common NDI methods i.e. ultrasonic inspection. Additionally, weak bonds are detectable by a mixture of AF and CF between good and bad adhesion. In case of an over-treatment a partial thermal degradation can occur followed by a decreased strength. For a potential pre-treatment process the limits can be specified between plasma intensity 2 and 4 (Figure 4-3).

Plasma intensity	1 highest	2	3	4	5	6	7	8	9	10 lowest
G1c value [J/m^2]	704	882	927	959	1057	956	596	320	209	168
Status	Over treatment	← Process limit	Good adhesion	Process → limit	Weak bond	Weak bond	Weak bond	Weak bond	Kissing Bond	Kissing bond
Failure mode:	AF / CF	CF	CF	CF	CF / AF	CF / AF	AF / CF	AF / CF	AF	AF

Figure 4-3: DCB results and failure modes with different APP intensities

Regarding the tensile test results obtained by the LUMifrac approach (Figure 4-4), a different behaviour can be observed. The deviation of the tensile strength concerning the various states of pre-treatment is not as clear as with DCB results. For LUMifrac six samples of each condition were prepared and tested. Only one exemplary pair of adherents are shown in Figure 4-4. The lowest strength, caused by insufficient treatment, is only 33% reduced compared to the maximum. For DCB the reduction is in the range of 85%. A higher spreading allows a better graduation between the different states. Regarding the failure mode, the differentiation between the states of treatment is possible but more difficult than with DCB. Neat adhesion failures are clearly and reliably detectable. Cohesive failure modes in good bonds quite often occur in combination with adhesion or delamination failure (DF). For the quality assessment of a bonded joint cohesive failures in the laminate are treated equally to cohesive failures in the adhesive. Both modes are acceptable.

Plasma intensity	1 highest	2	3	4	5	6	7	8	9	10 lowest
Tensile strength [MPa]	30,1	27,0	32,7	32,5	32,5	32,7	29,2	27,7	22,1	21,8
Status	Over treatment	← Process limit	Good adhesion	Process → limit	Weak bond	Weak bond	Weak bond	Weak bond	Kissing Bond	Kissing bond
Failure mode:	AF / CF	CF / DF	CF / DF	CF / DF	CF / AF	AF / CF / DF	AF / DF / CF	AF / CF	AF	AF
CFRP										
Adaptor (alu stamp)										

Figure 4-4: LUMifrac results and failure modes with different APP intensities

For the subsequent studies the LUMifrac test was used to cover the big number of specimens at reasonable costs. Furthermore, the test allows single specimen manufacturing with exact controlled parameters in limited spaces such as a glove box.

5. Identification of significant bonding parameters

The described experimental setup is taking only bonding process related parameters into account. Contaminations of any kind are not considered. The process is derived from a bonding initial design process. CFRP repair scenarios would incurred a much larger parameter set coming from in-service contaminations and the preparation of the repair area with potential pollutions. The subsequent discussed experiments are part of a screening DoE. The goal was to down select the significant parameters as a first step. Investigated parameter range

Within the performed process 14 controllable parameters were defined for investigation, listed in Table 5-1. They are composed of surface, processing, as well as environmental parameters. The used materials were Hexcel 8552/IM7 outfitted with a release film surface (Wrightlon WL5200). As adhesive the so called MoJo-Mix briefly described in section 4 was used.

Table 5-1: Overview of controlled process parameters parameters and conditions

Name	**Unit**	**Lower Spec Limit (LSL)**	**Upper Spec Limit (USL)**
CFRP part temperature	°C	18	27
Open time of adhesive post application	min	5	30
Moisture content of the adherend	%	0	0,3
Humidity @ open time	%	10	70
Time from bonding to mating	h	0,5	24
Curing temperature of adherend	°C	175	195
Distance of plasma nozzle from surface	mm	10	16
Speed of plasma nozzle	mm/s	3	6
Line spacing of plasma nozzle	mm	2,5	6
Cure time (adhesive)	min	60	120
Cure temperature (adhesive)	°C	66	100
Heating gradient (adhesive)	°C/min	0,5	2
Post h/w conditioning @ 70°C / 85% RH	h	0	1000
Thermal cycling	n/a	0	400

In order to keep the number of specimens at a reasonable level the Design of Experiment methodology was applied. A total number of specimens of 197 was manufactured. All tests were performed at room temperature.

