Fatigue of Composite Scarf Joints in Wind Energy Rotor Blades and in Spar Beams for Light Aircraft

Christoph W. Kensche
Hexion Specialty Chemicals GmbH
Am Ostkai 21/22, D-70327 Stuttgart, Germany
christoph.kensche@hexion.com

Arno van Wingerde
Fraunhofer Institut für Windenergie und Energiesystemtechnik IWES
Am Seedeich 45, D-27572 Bremerhaven, Germany
vanwingerde@iwes.fraunhofer.de

Denja Lekou
Centre for Renewable Energy Sources
19th km Marathonos Ave., 19009 Pikermi, Greece
dlekou@cres.gr

Presented at the XXIX OSTIV Congress, Luesse-Berlin, Germany, 6 August – 13 August 2008

Abstract

The paper presents results of fatigue tests on scarf joints in Glass Fiber Reinforced Plastic (GFRP)-components of wind energy rotor blades and in Carbon Fiber Reinforced Plastic (CFRP)-spar beams for light aircraft wings.

The GFRP-component tests were carried out in the Fifth-framework EU Project "OptiMat Blades" which will be introduced in this paper.[1] The tests were aimed at repair procedures for load carrying parts of rotor blades. If repairs are not accepted as a standard procedure, even localized deficiencies may require the destruction of the whole blade, which is crucial for larger blades. The typical repair procedure is surveyed step by step and adapted for the special needs for application on rotor blades. Practical stress calculation procedures are selected from a literature review and proposed for the evaluation of the restored strength during the repair design. Applications are experimentally evaluated through tensile testing both under static and fatigue loading of repaired coupons. Test results also are used to compare the repair methods applied. Among the evaluated techniques, the most promising method was the scarf repair with a slope of 1:50. Test data reveal that a strength restoration of over 80% can be achieved.

The CFRP-spar beams were tested within a program on the applicability of analytical and experimental certification procedures on the service life of light aircraft structures.[2] The 2 m long structures were loaded transversely at one end. In the load introduction part of the other end, the thickness of the strengthened spar caps was reduced with a splice ratio of 1:40. By means of thermography and ultrasonic inspections, applied during one-step fatigue tests, an increasing delamination was observed in the splice area. Therefore the splice ratio of subsequent test beams was redesigned to 1:100, which performed well during the fatigue tests. The structure of the spar beams, the fatigue tests and the NDT-inspections, as well as the stiffness behavior are discussed in this paper.

Scarf joints in GFRP

The OptiMat Blades project

In the 5th EU Framework project "OptiMat Blades" (ENK6-CT2001-00552[3-5], research was carried out by 18 partners in 10 countries. This may have been the first time that a material has been studied to this extend within a consistent research programme. Over 3000 individual tests were carried out on epoxy GFRP coupons, with numerous technical reports being issued to analyse and understand this data, which are available for download from the OptiMat Blades website for public review (http://www.wmc.eu/optimatblades.php). Additionally, all data points have been captured within the comprehensive database OptiDAT, which is available for download in MS Excel format from the same website.

For the design recommendations to be usable and accepted, it was essential that the OptiMat Blades research findings were presented in a logical way, so that they can be reviewed by interested parties including manufacturers.

The major results of the project are:

- Recommendations on testing and characterisation of materials
- Validated composite mechanics and FEM guidelines and recommendations
- Suitable repair techniques for FPR rotor blades
- Validated micro mechanics models
- New WISPER standard load spectrum
- Validated engineering model for residual strength prediction
- OptiDAT data base including analysis software
- Design recommendations for next generation of rotor blades

In total 39 design recommendations were formulated. These design recommendations will be considered for inclusion in the next version of the DNV/GL guidelines.

Repair methods within OptiMat Blades

Within OptiMat Blades, repair techniques have been reviewed and adapted to enable their suitability in applications for wind turbine blades. The objective of these investigations was the development of repair methodologies applicable to the load carrying laminates of wind turbine blade structures, so as to avoid possible rejection of products both during production and service life. Currently there are no recommendations available for repairing structural parts of blades or for assessing the load-carrying capability of damaged areas. Thus, blades which are damaged or have production deficiencies in their laminated structural parts are sometimes destroyed, even if the damage or deficiencies are local. As the blades become larger, more material is wasted due to such localized deficiencies.

To this end, the typical repair procedure, namely the damage identification on the structural part, the decision to repair, the removal of the damaged area, the reparation and the repair quality inspection[6] was surveyed step by step and adapted to the application in wind turbine blades. The location, type and importance of the damaged zone was identified and semi-empirical stress calculation procedures were proposed from literature for a preliminary repair design[6,7]. A minimum target value for the repair efficiency was stated with respect to both strength and stiffness. Repair techniques were surveyed and evaluated on aspects like complexity, suitability to highly stressed, load carrying laminated parts and, if possible, application on site. The most promising techniques were selected and applied to the repair of flat specimens. They were applied according to the principle “the least layer first” and “tapering”, see Fig. 1.

Within an extensive testing campaign, these repaired specimens were tested in uniaxial tension. The results, both strength and exhibited stiffness, were compared to those of flawless specimens, which were tested to form the necessary baseline. Static test data analysis has shown that the most promising of the selected repair techniques is the scarf repair with a slope of at least 1:50, which yielded a strength restoration of over 80%. Verification of the fatigue behaviour was carried out for the selected repair method with similar results.

