Automated Scarfing: A Prerequesite for Future Structural CFC Repairs?

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ABSTRACT

Composite materials are used extensively in military and civil aircraft structures. Bonded scarf repairs are very often the only viable solution to restore structural integrity to original design level in order to avoid costly component replacement. The current state of the art to perform a scarf is a manual sanding process with high effort in time and labour and with high manufacturing risk, especially for complex part contours and lay-up variations. To overcome these drawbacks of the manual sanding process, Airbus Defence and Space and Lufthansa Technik with several research partners jointly developed a mobile automated robot scarfing system within the government-supported R&D project CAIRE (Composite Adaptable Inspection and Repair). The solution is based on an industry robot in combination with a mounting system to attach the robot to a large variety of aircraft structures including upside-down positions. An adaptive software allows digitalization of the damaged surface and transition of the desired repair geometry to a milling path for the scarf geometry. The system automatically cuts out the damage, performs the scarf and delivers the data to produce tailored repair patches. Focus on user related requirements / design resulted in a system that can be operated by one person on civil and military aircraft.

The presented paper shows the design of the automated scarfing system, mechanical results obtained from automated scarfings as well as surface investigations. Furthermore the accuracy, repeatability and reduced working time of various scarfing geometries are highlighted.

1) INTRODUCTION

Composite materials have been in use in aeronautical structures for several decades in an increasing share of structural components. In civil aviation, for example, the industry has taken a major leap forward with the introduction of the A350 and 787 where over 50% of the structural weight is made from composite materials, mainly carbon fibre reinforced polymers (CFRP). In these aircraft the fuselage and wings are almost entirely made from CFRP. Comparably high usage is found in helicopters and military aircraft.

Throughout its life an aircraft is subject to damage such as lightning strike, bird strike and other mechanical collisions. These may result in a damaging of the structure and thus require repair actions. Despite the long experience of composite structures, the field of repair techniques still requires further development. In general, composite structures can be repaired in two ways, by a bolted or a bonded repair. Bolted repairs, where a doubler is attached to the structure have the disadvantage that the holes that are drilled for the bolts cut through the load carrying fibres thus weakening the structure. This leads to a structurally conservative design with increased weight as the result. However, the main advantage is that bolted repairs offer redundant load paths.

Bonded repairs on the other hand represent a far more appropriate repair technique for composite materials. The damaged area is removed from the structure and scarfing is conducted around the removed area in order to allow a load transfer between the laminate and the bonded repair patch via shear loads. Finally, a repair patch is bonded into the scarfed area, resulting in a flush repair as shown in Figure 1.

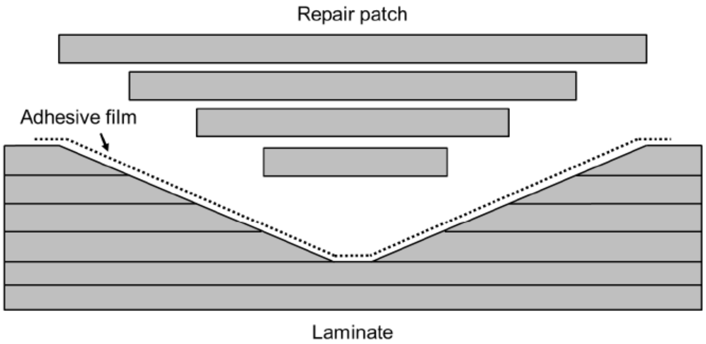

Figure 1: Bonded Repair of a composite structure

The challenge for bonded repairs on aeronautical structures is substantiation and certification. This is mainly due to numerous potential negative effects on the bonding strength. Contaminations such as water or chemicals on or in the laminate can weaken the bond without any detectable defect. Furthermore, most of the repair process is carried out manually allowing no quantifiable process control. EASA and FAA suggest three means of compliance where each could be used to substantiate a bonded repair [01, 02]:

i. If a bonded joint fails, the remaining structure should be able to withstand design loads. Larger disbonds should be prevented by design.
ii. Proof testing for each part with a bonded repair with applied critical design limit load.
iii. Non-destructive testing (NDT) measuring the strength of the joint.

However, these means of compliance are difficult to achieve:

i. As a bonded repair represents a single joint it inherently does not have alternate loading paths. This can only be overcome with additional fasteners in the bonding area resulting in the problems with bolted repairs. Accordingly, bonded repairs are limited in their size to small or cosmetic repairs or can only be applied to secondary structure.
ii. The effort of part proof testing is both technically and economically unpractical.
iii. No NDT methods exist to quantitatively determine the bonding strength.

