CONCEPT DEVELOPMENT AND DEMONSTRATION OF A VISUAL ASSISTANCE SYSTEM FOR MANUAL SCARF REPAIRS OF COMPOSITE STRUCTURES MADE OF FIBRE REINFORCED PLASTICS

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Abstract

Manual repairs of composite structures are state-of-the-art across various industries. Regarding scarf repairs of carbon fibre reinforced plastics in particular, the underlying manual grinding process is time-consuming and therefore cost-intensive. Furthermore the grinding quality is inconstant and the achievable accuracy is limited. Due to multiple technological challenges in the automation of scarf repairs a largely manual execution can be expected to remain in the future.

A concept of a visual assistance system is presented, which can contribute to increase the process robustness and decrease the impact of individual capabilities. This system scans the actual shape of the repair area and compares it to a reference geometry. An integrated projector displays the result on the processed surface by using a multi-colour scheme. Thereby the technician obtains a feedback about the current state of the grinding process.

A first experimental test of the system demonstrates the principle feasibility of the assistance concept. Based on these results the potential for improvements of the process performance is shown and further development needs are derived.

1 INTRODUCTION

Large parts of modern civil and military aircraft models are made of carbon fibre reinforced plastics (CFRP), particularly components of the outer skin [1, 2]. These regions are especially prone to impact damages in form of accidental damage and environmental deterioration [2]. Up to a certain extent, the damaged areas are mechanically repaired. For bonded repairs the state-of-the-art method is the scarf repair, whereby the damaged and the surrounding material are manually sanded off to a taper-shaped geometry. Afterwards the scarf cavity is filled with a matching repair patch. Even though there are multiple research approaches to fully automate these kinds of repairs. However, a profitable replacement of the manual repair method by robotic solutions is not expected to be accomplished on a midterm scale. Certainly manual repairs have the drawbacks of varying quality, process time and repeat accuracy due to the manual nature of the repair process [3]. The aim of the assistance system presented in this paper is to visually support the technician during the sanding step and therefore reduce the negative impact of human factors. Consequently the process efficiency, quality and robustness could be increased, while the sanding time could be reduced and the documentation is enhanced.

2 SCARF REPAIRS ON CFRP STRUCTURES

The whole process for repairing damages in CFRP structures is complex, challenging and always individual. Laminate stiffness, strength, environmental resistance and aerodynamic effects have to be considered. The main objective of a repair is to restore these values to the original condition as much as possible [4]. To give an overview, *Figure 1* shows the general process steps for a permanent, bonded composite repair, which were derived from Structural Repair Manual (SRM) and from [3]. The damage removal step is mainly regarded in this work.

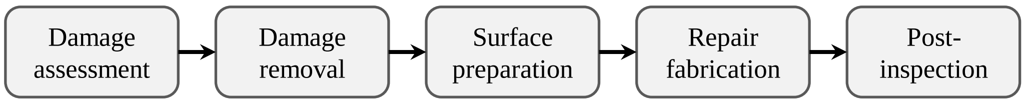
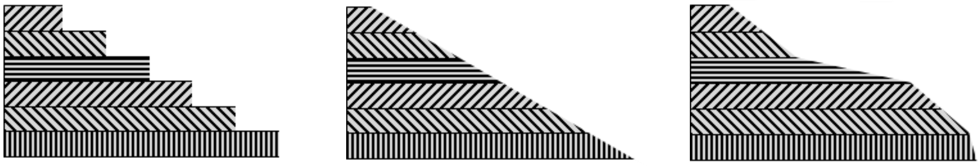


Figure 1 – General process steps for a permanent, bonded composite repair

First of all, damages have to be detected and assessed by diverse non-destructive testing (NDT) methods. This might be challenging because of barely visible damages (BVD) and various damage types [5]. Further damage propagation has to be prevented by removing the damaged area completely. This can be achieved by using manual or automated scarf techniques or by replacing the damaged component. During machining a high accuracy is necessary to achieve a designed scarf geometry and to assure a constant adhesive thickness in the bond line.

There are three different types of scarfing techniques, which are presented in *Figure 2*. Stepped and tapered sanding are possible to perform manually with a hand-held router [4]. The fibre oriented scarf is still in a development stage and primarily intended for automated systems. For further details on the potential of fibre oriented scarfs see [6] and [7].



a) Stepped scarf *b) Tapered scarf* *c) Fibre oriented scarf*

Figure 2 – Types of composite machining to create a scarf joint

While sanding, the technician orients himself at the ply pattern to identify the local depth. To get the correct shape or diameter of the scarf, the technician uses an individual template [8]. The quality and durability of the bonded joint is directly related to the subsequent surface preparation [9]. There are several options to implement a scarf patch: A soft-patch, a moulded hard-patch and a machined hard-patch [10]. After reparation, an NDT inspection (post inspection) of the repair and the surrounding area has to be done to detect any debonding or delamination. An inspection record provides quality control.