The basis of the repair design follows logical repair criteria. Some of repair criteria that were addressed during the analysis, at least from a theoretical point of view, were: static strength and stability, the fatigue behaviour and stiffness. For the static strength, a strength restoration of at least 80% was set as target, while the fatigue behaviour was assessed through fatigue testing of the repaired coupons. The stiffness requirements were assessed through monitoring exhibited strain during static testing. Due to geometrical constraints posed on the testing of coupons, the damage was modelled as a through-the-width of the specimen delamination by a channel of 10 mm width. The proportion of the laminate that was considered to be "damaged" was either $^1/_3$ or $^2/_3$ of the total thickness.

For the scarf repair, the "damaged" region was removed, leaving a straight channel. The straight channel, then, was tapered to a predetermined slope and over this region a patch with tapered (or stepped ends) was bonded to the parent laminate. This repair configuration has the benefit of a nearly uniform shear stress distribution in the adhesive layer. In addition, due to the lack of eccentricity in the load, the patch peel stresses are low. Therefore, scarf repairs are considered highly efficient and particularly suited to external repairs of thick laminates (such as those in wind turbine blade load carrying parts) because of the unlimited thickness of material that can be joined and the smooth surface contour that can be produced. Single-sided scarf patches also can be employed to repair part-through or full-penetration damage.

Scarf repairs are usually based on patches with a ply configuration similar to the parent material and patches are generally co-cured to avoid the severe fit-up problems encountered with pro-cured patches. To cure the patch and adhesive, a vacuum bag - heater blanket procedure can be used to apply pressure. The process used during the manufacturing of the coupons in the course of the OptiMat Blades project was selected by each participating manufacturer, in this case, LM Glasfiber A/S from Denmark and Gamesa Eolica SA from Spain.

Experimental program

An extensive experimental campaign was conducted to find the applicability of the repair methods selected. To this end, more than 100 static tension tests and 60 fatigue tests were carried out on Glass/Epoxy coupons. The coupon dimensions were selected so the scarf repair could be applied. This resulted in fairly long coupons as shown in Fig. 2, where all dimensions are given in mm. Composite material coupons in final dimensions, including the tabs, were delivered by either Gamesa Eolica SA or LM Glasfiber A/S and were tested either at Centre for Renewable Energy Sources (CRES) or Knowledge Centre WMC, according to the test programme. Plate lamination sequence was $[(\pm45/0)_4/\pm45]$, where the 0º reinforcement coincides with the longitudinal axis of the coupon. Strain measurement was performed on a back-to-back configuration by either strain gauges or clip gauges to monitor both stiffness and eventually exhibited bending strains.

Section dimensions were measured at a minimum of five locations along the gauge length for all specimens, due to their longer-than-standard length. It should be noted that a large thickness variation was observed on the repaired coupons. As the repaired coupons were longer than the standard test coupons used in the research project, tests on coupons of the reference material (without repair) with the same geometry (and testing conditions) were conducted to attain comparable results and eliminate any geometrical effect.

To investigate the effect of the repair depth, two batches of coupons were tested for each repair method selected. The first batch was repaired at $^1/_3$ of the specimen thickness and the second was repaired at $^2/_3$. For the determination of the optimal scarf slope, coupons with repair slopes of 1:25, 1:40, 1:50, 1:75 and 1:100 were tested. Moreover, to examine the effect of the material form in the repair, repaired coupons with prepregs also were tested using the scarf repair with slopes 1:50 and 1:75. These results were compared with the respective ones using liquid resin as an alternative to the prepreg. Additionally, as an alternative to the pure scarf repair with slope 1:50, an additional layer was used as a cover of the repair laminate in the form of tape. It should be noted that for each repair variant, 5 to 6 coupons were tested. Carbon/Epoxy coupons with repair similar to the last one also were tested and compared to those without an additional layer in the report by the FAA[8]. Based on the results of the static tests, the scarf repair with a slope of 1:50 was selected for fatigue testing and both manufacturers delivered specimens. LM Glasfiber used liquid resin for the repair with no additional covering layers, while Gamesa Eolica used prepreg with an additional ±45° layer to cover the repair.

Static tests were carried out in a stroke controlled mode with a constant stroke rate of 4mm/min due to the specimen length. During testing, the applied load and exhibited strains were continuously recorded. Fatigue tests were conducted at load control mode at a stress ratio, R, equal to 0.1. The test frequency varied according to the findings of OptiMat Blades project[4], so that the temperature of the coupon under test did not exceed 35°C during the fatigue loading (except just prior to failure). Thus, the testing frequencies were in the range of 2-6 Hz.

Results

In Fig. 3, the effect of the slope of the scarf repair on the static strength of the coupons tested with a repair depth of $^2/_3$ of the total thickness is presented. Each bar in the figure represents the average value of the batch tested, while the minimum and the maximum strength values obtained for each batch are also shown. The failure stress of the coupons has been normalized to the average static strength of the reference coupons. Therefore, it can be seen that there seems to be a limiting slope of the scarf, above which the strength of the repaired laminate is theoretically restored. Tests on coupons with a scarf slope of 1:40 also were conducted (but not shown on the figure), with results similar to the 1:25 slope. Similar results also were obtained for the $^1/_3$ repair depth. Thus, for the presented case, the limit is between 1:40 and 1:50.