An alternative to allow structural bonding for repair applications could be to increase process stability including additional QS steps. This can be achieved amongst others by replacement of manual tasks through automation and determination of process parameters by various methods. This paper focuses on the development of an automated system for scarfing on composite structures.

2. SCARFING REQUIREMENTS

The current challenges of manual scarfing are the reproducibility of the scarfing geometry and surface quality. This is mainly limited by the human factor. In manual scarfing, workers orient themselves along the visible reflection between adjacent plies with different orientation. Based on the ply thickness and the desired scarfing ratio the width of each cleared ply is known. As the thickness of the plies usually is well below 1 mm accuracies in the range of at least 100 µm is required. Due to this, scarfing geometries are in most cases limited to circular and rectangular shapes. Elliptical, adapted or freeform geometries as shown in Figure 2 cannot be produced in acceptable quality and time as the scarfing ratio varies circumferentially. This effect is amplified when considering complex aeronautical structures having multiple curvatures as well as laminate stackings with interplies. The latter removes the visual orientation as shown in Figure 3.

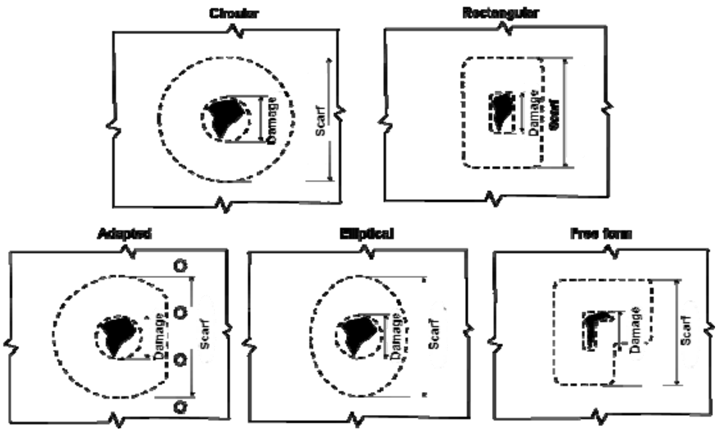

Figure 2: Scarfing geometries

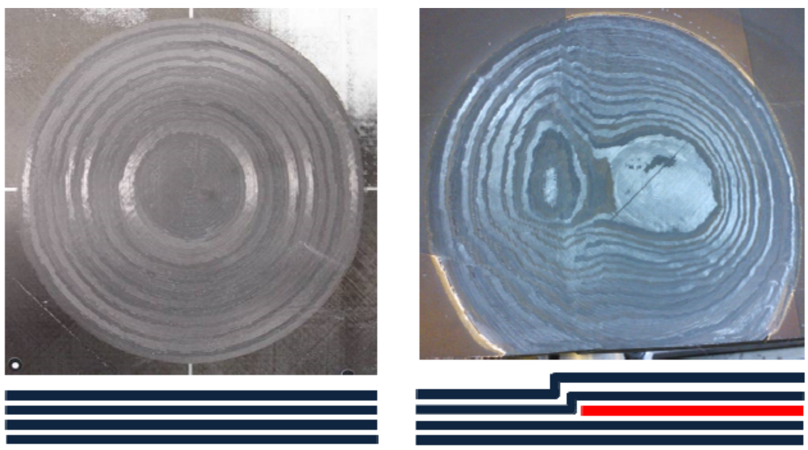

Figure 3: Scarf in an area without (left) and with interplies (right)

To overcome these challenges a mobile automated solution was developed within the R&D project CAIRe – Composite Adaptable Inspection and Repair (2012-2015). The project was co-funded within the framework of the national research program LuFo (Luftfahrtforschungsprogramm – Aeronautical research program) by the German Ministry of Economic Affairs and Energy. Within the project further technologies such as e.g. contamination detection and analytical methods for bonded repairs were developed. This paper focuses on the mobile automated scarfing technology.