5.1 Specimen manufacturing

The laminates featured a quasi-isotropic stacking sequence with a total thickness of 4 mm. The bondable surface was created with a release foil, in particular Wrightlon WL5200. The chosen release foil is very easy removable. A premature departure of the foil during handling could expose the surface to potential contaminations. In order to prevent that special precautions have been taken. The release foils were applied as discs and covered with peel ply during manufacturing. The peel ply as well as the release foil were kept in place during handling and conditioning. A sample is depicted in Figure 5-1.

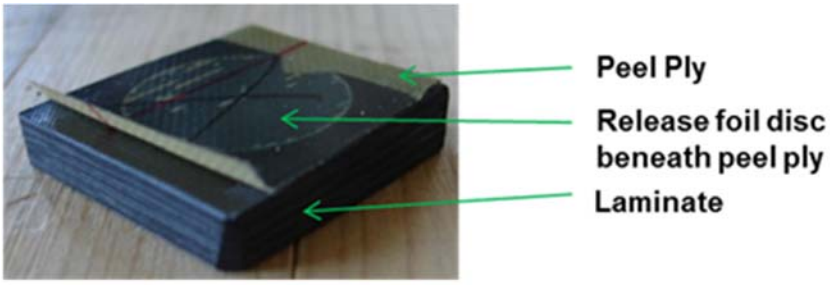


Figure 5-1: Substrate for LUMifrac test

Once the target condition had been reached the release foil as well as the peel ply were removed.

The laminates were manufactured at different curing conditions to alter the degree of cure. After cure some laminates were exposed to conditioning. The target saturations were achieved using different salt climates over time. Subsequently, after release material removal, the plasma treatment with the individual parameters, such as distance of the plasma nozzle, line spacing and speed were applied. Before bonding the laminate samples were brought up to target temperature within a glove box. There, the surrounding humidity during bonding was controlled as well. The adhesive was applied on the LUMifrac adapter and left there for exposure to humidity over a specified time. After assembly of the adapter onto the laminate the specimens were cured according to the specified cure schedule. There the parameter temperature, time, and the heat up gradient were controlled. After cure a set of specimens was exposed to conditioning in the climate chamber and temperature cycling. With the assembly of the copper weight guided in the bush the specimen was ready for testing. The principle process flow is depicted in Figure 5-2.