The theoretical justification behind this limit is that, when this limiting slope is exceeded, the shear stresses on the adhesive are lower than the shear strength of the adhesive and, thus, the repaired laminate does not fail in the adhesive under tension loading (but rather due to axial stresses on either the parent or the repair laminate). It should be noted, however, that the limiting slope depends on the properties of the adhesive and the parent laminate in the structure. Nevertheless, for all systems tested during the current research it was found that a slope of 1:50 suffices. Moreover, due to the variation in thickness observed for the repaired coupons, all results have been normalized by use of a nominal thickness.

The stiffness of the repaired specimens was found to be within 10% of the reference elasticity. The elasticity obtained is usually not reported for repaired coupons in the literature. Even the report of the FAA[8], which evaluates in detail the scarf repair on Carbon/Epoxy composite material, does not present strain response. Most of the studies concentrate on the strength obtained by the repair. However, in the case of repairing blades, stiffness also is of interest since for large blades, at least for the current state-of-the-art blades, the driver force during design is stiffness and not strength. Although the stiffness of the repaired coupons was found to be similar to the parent structure, the back-to-back strain readings showed that the stress-strain behaviour of the repaired patch was different from that of the parent material. This fact might imply a poor stress transfer from the parent to the repair laminate.

For the fatigue tests, scarf repairs with a slope of 1:50 were used based on the results of the static tests. Fatigue results for the first material alternative are presented in Fig. 4 for both repair depths studied. The experimental data show that the repair affects the slope of the S/N line, since at higher fatigue cycles both reference and repair coupons are quite close. Obviously the S/N curve for the repaired coupons lies lower than that of the reference since, during static experiments, the strength of the repaired coupons was on the order of 80% of the reference ones for this material combination. Moreover, the results for $^{2}/_{3}$ repair depth were inferior to that of the $^{1}/_{3}$ repair depth. However, the influence of the repair depth seems small and no hard conclusion can be drawn from these data only.

Experimental data from the fatigue tests of coupons from the second repair variant are shown in Fig. 5. For this case, the slope of the S/N curve seems also to be affected by the repair, but exactly opposite than for the former material, with the differences being larger for higher number of cycles. One repaired coupon sustained more than 7 million cycles without breaking and therefore was marked accordingly on the graph.

Fatigue behaviour of different scarf ratios in CFRP-spar beams

Motivation

The influence of different scarf joint ratios on the fatigue behaviour of UD-orientated CFRP in highly loaded spar beams was experimentally analysed during a project on aircraft structures. The project was the *Applicability of Analytical and Experimental Proof of Service Life*[2]. The study was supported by the German Ministry of Transport, Building and Urban Affairs (BMVBS). The participants were various research institutes and Universities as well as industries for sailplanes and light aircraft.

The aim of the study was to investigate the possibility of replacing extensive and time consuming service life tests on light aircraft structures by means of constant amplitude fatigue tests while monitoring damage development by various Non Destructive Testing (NDT)-inspection methods.

During preliminary tests, aimed at developing a suitable geometry of the research beams, a delamination in a scarf joint in the load introduction area of the CFRP spar caps was observed. This necessitated an improvement of the splice design to carry out the fatigue tests successfully. The details of the respective actions and observations on the fatigue behaviour of the scarf joints in the spar beams are discussed in the following sections.

Spar beam design

The spar beams were 2 m long slender box-shaped structures of 100 mm height and 40 mm width. A foam core, filling out the complete cross section area, supported the load carrying fibre compound against buckling. The spar caps were of HT-CFRP rovings and the CFRP shear webs of twill cloth with a ±45° lay-up. The beams were loaded transversely at one end and supported with two transverse force bearings at the other end. The spar caps had to be strengthened between the bearings to ensure that failure would occur at a cross section which was 300 mm apart from the maximum thickness of the spar caps. Thus, a tapering of the spar caps was necessary between this measurement cross section and the inner main bearing.

The initial geometry of the spar beam design is presented in Fig. 6. For better illustration, the area of the splice with a ratio of 1:40 is amplified. The photographs show the cross sections at the two ends of the scarf joint. The cross section area between the measurement section and the right end of the beam was constant.

Experiments

The spar beam with the geometry as described above was exposed to a constant amplitude fatigue test. The stress ratio was R = -0.55. This stress ratio applies also for the KoSMOS load spectra developed for light aircraft and sailplanes[9]. Therefore, possible damages from spectra tests are anticipated at maximum loads to develop similar to those in the one-step fatigue test. The fatigue tests for both load spectra and one-step fatigue tests were carried out displacement-controlled. The maximum compression strain in the upper spar cap was minus 0.5%. The location of the maximum strain was the measurement cross section which was outfitted with strain gauges at the spar cap and the shear webs. The testing frequency was 0.4 Hz. In Fig. 7 the spar beam is shown at maximum load in the test bench.

Various means for the detection of damage development were applied by NDT methods at DLR. Beside lockin-thermography and acoustic emission, also thermography and ultrasonic scanning means were used. Especially the thermography method was helpful by visualizing the damage development at the splice area during fatigue testing.