A cross-section view of a typical scarf repair is shown in *Figure 3*. An assessed damage in a thin CFRP layer is removed by a tapered scarf with a common scarf ratio between 1:20 and 1:50 (thickness : scarf length) [4]. An adhesive film covers the complete scarf cavity to bond the patch plies with the parent laminate.

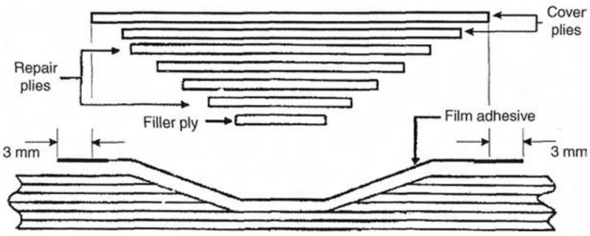


Figure 3 – Scarf repair of a composite laminate with a tapered scarf [4]

3 CONCEPT DEVELOPMENT AND DEMONSTRATION

To answer the question, how a technician can be supported to execute the damage removal by sanding in a suitable way, a concept of a visual assistance system (VAS) is developed and demonstrated.

3.1 Addressed quality aspects

First of all, requirements for a VAS have to be defined. Therefore quality aspects of the damage removal process are specified and categorised as shown in *Figure 4*. The first category contains machining, geometry and process aspects. Nowadays, the repair dimensions like scarf angle and shape are carefully evaluated by a qualified repair design engineer, because every repair is individual [11]. Required materials, already existing repairs, adjacent damage locations, damage size and location, aerodynamic requirements and much more have to be considered. The accuracy of the scarf geometry is important to avoid excessive bond line thickness after placing the repair layers or repair patch. [4]. An adhesive thickness between 0.05 mm and 0.2 mm results in the highest strength [12]. The second category contains technician-related aspects. Skill and knowledge are the decisive aspects for accuracy and quality of the scarf repair [3, 4]. Repeatability and consistency are strongly related to human factors. While sanding for example, the technician orients himself at the ply pattern [8], which requires high concentration of the technician. A weakening concentration because of tiredness cannot be completely avoided. Another point is the respect of work instructions. Their compliancy is depending on human errors, which differ between accidental and intentional errors. The third category contains further aspects like process time, documentation and post inspection (detecting any debonding or delamination in the repair area). All of the described aspects are discussed in chapter 4.

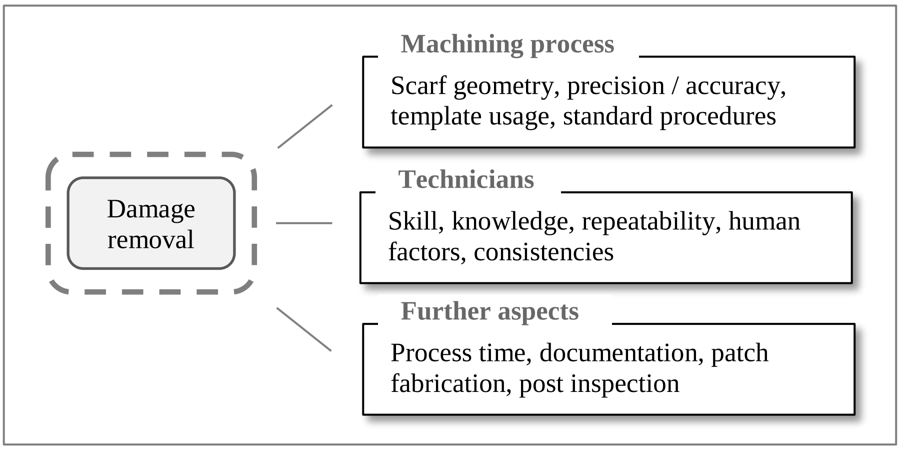


Figure 4 – Quality aspects of the damage removal process

3.2 Concept description

The idea of the presented concept is to give the technician a continuous feedback about his sanding progress. To realise this feedback function, a technology which can capture the actual state of the sanding process is needed. *Figure 5* shows a developed flowchart for a VAS with the required process steps.