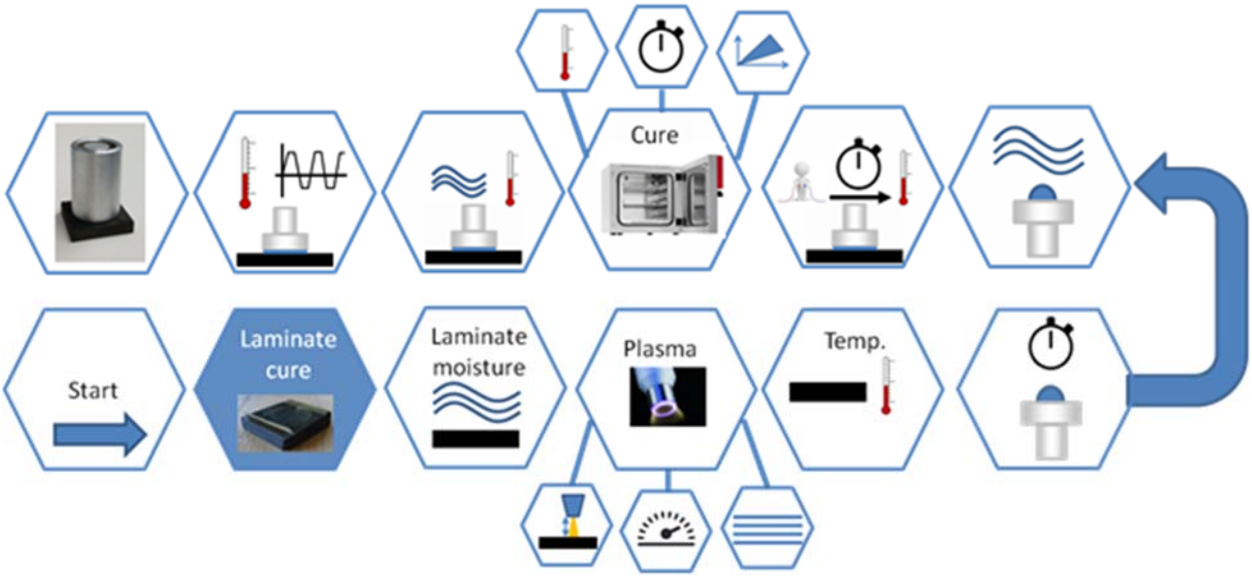


Figure 5-2: Process flow chart

5.2 Evaluation of test results

The specimens were tested in the centrifuge which delivered the strength of the bondline. The obtained results were evaluated using the statistical software Minitab 16. In Figure 5-3 the parameter main effects are shown. The inclination of the graphs give the indications of the significance. The higher the inclination the higher the significance. As an example, the closer the nozzle to the surface the higher was the resulting bonding strength. The heating gradient as well as the cure time have no big influence. The suggested linear behaviour of all parameters is due to the experimental set-up. Non linear effects will become apparent once higher resolution experiments are performed like response surface modeling.

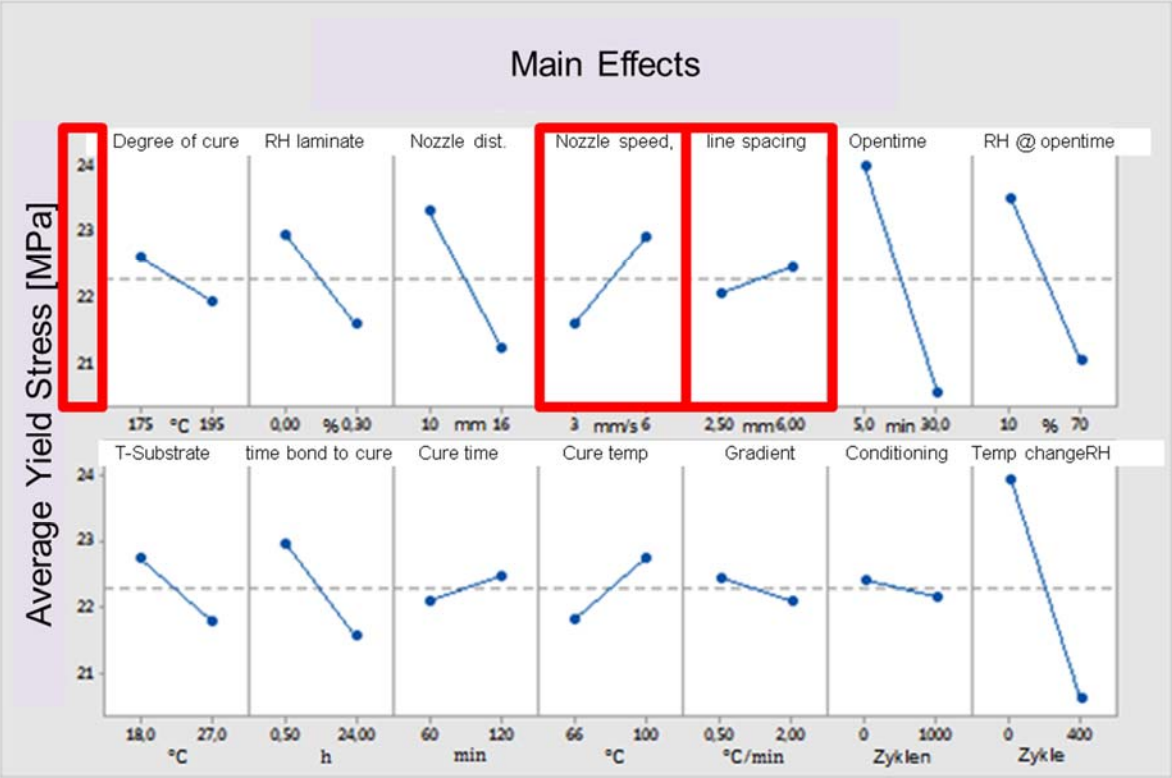


Figure 5-3: Main effects evaluation chart

While examining the main effects two points become apparent. First the spread of just 3 MPa in which the effects are assessed. Second, the main effects of the plasma parameters are in contradiction with previous experiences. Usually, a slower speed (up to a certain point) produces a higher bonding strength. The same applies for the line spacing of the plasma treatment. This can be, at least partially, explained by examining the model fit. Out of the ANOVA analysis an RSq with 47,6% is quite low indicating a high degree of variation.