Results

The thermography images in Fig. 8 show a high temperature ‘hot spot’ at the end of the splice during the first cycles of the fatigue loading. After 800 cycles, the area of the spot has enlarged. At 8,900 load cycles, finally, the length of the hot spot was about 300 mm demonstrating impressively that a severe delamination has happened in the splice area. These observations were accompanied by a significant increase of the beam deflection at the loaded end of about 6.5 %. Note, the three pictures in Fig. 8 use different temperature scales. So, the development of the local temperature is actually larger than the colors in the pictures indicate.

The fatigue investigation of the spar beam was stopped after taking the last thermography image. Then, the spar was cut along the delamination zone to confirm the NDT measure by visible inspection. Figure 9 shows a piece of the spar beam with the longitudinal cut. The delamination line of the 1:40-splice is marked by the arrows. Also, in the foam core, a crack was initiated at the tip of the splice (left side of photo). The damage development was not detectable by the strain gauges located at the measurement cross section 50 mm left from the tip of the splice.

After these analyses, three new spar beams were fabricated with splice ratios of 1:100. The maximum applied compression strain in the upper spar cap was again -0.5 %. The first one was fatigued in a one-step test. It failed at the inner bearing after more than 65,000 load cycles. This cycle number was sufficiently high to compare the lifetime with those of the next two spar beams. These were exposed simultaneously to a service life test with the KoSMOS load spectra[9]. One life cycle of this standard represents 6,000 flight hours. Eighteen (18) life cycles were applied on the structures corresponding to 108,000 simulated flight hours. The investigation process, then, was stopped without any detected failure of these two beams.

Stiffness degradation and damage equivalent

The only significant degradation during the life of these three spar beams was observed by means of stiffness checks at certain time intervals. The degradation of the stiffness was evaluated by means of the global increase of deflection at the loaded ends. The results are presented in Fig. 10 for the beam with the constant amplitude test and in Fig. 11 for one of the two beams tested with KoSMOS.

The decrease of stiffness was about 2.5 % for the spar beam tested in constant amplitude and 2.0 % for the other two. For a CFRP-structure, this reduction is relative high. A possible cause may be a stiffness decrease of the shear webs made of twill cloth laminate with its high undulation. On the other hand, the fatigue loading applied (strain of 0.5 % in the spar caps leading to a strain of about 0.3 % in the ±45° fibres of the web) was unusually high for a primary CFRP-structure and little experience is available on that point.

The stiffness change may offer an important opportunity. One aim of the project was the comparison of the damage due to the one-step tested and the service-life tested CFRP-spar beams as representatives for similar constructions. Lifetime assessments applied could not lead to a satisfactory result since the lives of the spar beams tested with the KoSMOS load spectra were not yet finished. Posing the stiffness degradation as a reliable measure of the fatigue damage leads to the conclusion that for the beams tested here a lifetime of about 100,000 flight hours corresponds to about 35,000 load cycles in a constant amplitude fatigue test.

This result, which must be confirmed by further experimental and analytical investigation, gives hope that in future certification procedures for primary aircraft structures time consuming service life tests can be replaced by short constant amplitude fatigue tests.

Conclusions

Tests on flat repaired Glass/Epoxy coupons were conducted under tensile static as well as fatigue loading. Test results showed that the scarf repair with a slope of at least 1:50 provides a restored static strength of over 80% with adequate material use. The results of the tension-tension fatigue tests have been also deemed acceptable for this repair configuration. The current repair specimens are 1-dimensional and therefore prone to produce conservative results, since no support from the material next to the repair is taken into account.

During constant amplitude fatigue tests of CFRP-spar beams, splice delaminations were detected by means of thermography methods. Changing the scarf joint ratio from 1:40 to 1:100 improved the fatigue behaviour significantly. The stiffness degradation was measured and is suggested as a means for a possible damage equivalent between constant amplitude- and service life-fatigue tests.

The two investigations on wind turbine and light aircraft structures were treated together since both cases reveal the fatigue sensitivity to different scarf ratios of tapered repairs or joints in GFRP and in CFRP. Although the results obtained from the wind-turbine blade might not be completely applicable to sailplanes or light aircraft, the reduced residual strength of the repaired rotor blade components suggest a critical view on the repair techniques existing in the area of light aircraft.

Acknowledgements

The research on the fatigue of the GFRP scarf joints was supported by the European Commission within the Fifth Framework Programme within the Energy, Environment and Sustainable Development Programme under contract number ENK6-CT2001-00552 (OptiMat Blades). The investigation on the CFRP spar beams was carried out in the labs of the German Aerospace Research Establishment (DLR) and supported by the German Ministry of Transport, Building and Urban Affairs (BMVBS).

References

[1] D. J. Lekou, A. M. van Wingerde, *Repair Techniques For Composite Materials Applicable To Wind Turbine Blades*, Proceedings of the 27th Risø International Symposium on Materials Science; Polymer Composite Materials for Wind Power Turbines, Roskilde, Denmark, Eds. H. Lilholt, B. Madsen, T. L. Andersen, L. P. Mikkelsen, A. Thygesen, pp. 205-212, September 2006.