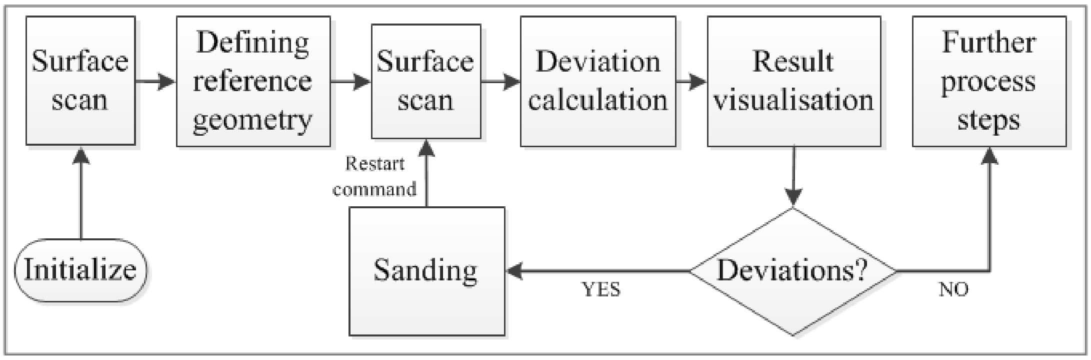


Figure 5 –Flowchart of the visual assistance system

In an initial step, the assistance system is set up and input values like material thickness, damage dimension and type are entered. The next step is to scan the examined surface with a scanning device to generate an initial point cloud data. Based on this, a reference geometry (representing the target geometry) is defined automatically, see chapter 4.

The feedback function is realised by a loop, which is started by a command of the technician. Every loop begins with a surface scan which is used to calculate deviations to the reference geometry. Then the results are visualised by projecting them onto the processed surface - the so-called Spatial Augmented Reality (SAR) [13]. A suitable colour scheme indicates deviations to the reference geometry. After that the technician decides to continue the sanding where necessary or to proceed with further steps when the achieved results are within the acceptable limits. After sanding, a deviation calculation has to be done again.

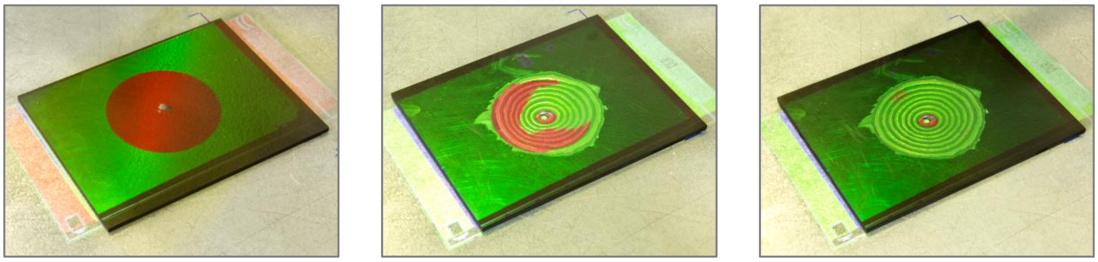
3.3 Concept demonstration

For a proof-of-concept a device is required, which offers a combination of an optical scanner with suitable accuracy in the micrometre range, an integrated processing unit, and a multicolour projector. This combination is provided by the 3D surface scanner of the company 8tree GmbH [14]. It uses a white light scanner with a resolution of 50 µm to create a digital record of the surface, which can be used for further calculations inside the device. An integrated projector is available for visualisation. The complete scanning and visualisation procedure needs only between one and two seconds. Mounted on a stand, the device can be used as a VAS, as shown in *Figure 6*.

Figure 6 – Demonstration set-up of the visual assistance system (left) and the sanding process with visualised deviations (right)

To enable a deviation calculation a reference geometry or rather a reference surface is needed. For this demonstration a pre-finished sample with a constant scarf angle is the basis for the reference geometry. This scarf is scanned by the 8tree device and the digitized surface is saved as reference.

The used component in this demonstration is a quasi-isotropic, flat 6 mm plate made of 32 layers of carbon fibre prepreg. After an initial scan, the deviations to the reference including the intended shafted area are automatically calculated and visualised on the component (compare with *Figure 6*). In this way it is possible to visualise the actual state of the sanding progress aligned with the processed surface. Two different colour schemes were tested during this proof-of-concept. They are discussed in the next chapter. ***Figure 7*** shows three visualisations with a stepped colour scheme from the beginning to the end of the damage removal process. By highlighting the areas where the reference is reached (green colour) or material still has to be removed (red colour) or too much material was removed (blue colour), the technician gets a clear feedback about his sanding progress.



a) Status 1 *b) Status 2* *c) Status 3*

Figure 7 – Deviation visualisation in the initial status a), an mid-term status b) and an end-term status c)

4 DISCUSSIONS ABOUT THE PRESENTED CONCEPT

This chapter discusses expected improvements, future potential, possible solutions and limitations of the presented concept of a VAS. According to the NASA defined Technology Readiness Level (TRL) the presented technology is at TRL 2, because of a first practical application to the developed concept [15].