To evaluate the bondline performance the bonding strength is of the utmost important. However, the resulting fracture modes have to be considered at the same level. Figure 5-4 shows an example of two samples with very different fracture modes. Although, the fracture modes are obviously different the resulting bonding strength of this example is almost the same. Specimen PP03-01 failed at 20,4 MPa whereas specimen PP01-05 failed at 20,2 MPa.

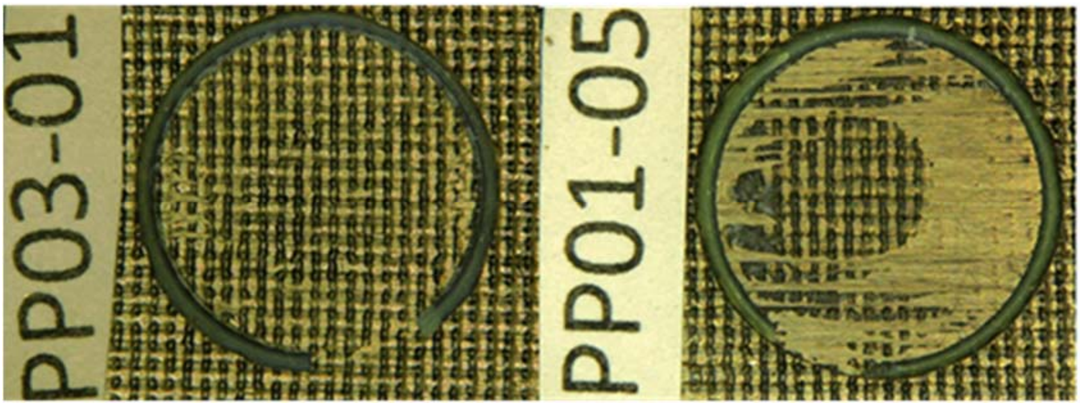


Figure 5-4: Fracture modes (left: low plasma treatment; right: amin blushing of adhesive)

The almost full adhesion failure of sample PP03-01 can be traced back to insufficient plasma treatment whereas the partial adhesion failure of sample PP01-05 can be explained with amin blushing due to prolonged exposure of the adhesive to moisture and temperature.

6. Introducing complex bonding strength

The results indicate the difficulty pinning down the significant process parameters with a high degree of confidence based on failure load data. The observed fracture modes in contrast do show significant differences. Subsequently, it will be discussed how bonding stresses and fracture modes can be combined into a so called complex bonding strength (CBS) value. The idea is to decrease the strength value in the case of adhesion failure and to increase the value in the case of cohesive failure.

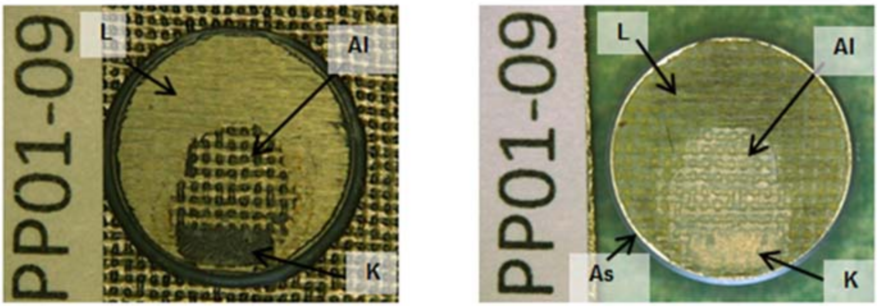
The first step is to perform image acquisition, followed by the quantification of fracture modes. These data will be merged with the bonding strength data. Finally, the statistics will be revisited, refer to Figure 6-1.