[2] M. Belz, L. Buchta, M. Heide, F. Karl, Ch.W. Kensche (ed.), O. Meister, D. Oppel, A. Reimer, V. Trappe, *Abschlussbericht zum Forschungsvorhaben des BMVBS Nr. L-2/20 03-50.0298/2002: Anwendbarkeit analytischer und experimenteller Lebensdauernachweise*, DLR Stuttgart, Juni 2007.

[3] R. P. L. Nijssen, *Fatigue life prediction and Strength Degradation of Wind Turbine Rotor Blade Composites*, ISBN-10: 90-9021221-3, ISBN13: 978-90-9021221-0, Ph.D. thesis, Delft University of Technology, The Netherlands, 2006.

[4] L. G. J. Janssen, A. M. van Wingerde, Ch. W. Kensche, T. P. Philippidis, P. Brøndsted, A. G. Dutton, R. P. L. Nijssen, O. Krause, *OptiMat Blades- Final report*, OB_PC_R017 rev. 001, June 2006.

[5] A. M. van Wingerde, D. R. V. van Delft, L. G. J. Janssen, T. P. Philippidis, P. Brøndsted, A. G. Dutton, T. K. Jacobsen, R. P. L. Nijssen, Ch. W. Kensche, D. J. Lekou, D. van Hemelrijck, *OptiMat Blades: Results and Perspectives*. In: Scientific Proceedings of the European Wind Energy Conference and Exhibition 2006. European Wind Energy Association (EAWE) pp. 69-72, 2006.

[6] R. B. Heslehurst, *Analysis and modelling of damage and repair of composite materials in aerospace*. In: Numerical analysis and Modelling of Composite Materials. Ed. J.W. Bull (Blackie Academic & Professional) pp. 27-59, 1996.

[7] B. C. Hoskin, and A. A. Baker, *Composite Materials for Aircraft Structures* (American Institute of Aeronautics and Astronautics, Inc.) pp. 193-216, 1986.

[8] Federal Aviation Authority, *Repair of Composite Laminates*, DOT/FAA/AR-00/46. Washington: Office of Aviation Research, 2000.

[9] H. Kossira, W. Reinke, *KoSMOS – Ein Lastkollektiv für Leichtflugzeuge*. DGLR-Jahrestagung, Hamburg; DGLR-Jahrbuch I, Bonn 1989.

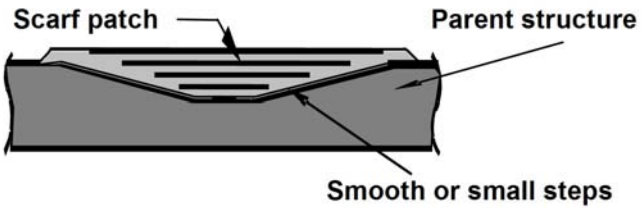

Figure 1 Repair technique.

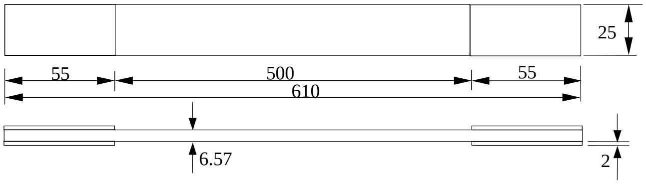

Figure 2 Coupon dimensions.

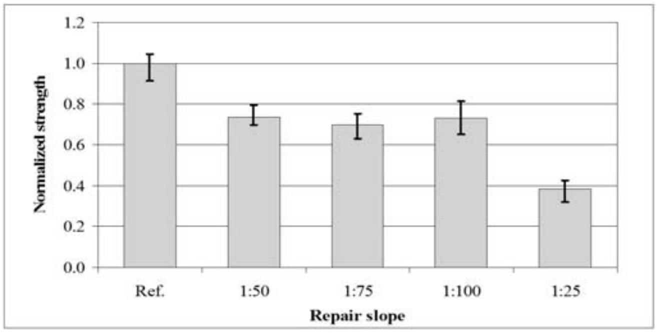

Figure 3 Effect of the slope for scarf repairs on static strength (Repair at 2/3 H).

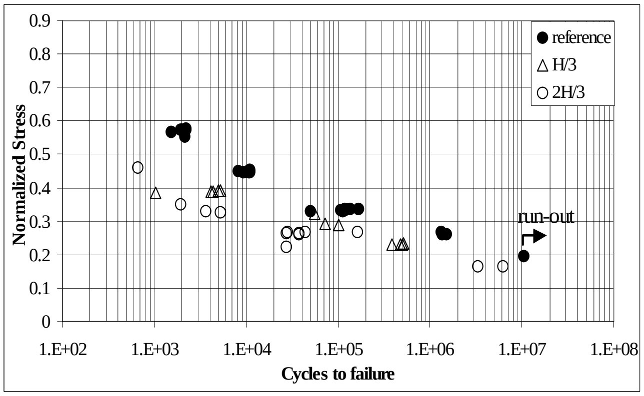

Figure 4 Fatigue results for different repair depth (scarf repair with slope 1:50).

