NUMERICAL AND EXPERIMENTAL INVESTIGATION INTO THE INFLUENCE OF GEOMETRIC PARAMETERS OF HYBRID COMPOSITE REPAIRS ON MECHANICAL PERFORMANCE

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Keywords: composite repair, co-bonded joint, hybrid joint, reinforcing yarn

Abstract

The work deals with a hybrid repair technique for composite components made of glass fibre reinforced plastics (GFRP) specimens where the bonding area is reinforced with high performance multifilament yarns. This hybrid joint is a combination of a co-bonded patch repair with additional relatively small scale form fitting elements which are built due to the curing of the introduced multifilament yarns during the co-bonding process. The load transmission is consequently realized by the adhesive and the yarns. In tensile testing, the strength of the repair can be restored to 86 % of the undamaged specimens without any specific surface treatments. This is due to the fact that the reinforcing influence of the yarns on the bonding area can outperform the weakening effect of the drilled holes which are needed for the connection between parent part and dry textile repair patch. As no specific surface treatment is needed, unfavourable environmental conditions or limiting geometric constraints have a lower impact on repair performance in comparison to general bonded joints.

1. Introduction

Reliable repair of high performance composite components based on bonding is still an unsolved issue. One primary reason for that is concerned with the fact that it is not possible to measure the residual strength of a bonded repair without destroying it. This is due to the fact that the repair success is strongly influenced by environmental conditions like humidity or surface contamination prevailing during the repair process. As a result, the repair success cannot be secured with sufficient probability under field conditions where the worker is frequently faced with unfavourable environmental conditions [1].

In order to overcome that situation, the repair quality is controlled as far as possible on the one hand. This is achieved by automisation of the repair process [2] and by improved procedures for surface treatment to enhance the adhesion between the mating partners [3]. Several improvements have been achieved concerning quality control in the past years. Nevertheless, this approach does not solve the basic problem of checking the strength of the adhesive interface by non-destructive testing. As a consequence, the application of bonded repairs is still limited to damages where the failure of the repair does not endanger the operational safety, in particular, in the aviation industry.

Excerpt from ISBN 978-3-00-053387-7

On the other hand, the mechanical performance of bonded repairs can be improved by additional relatively small scale form fitting elements. Partially, so called z-pins are introduced into the bonding area (see e.g. [4]) additionally joining the mating partners. Another repair approach is based on high performance filament yarns instead of z-pins. After removing the damaged area, a dry textile that will be the repair patch after curing is connected to the parent structure by yarns. The dry textile is sewed to the parent part through holes which are drilled into the parent structure. The dry repair patch is then impregnated with resin in a vaccum assisted infusion process together with the sewing yarns. As a result, the yarns reinforce the bonding area after both mating partners are co-bonded. A scheme of such repair approach is sketched in Figure 1.