Figure 6-1: Flow chart for Complex Bonding Strength

6.1 Image acquisition and quantification of fracture modes

For image acquisition different options were explored such as an Alicona infinite Focus G4, a Keyence Laser scanning microscope (VK-X200), and a Keyence digital microscope VHX700. A trade-off showed that the Keyence VHX700 delivered the best compromise w.r.t. quality and time to image. For the VHX 700 the parameters magnification, lighting, corner threshold, as well as Gamma settings were fixed for all specimens.

In terms of fracture modes it is important to analyse the CFRP as well as the adaptor surface. Figure 6-2 shows an example of a failed specimen with the associated fracture modes.



L-laminate failure (cohesive)

K-adhesive failure (cohesive)

AI-adhesion failure CFRP

As-adhesion failure Alu

Figure 6-2: Classification of fracture modes (left: CFRP part; right: adaptor)

For the quantification of the fracture modes the software Photoshop was used. It is not as sophisticated as advanced image processing methods as discussed later on, but for proof of concept it was deemed sufficient. As a first step the fracture area is truncated. Subsequently, the image has been split into the fracture modes described before. In Figure 6-3 an example is shown. The total number of pixels is 14931 = 100 % = A_{tot}. The laminate fraction is simply calculated as follows:

$$L = A_{tot} - K - As - AI \qquad [1]$$

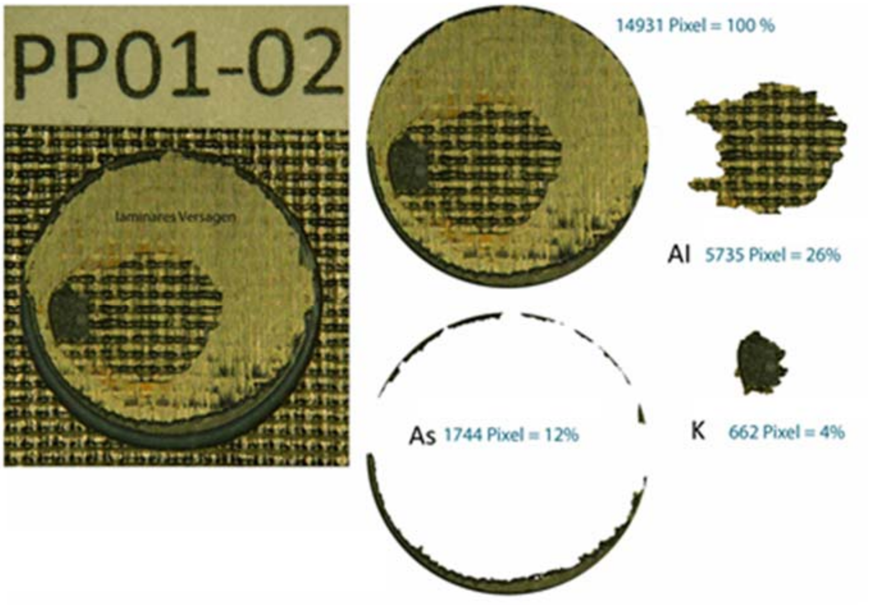


Figure 6-3: Clustering of fracture modes

These were applied to all 197 specimens.

6.2 Evaluation of complex bonding strength (CBS) data

Before further processing of the data into the complex strength value a transfer function has to be derived. In section 4 a sensitivity comparison was performed between DCB and headpull test method (LUMifrac). Close examination of the DCB test results produced a spread of data between good adhesion (927 J/m²) and bad adhesion (168 J/m²). That translates into a spread factor of approx. 5,5 between good vs. bad adhesion. In contrast, the headpull test method produces a spread of 1,6 on the same material. The goal is to find a transfer function that enlarges the spread of the headpull data to at least 5,5 or even higher.