Expected improvements in quality aspects

The quality of the bonded composite repair is significantly influenced by the skills, knowledge, human error and inconsistencies of the repair technician [3]. The impact reduction of these aspects is the main aim of the presented VAS. Skill and knowledge are still irreplaceable but the evaluation and documentation of accuracy and uniformity of the scarf can be performed by the assistance system. This means that even less experienced technicians can carry out repairs. Accuracy and uniformity of the scarf largely depends on the skills of the technician [10]. By supporting the technician with a VAS and a calculated reference geometry, the dependencies shift from the technician in the direction of the assistance system. The need of templates and markings is reduced as well. Altogether a reduction of process time and errors through the use of SAR is possible, as also mentioned by Jetter [16].

Standard procedures and the necessary revision service can be implemented into the assistance system. However, the system is currently not able to display work instructions. In [17] the limitation of occlusion was shown when SAR was used. This limitation does only carry little weight in the presented concept, because only the hand of the technician is in the projection area and the visualisation is not a live sequence.

Defining the reference geometry

Manufacturing a scarf on a flat component is rather straight forward. In this case the reference geometry can be calculated from scans of the surrounding undamaged area. However, for curved components or if the material thickness varies it should be calculated externally and then transferred onto the device. In [8] it is shown, how a reference geometry can be calculated on a curved surface by giving input values like a scarf diameter, scarf ratio and scarf deepness. It also has to be tested for which repair dimensions the used device is suitable.

Colour scheme

A colour gradient and colour steps were tested to visualise deviations to the reference geometry. It became apparent that the colour gradient was only moderately suitable because of the difficult differentiation of the gradients. The outer diameter of the scarf was not clearly visible as well (see *Figure 8*). For small deviations the stepped colours with clear contours were more suitable. It should be tested in future experiments if swapping the colour scheme during the sanding process or using mixed colour bars containing gradual and stepped transitions is beneficial.

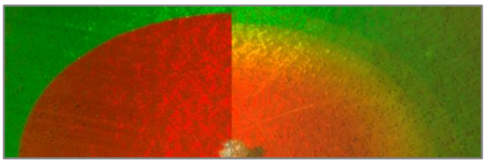


Figure 8 – Comparison between colour steps (left) and colour gradients (right)

Damage localisation and tracking techniques

One step to make this concept feasible is to localise the damage and to reliably project the deviation result onto the same area. The test showed that a shift of the device leads to a misplaced projection. In [17] the surface under consideration is scanned and then connected with annotations to project them onto the right place. On airplane surfaces, there are not always enough surface features to use these as references, so that the application of tracking markers shall be tested. However, the usage of surface features or tracking markes as references is state-of-the-art.

Further usage of the digitized surface

The SRM requires an inspection record. This includes e.g. aircraft and part identification, damage description, a process check list, etc. The creation of this inspection record can be implemented into the VAS and transferred to the repair facility afterwards. Using the containing information, a part damage map and history can be established. Furthermore the digitized surface of the finished scarf can be used for numeric simulations in a digital twin or to calculate templates for patch fabrication. It is also considerable to assist in the positioning of repair layers or repair patches into the scarf cavity.

5 CONCLUSION AND OUTLOOK

A concept for a visual assistance system for a manual sanding process in scarf repairs of aerospace CFRP components was developed and proven. The main aim is to reduce the influence of human factors in the scarf quality. The concept uses a surface scanner with an integrated projector as a visual assistance system to give a direct feedback to the repair technician. In addition to the reduction of human factor influences a reduction of process time is expected. The discussion shows, that the VAS has an impact beyond the process step of damage removal. Also the damage assessment by locating and describing the damage, the repair fabrication by instructing the patch manufacturing and the post inspection by generating an inspection report can be concerned. The TRL 2 status was reached and further developments and studies have to be taken. The next steps will be to establish the reference geometry calculation, the tracking system and to evaluate the improvements in accuracy and process time of the assisted compared to the unassisted scarfing.

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