3. AUTOMATED SCARFING SYSTEM DESIGN

In general different kinematic systems and abrasion technologies can be applied for automated scarfing. For the presented system an industrial robot was chosen. The system consists of a Kuka KR6 robot which is equipped with a mill and a laser scanner. The laser scanner measures the part's exact geometry and transfers it to the software which was developed by iSAM AG. Within the software the user can design the scarfing geometry or upload it from CAD. The chosen geometry is then developed into the parts geometry. This allows the transfer of complex scarfing geometries to complex shaped parts. Milling is carried out with parameters optimized for the use on CFRP with the described system. In order to bring the automatic scarfing device to the place of repair, Luratec AG developed a connection unit allowing mounting on any composite aircraft structure. The connection unit consists of a V-shaped integrally manufactured structure from CFRP with three suction cups. The system can be seen in Figure 4.

Figure 4: Robotic scarfing system

The main advantages of using a standard industrial robot are the high availability and comparatively low costs. Most robots have a good repeat accuracy and they are very flexible in their use. Furthermore, as robots can be easily exchanged as a system component, it enables the operator to participate in future new developments in robot technology. However, some challenges come with the use of a standard industrial robot. Due to the series connection of several gear boxes and thus their back lash the absolute accuracy is lower than e.g. cartesian kinematics. Also the resilience of a robotic system has an influence on the accuracy. During scarfing, the entire system resilience between the structure, on which the scarfing robot is mounted and all its components results in the total scarfing accuracy. As the robot and structure resilience cannot be altered, the system rigidity had to be optimized.

To improve the absolute accuracy of the robot system, the milling device and the laser scanner were mounted on the same robot axis. Thus the system accuracy becomes the repeat accuracy. The concept is shown in Figure 5.

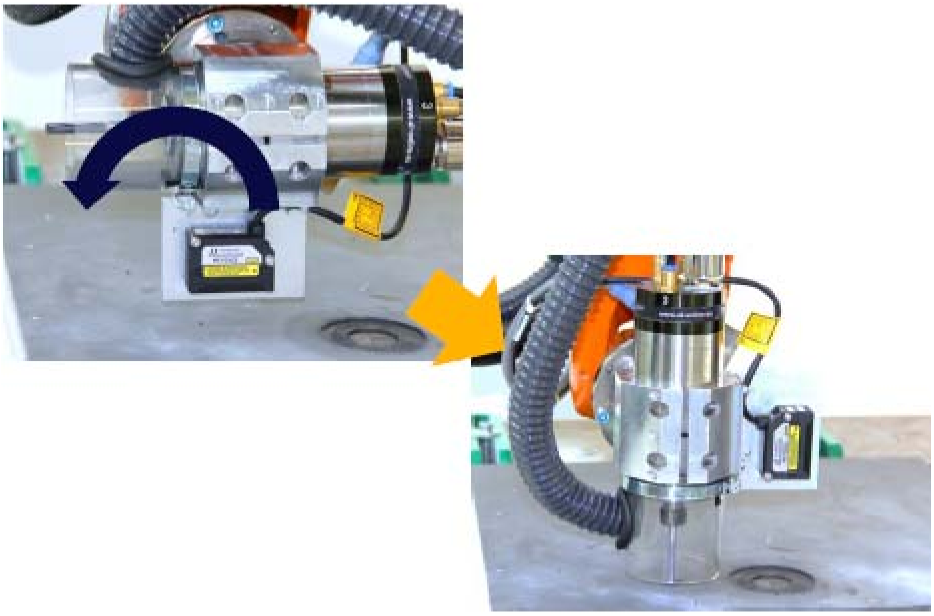

Figure 5: Scanner and milling device in operation [3]

Further improvements were achieved by adjusting the vacuum suction cups and the connection unit. The lay-up of the V-shaped structure and the suction cups were designed and optimised to give the entire scarfing device the stiffness sufficient to yield the required accuracy for machining. Reduction of moveable parts and integral manufacturing reduced stiffness loss in connections. Fast and easy fixture without complex adjustments to three dimensionally curved structures is possible with the system. It covers all relevant parts on civil aircraft or a military aircraft.

Scarfing accuracy of the robot with the fixture and the employed scanning/milling strategy is within the range of ±0.1 mm in thickness direction. The range of ±0.1 mm varies depending on the position of the robot (upside down, vertical, horizontal…) and the distance between the scarfing area and the robot.