A set of emperical transfer functions have been explored w.r.t. their ability to increase the spread as observed for DCB testing. The most promising transfer function for the complex bonding strength σk is shown in the following equation with a spread factor of approx. 8:

$$\sigma_k = 0{,}8 * \frac{\sigma}{(1 + \%(As + Al))} + 1{,}3 * (\sigma * (\%K + \%L)) \tag{2}$$

An evaluation example is shown in Figure 6-4. The almost fully adhesion failed specimen with an initial strength of 20,4 MPa has been reduced to a CBS value of 9,8 (MPa). The mixed mode sample with an initial strength of 23,8 MPa has been increased to a CBS of 27,6 (MPa).

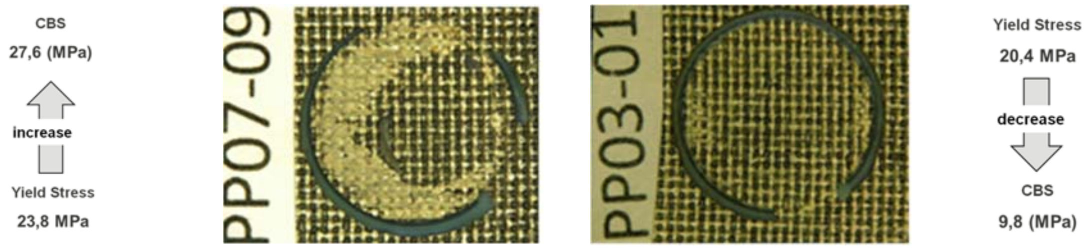


Figure 6-4: Example of CBS application

The approach was taken and the DoE was revisited. In Figure 6-5 the two main effect diagrams are shown for the regular analysis (blue graphs) as well as for the CBS analysis in red graphs.

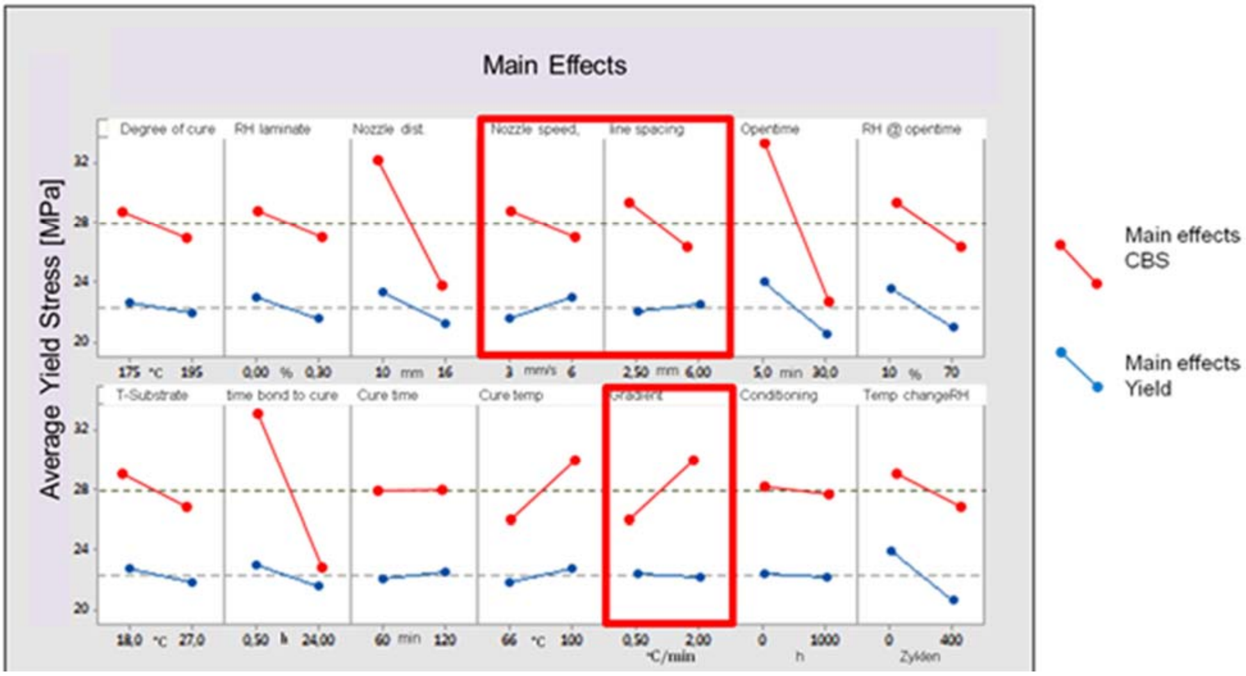


Figure 6-5: Comparison of main effects (regular vs. CBS)