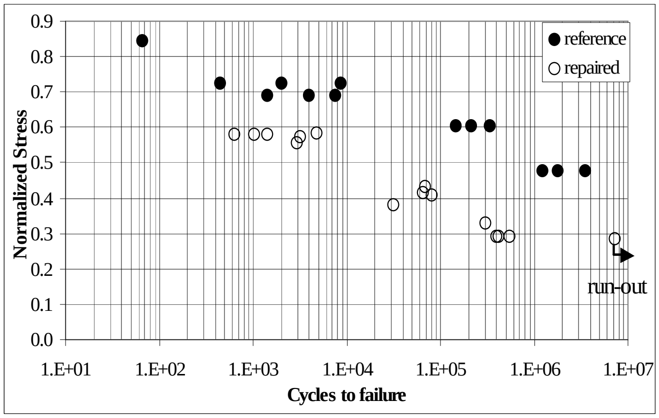

Figure 5 Fatigue results of alternative material (scarf repair slope 1:50, repair depth 2/3 H).

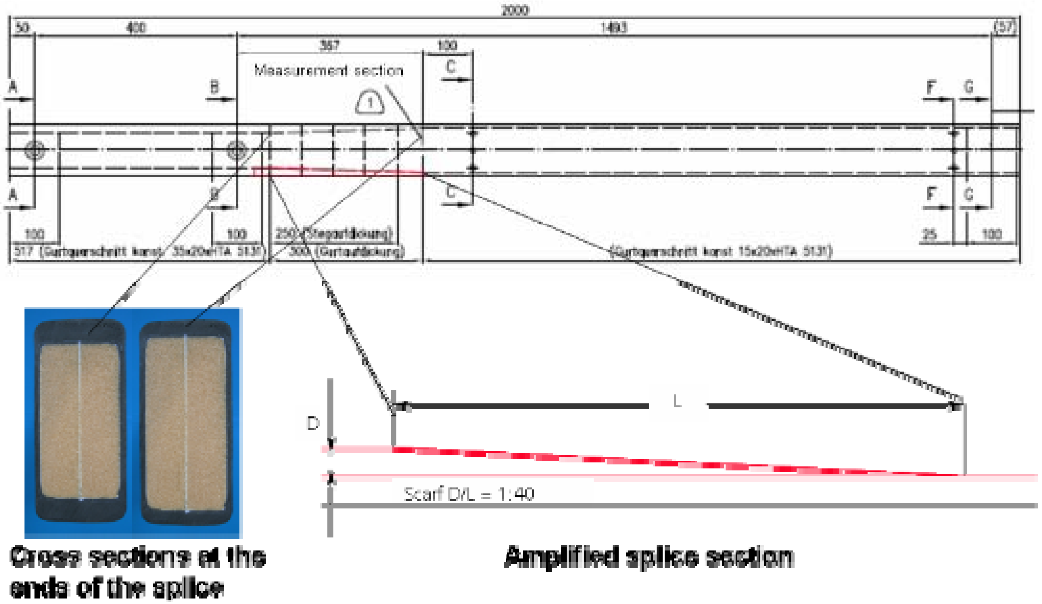

Figure 6 Initial geometry of spar beam.

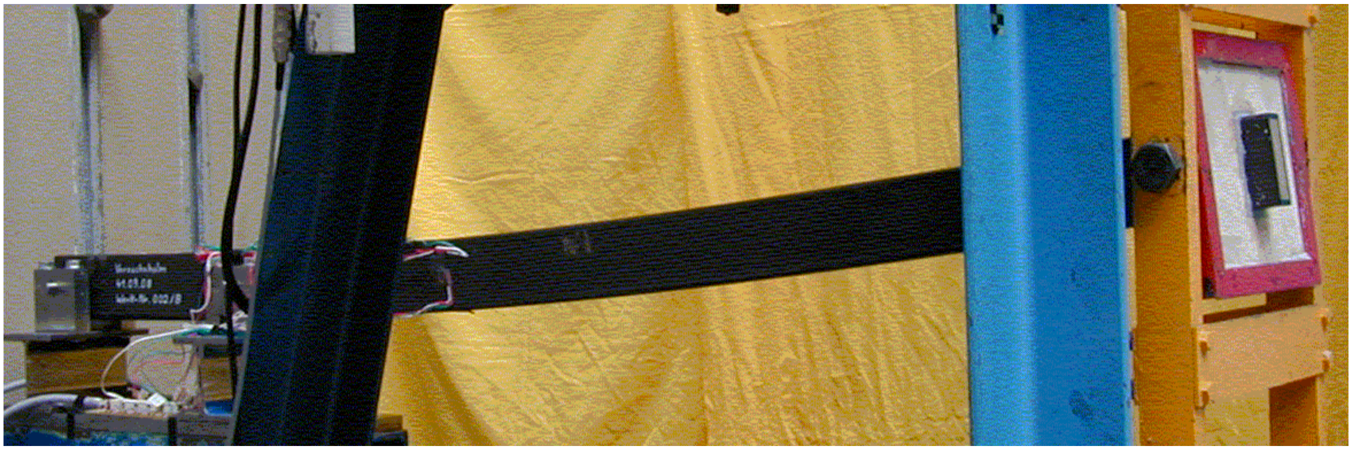

Figure 7 CFRP-spar in test bench at maximum load.