To further improve the scarfing accuracy, an active support concept was developed. In order to bypass the remaining system rigidity as depicted in Figure 6 the robot uses a frame which is gently pressed onto the surface. An anti-friction surface is applied on the side of the frame in contact with the part. Contact forces are chosen low enough to enable movement of the frame along the part without part deformation. The mill is mounted in the frame on a linear bearing and advanced by a servomotor in z-direction based on the position in the scarf area. Thus accuracies in the range of the servo motor in the range of ±0,05 mm can be achieved. Furthermore, robot position and distance of the repair from the robot base do not influence the results. This is exemplarily shown for a stepped scarf at 800 mm distance from the robot base in Figure 7.

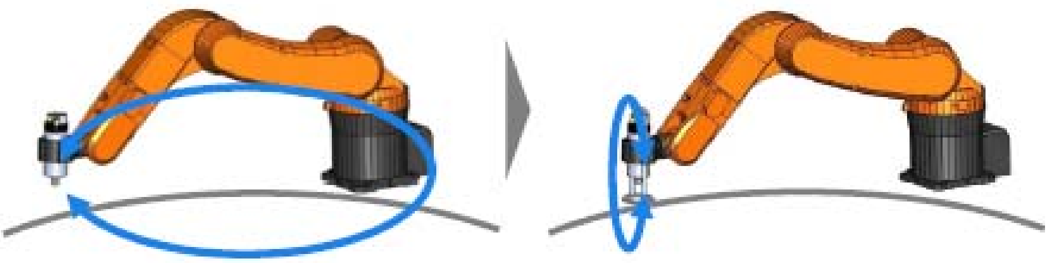

Figure 6: Increased scarfing accuracy through active support [3]

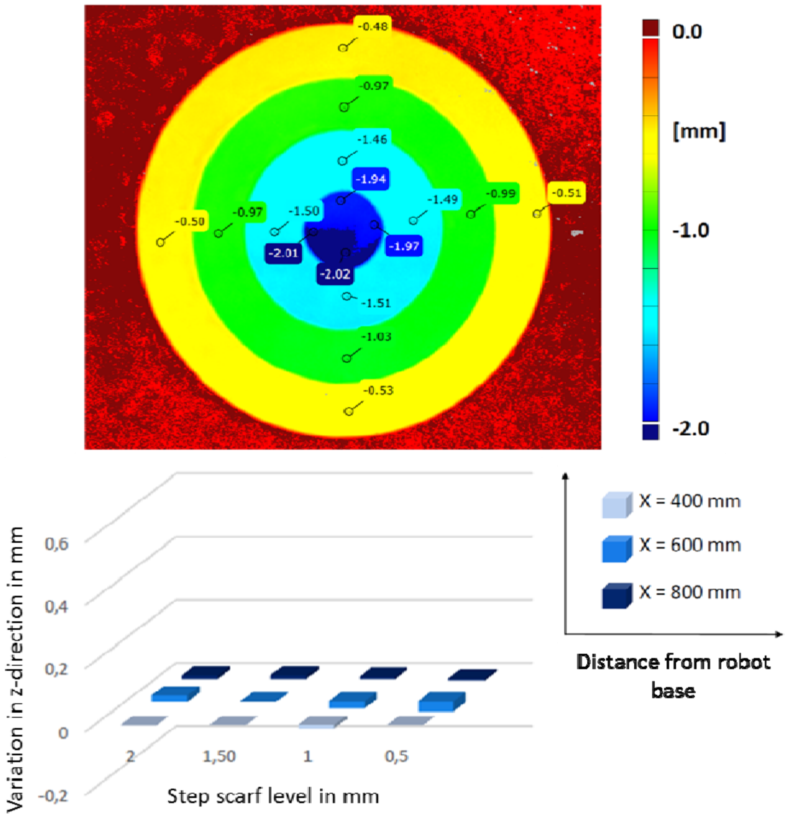

Figure 7: Scarfing accuracy of a step scarf in 800 mm distance from robot base through active support [3]

In addition to scarfing accuracy, one further important system design feature was solved within the projects: the mounting concept. For easy handling of the scarfing system, health and safety aspects and avoiding damage to the aircraft structure during mounting or operation, an ergonomic mounting and antifall guard system was developed. It allows a one operator set-up and operation. The system consists of a frame mounted cardanically at the system center of gravity. Easy manipulation in all degrees of freedom is feasible. Latches allow fixing the system when in position. For a flexible use, the system can be connected with forklifts, gantries, hand lifts etc. depending on the equipment available on the site of repair. With the mounting system, the system set-up takes less than one hour from opening the transport boxes to starting the scarfing. A schematic drawing of the system can be seen in Figure 8.