It becomes clear that the spread in the main effect analysis has been improved from 3 MPa to more than 12 MPa. Furthermore, the effects of the plasma treatment (speed and line spacing) have been reversed. In addition parameters like plasma nozzle distance or the time between assembly and cure are much clearer and significant now. The parameter “open time” the time the adhesive is exposed to atmosphere is indicating a severe drop in strength. As mentioned before for Fig. 5-4 the reason is to find in the amin blushing of the adhesive. This effect, associated with adhesion failure, was also observed well before 30 min exposure time in other experimental set-ups. This effect is not new and was already described in a Hysol study [7] in the 1980s. For bonding processes involving open atmosphere exposure the use of this material needs to be carefully considered.

However, this shows that the incorporation of fracture mode data contributes significantly to determine the significance of bonding process parameters. The associated model fit with an RSq of 86,5% has improved significantly leading to an increased level of confidence to select the right parameters for further investigation. In this study the feasiblity of the approach has been shown.

6.3 Automated fracture mode quantification

While the use of the centrifugal headpull test promises significant cost savings in specimens preparation and test, the relatively high evaluation effort relating to fracture mode analysis may compromise any advantage gained. Nevertheless, the fracture mode analysis could and should be applied to all kinds of test methodologies to improve their sensitivity. In particular for the LUMifrac test a tool has been developed to automatically quantify the various fracture modes observed in a test series. Within here it will only superficially described to indicate the feasibility of a remedy. The focus on the development was on performing fracture mode analysis on microscopic level rather than the level showed before. Figure 6-6 gives an example out of a plasma trial study performed in LuFo Schach that produced a mixed mode failure on microscopic level (200 fold magnification) very hard to evaluate with Photoshop, as practised before.

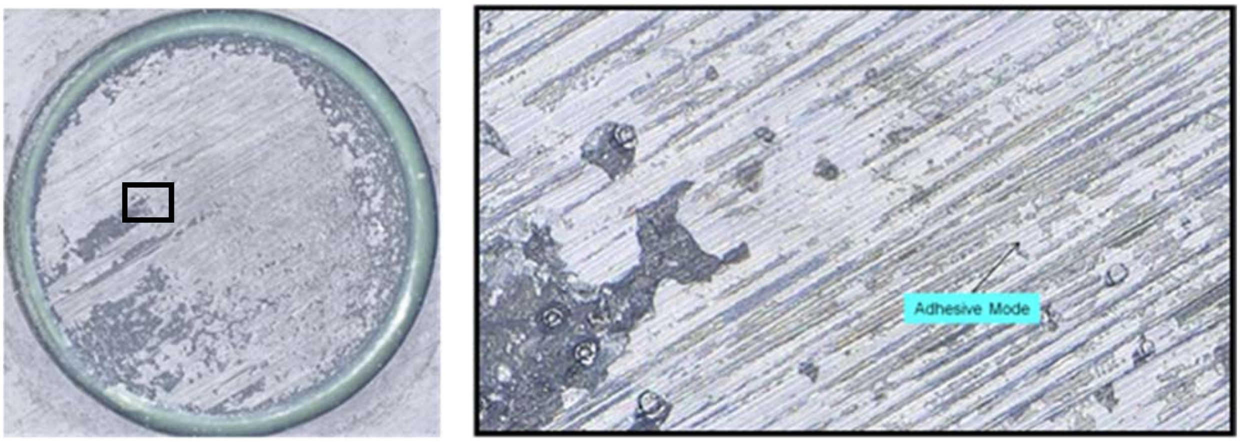


Figure 6-6: Fracture image and fracture modes (200 magnification)

For the automated evaluation of the fracture modes a Matlab code has been developed. The resulting fracture mode clustering is shown in Figure 6.7.