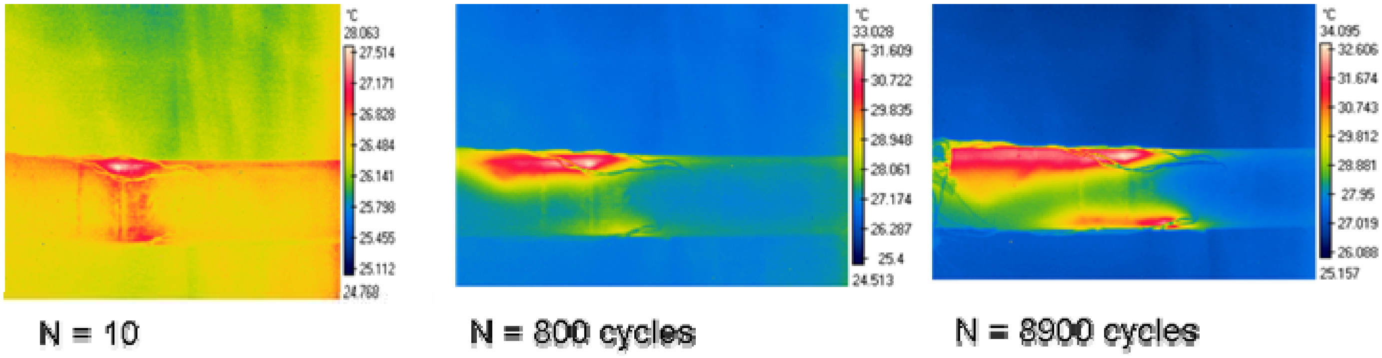

Figure 8 Thermography image of CFRP-spar beam in a constant amplitude fatigue test at various stages.

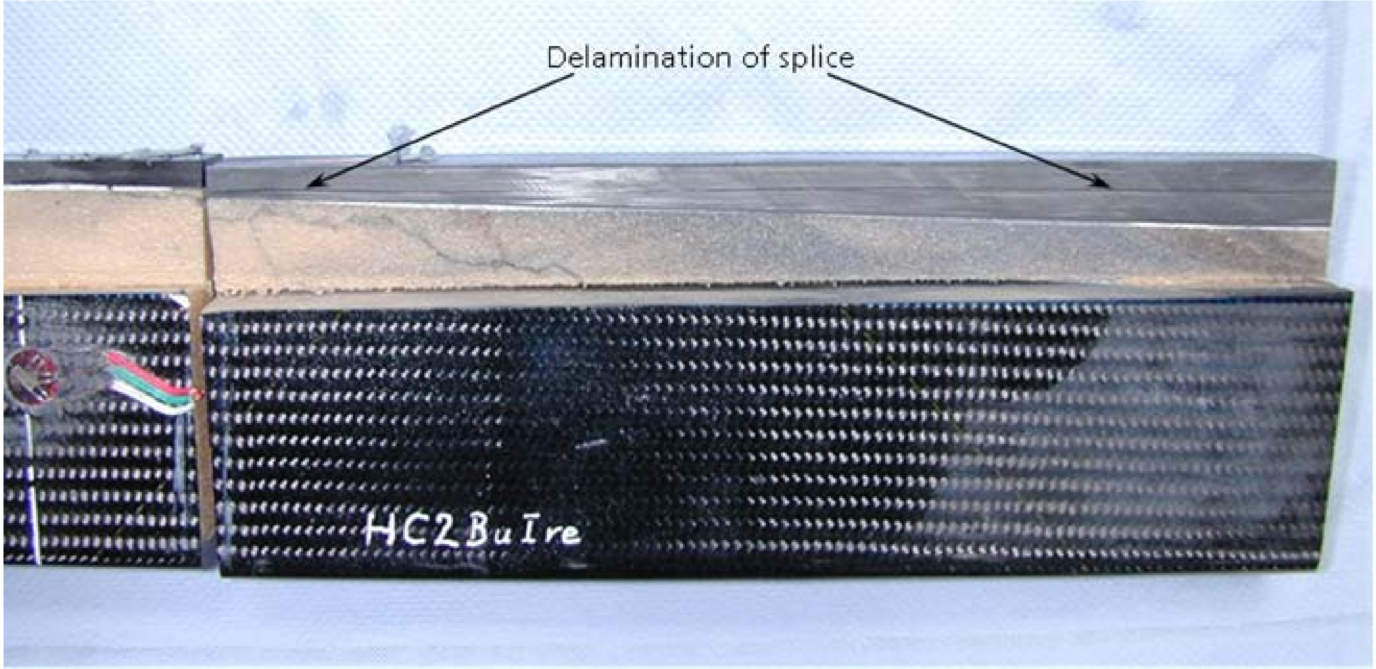

Figure 9 CFRP-spar beam with delamination of the splice in the longitudinal cut.