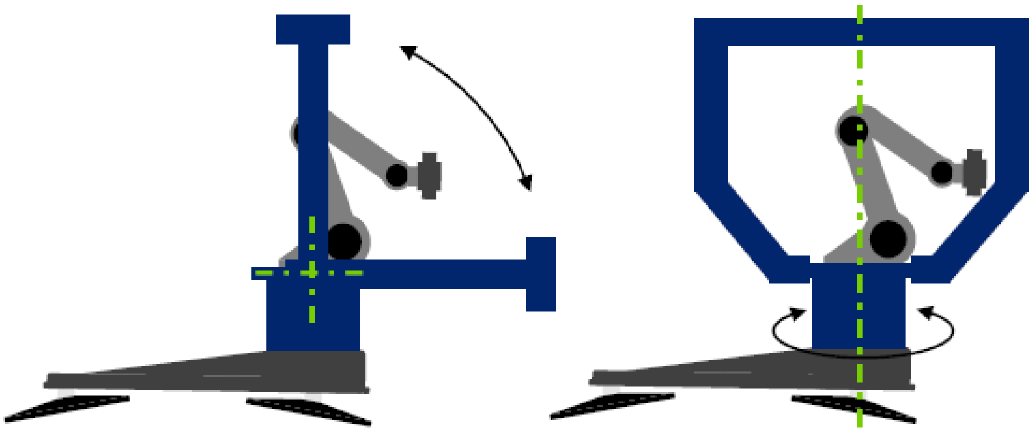

Figure 8: Schematic drawing of the mounting system [3]

4. PERFORMANCE OF AUTOMATED SCARFED JOINTS

In order to assess the performance of the automated scarfed joints a series of mechanical tests were conducted.. The specimen geometry is acc. to prDIN EN 6066 but the scarfing ratio was altered to 1:10 in order to force specimen failure to the scarf. To investigate whether these results transfer to larger structures 2,5D specimens were tested. 2,5D specimens are specimens where a circular scarf repair is conducted on a large plate with dimensions of 350x750 mm². A cross section of the scarfed tensile specimen and the geometry of the 2,5D specimens can be seen in Figure 9. All specimens were manufactured from Cycom 985GF3135-H8 and co-cured with a FM350 supported adhesive film according to manufacturer processes.

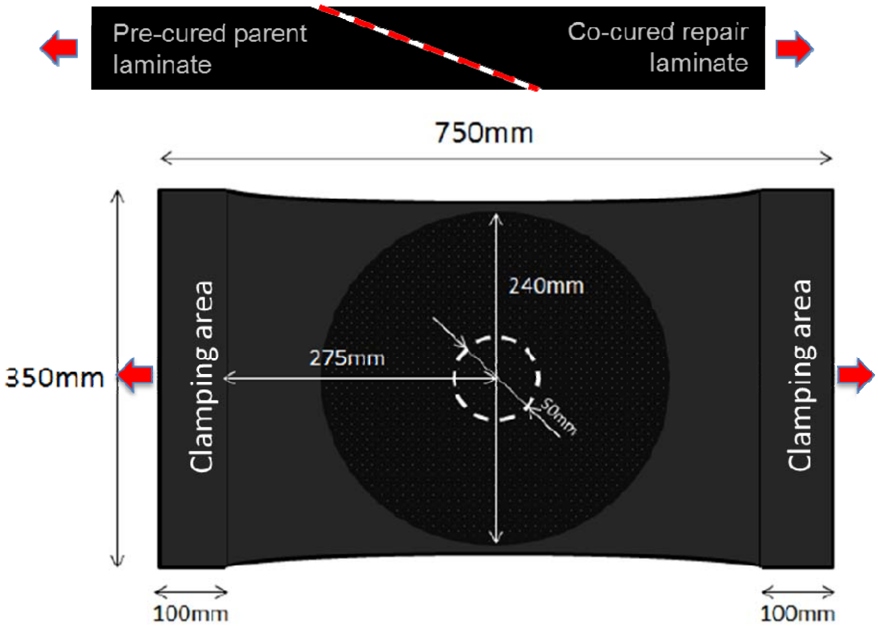

Figure 9: Schematic depiction of the scarfed tensile specimen and the 2,5D specimen