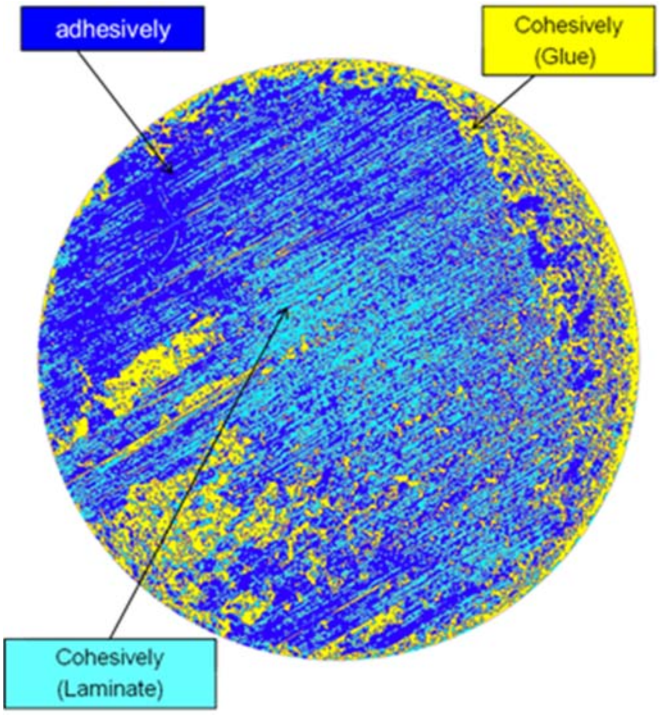


Figure 6-7: Example of result of automated fracture mode classification [8]

LUMifrac's head pull test method is not the most sensitive method to determine the bonding strength. However, specimen cost is fairly low and the produced fracture images are comparable or even better to the DCB test. In combination with the automated fracture mode analysis and the application of the CBS the number of samples can be increased to safely identify critical parameters of the bonding process.

7. Summary

Process safety is key for structural adhesive bonding. It is important to use an appropriate mechanical test for detecting insufficient adhesion. This paper describes a comparison of different tests, identifies DCB as the most sensitive common method and introduces a new method to characterise the strength of bonded joints. Furthermore, it sketches the way to assess the criticality of process parameters associated with the bonding process. As an example the results of a 14 parameter DoE are discussed. In addition a new method was introduced to assess bondline performance by means of bonding strength as well as a quantified fracture mode analysis. Both properties are combined into a complex bonding strength (CBS) value that allows a better differentiation of the main effects of bonding parameters. Finally an outlook was given on the potential of automated fracture mode analysis to move from a subjective visual assessment of fractured surfaces towards a data driven quantitative assessment.

With sound process knowledge the process capability level can be increased and hence the level of confidence. This is one key aspect to further enable bonding technology with its weight and cost saving potential (if designed properly) in new disruptive structural concepts for new fighter as well as transport aircrafts.

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9. References

[1] Advisory Circular AC20-107B; http://www.faa.gov/documentLibrary/media/Advisory_Circular/AC20-107B.pdf

[2] LuFo-Schach, Aeronautics Science Project IV under the framework of the German Ministry of Economics and Energy

[3] Bossi, R, Housen, K., Walters, C. „Laser Bond Inspection Device for Composites: Has The Holy Grail Been Found?“ Boeing Phantom Works, Seattle, WA CWA, Dublin, OH (2004)

[4] Huke Ph., Meer T., Stoessel R. „Qualitätssichere Klebverbindungen mittels prozessintegrierter ZfP“; DGZfP; 2013

[5] LuFo-Azimut, Aeronautics Science Project IV under the framework of the German Ministry of Economics and Energy

[6] DIN EN 6033; Carbon fibre reinforced plastics – test method – Determination of interlaminar fracture toughness energy – Mode I – Gic

[7] Hysol, Open Time Study EA9394 & EA9395, memo, 1987

[8] Macha, Martin, Development of an automated method to quantify fracture modes, master thesis Airbus Desfence and Space, 2017

[9] Meer T. “AP-Plasma Vorbehandlung für das strukturelle Kleben von CFK“; DLRK 2014; 340067

[10] DIN EN 1465 – Adhesives – Determination of tensile lap-shear strength of bonded assemblies

[11] DIN EN 2243-2 – Adhesives – determination of peel resistance of high-strength adhesive bonds – floating-roller method