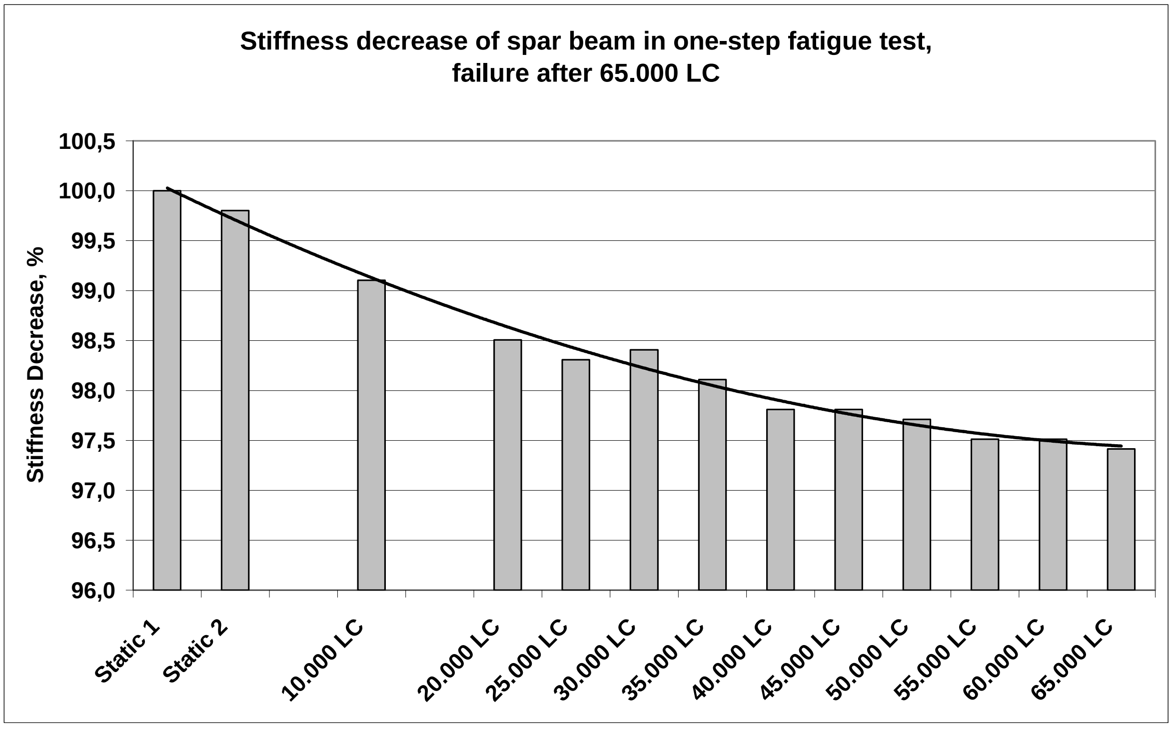

Figure 10 Stiffness change versus load cycle numbers.

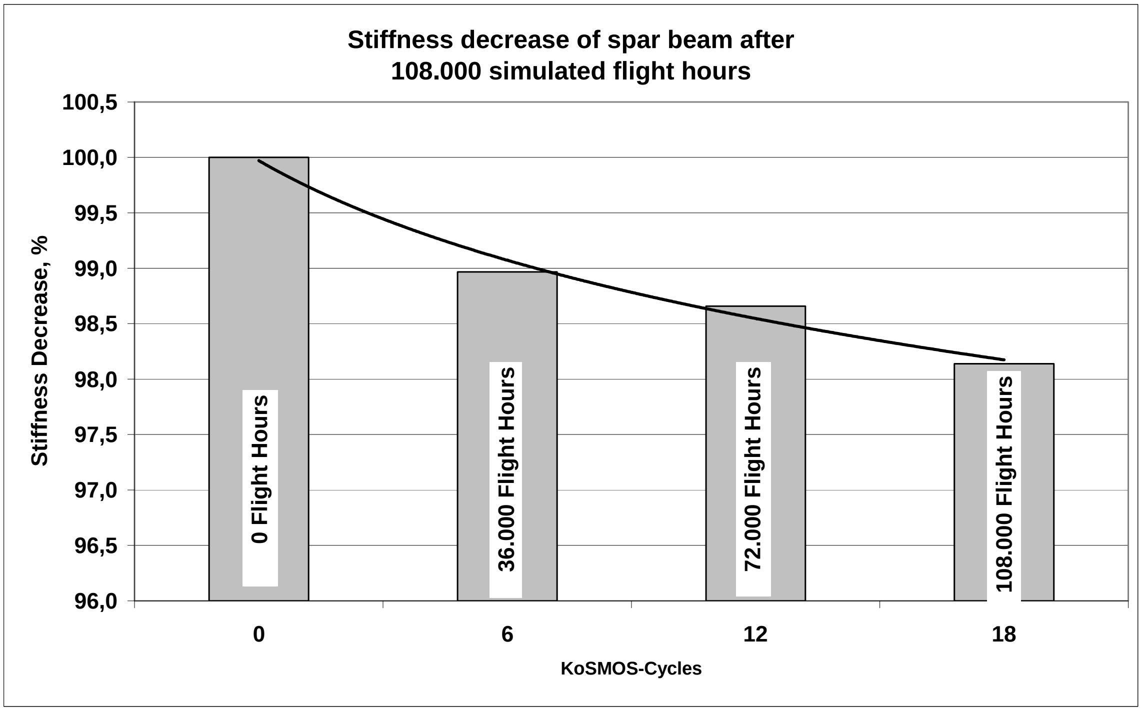

Figure 11 Stiffness change versus KoSMOS-cycles**.**