For the scarfed tensile specimen (prDIN EN 6066) different milling parameters and cutters were investigated as well as wear of the cutter. For this the cutter milled through 400 m of CFRP which corresponds to the track a cutter makes during a large repair. Afterwards the specimens were milled. Prior to bonding the specimens were investigated at W+R Automation GmbH using the aerosol wetting test (boNDTinspect). The non-destructive inspection system is a variation of the water break test. It consists of an ultrasonic sprayer distributing small droplets over the inspection area. These are visualized with a camera system before they evaporate from the surface. The number of drops per unit area and the wetted surface can be used to determine the surface quality. After inspection the specimens were co-cured with the repair laminate and tested. Between the milling parameters, different cutters and cutter wear no significant variation could be determined. However, all milled specimens performed better that the manually sanded specimen. In line with the mechanical results, the aerosol wetting tests indicated the same differences at a quantitatively comparable level. Representative results are shown in Figure 10.

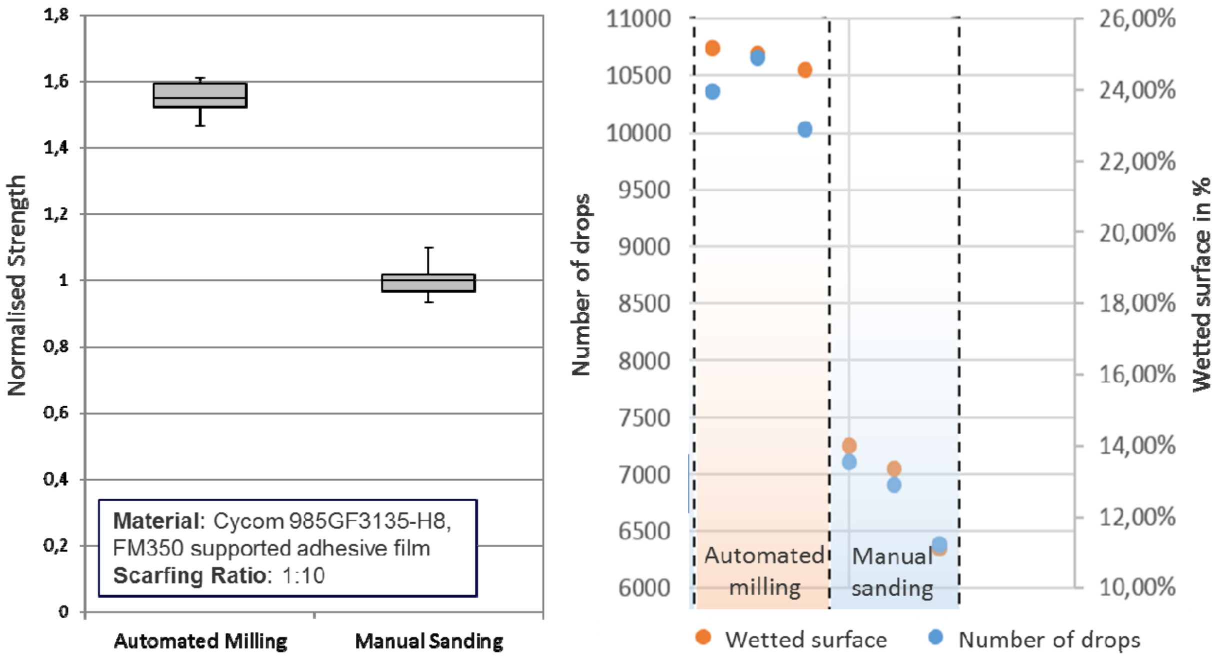

Figure 10: Normalized strength and aerosol wetting test results of the scarfed tensile specimen

From the 2,5D specimens, 6 were manufactured and tested at DLR (German aerospace center). After automated scarfing or manual sanding the scarfing geometry was scanned with the GOM ATOS system. Not surprisingly, the automated scarf showed higher accuracy than the manual sanding. The better performance of the automated milled surfaces could also be seen in the higher failure loads of the 2,5D specimen. The results of the mechanical tests and the ATOS Scan can be seen in Figure 11.

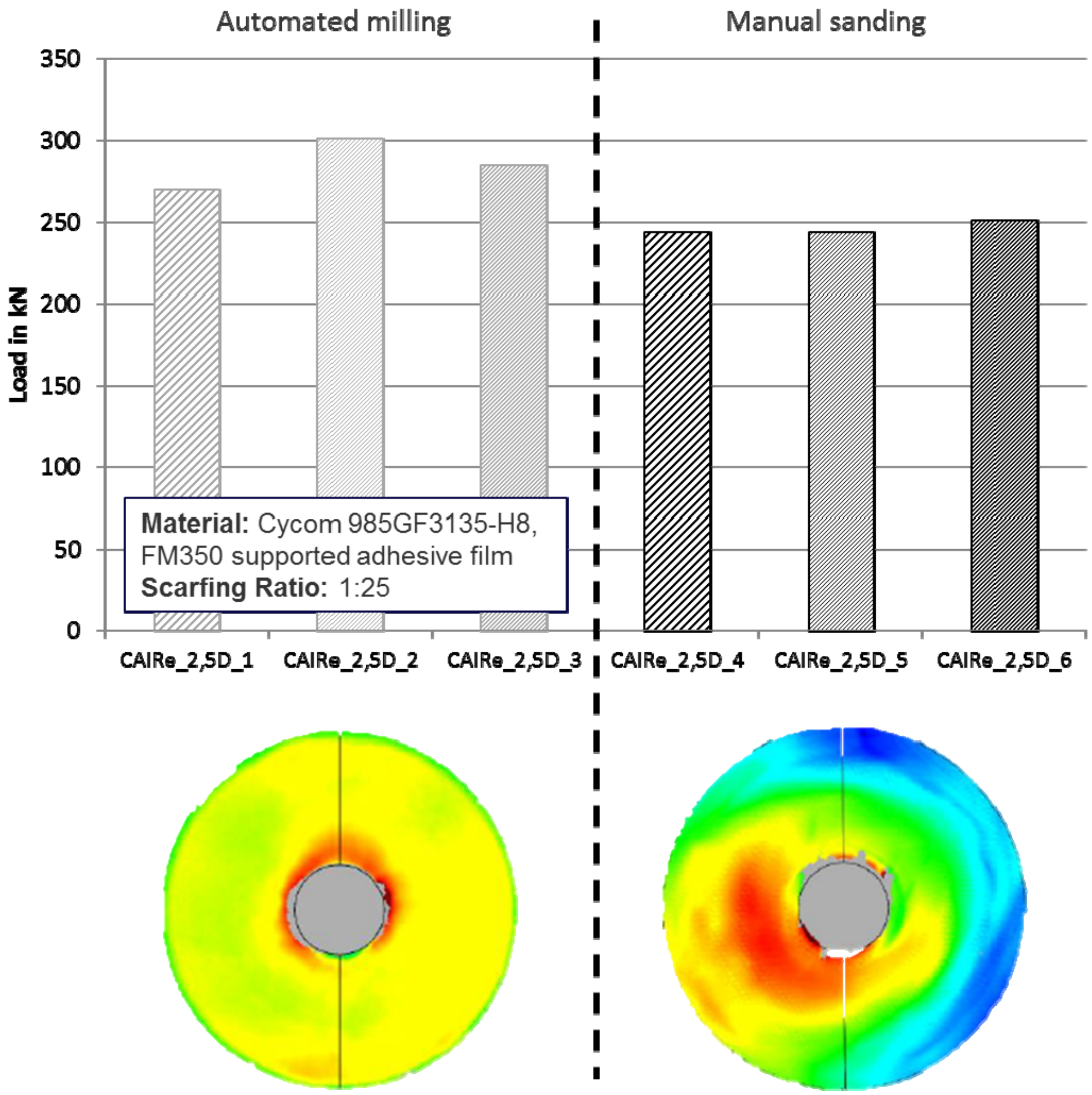

Figure 11: Failure load and scarfing geometry of 2,5D specimen

5. SUMMARY

The presented automated scarfing system allows repairs to be carried out with a high accuracy and repeatability. In addition, new arbitrarily complex repair geometries can be carried out in the same quality. The system has been designed for mobile use on aircraft with maximum flexibility and applicability for composite structures over an entire aircraft. First tests show that the mechanical performance of the automated milled scarfs is better than sanded surfaces. The aim of future investigations will be to better understand the bonding mechanism on milled CFRP surfaces and to gain a better understanding of the aerosol wetting test.
In combination with the other technologies for advanced process control regarded witin the a.m projects, contamination detection and numerical simulation, the mobile scarfing system represents a major step on the way to certify structural bonded repairs for composite structures.

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