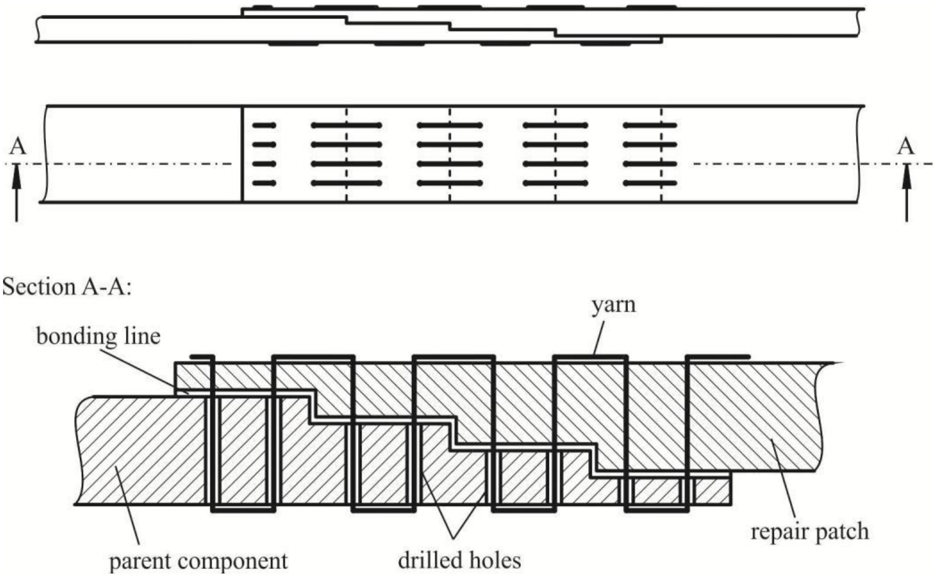

Figure 1: Scheme of a co-bonded repair with additional yarns forming a form-fitting connection between the repair patch and the parent component [5].

The repair approach based on reinforcing the bonding area by yarns is investigated in [5, 6] for some specific geometric and material combinations indicating the potential of such a repair procedure. In this article, further influencing parameters are discussed and achievable repair improvements are estimated based on experimental tensile tests. In the following, the repair procedure is described first. Secondly, the specimens under investigation are defined so that subsequently, the applied Finite Element (FE-) idealization is thirdly illustrated together with some computational validations. Fourthly, numerical investigations are discussed exhibiting the significant influence factors on the mechanical performance so that the performance improvements of deduced repair configurations are validated based on experimental testing. The article ends with a conclusion.

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2. General Repair Approach

The repair approach under investigation in this artcile is a combination of a co-bonded patch repair and additional relatively small scale form fitting elements. The combination of adhesive and form fitting load transmission is referred to as a hybrid joint or hybrid repair method, following the definition from [7].

For the co-bonded patch repair, the damaged component is prepared for the repair by mechanically removing the damaged material and milling the area around the removed material in a stepwise manner. The height of the steps equals the thickness of the layers of the respective component. A previously prepared textile repair patch is placed into the stepped repair area as shown in Figure 1, resulting in a doubling in the bonding area by one ply. No filler ply is used in the area where the parent material is totally removed. The dry repair plies are impregnated with a low viscosity epoxy resin using a vacuum infusion process. The matrix resin of the repair patch also serves as adhesive for the connection between the repair patch and the already cured parent component (co-bonding process) [5].

The additional form fitting elements are formed by a thread of carbon fibre multifilament yarn which is stitched through the repair patch and through holes drilled into the parent component (cp. Figure 1 bottom). The carbon fibre yarn is impregnated and cured together with the repair patch, forming consolidated pin-like elements at the same time the repair patch is cured and the adhesive bond is established [5].

The stitching pattern and thus the geometric parameters of the pins are determined by the diameter and angle of the holes drilled into the parent component and the distance between them. Figure 2 shows a carbon fibre yarn stitched through a GFRP parent component at an angle of 45°.

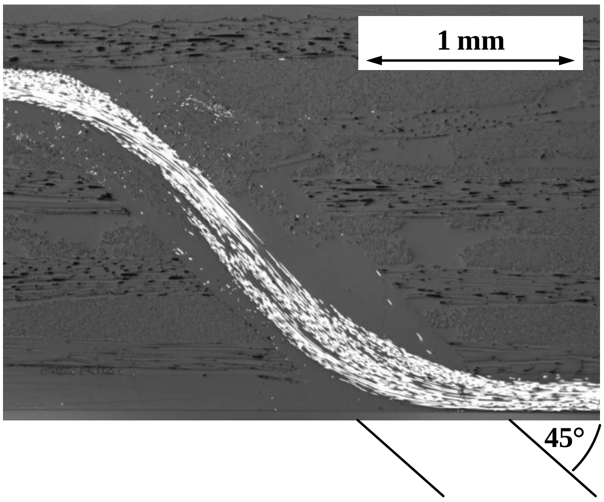

Figure 2: Carbon fibre yarn stitched through a GFRP parent component at 45° (scanning electron microscopy).

The resin infusion process with additional carbon fibre yarns stitched through the repair patch and parent material can be performed the same way as for the pure co-bonding repair. The resin infusion process for coupon hybrid repair samples ist shown in Figure 3.

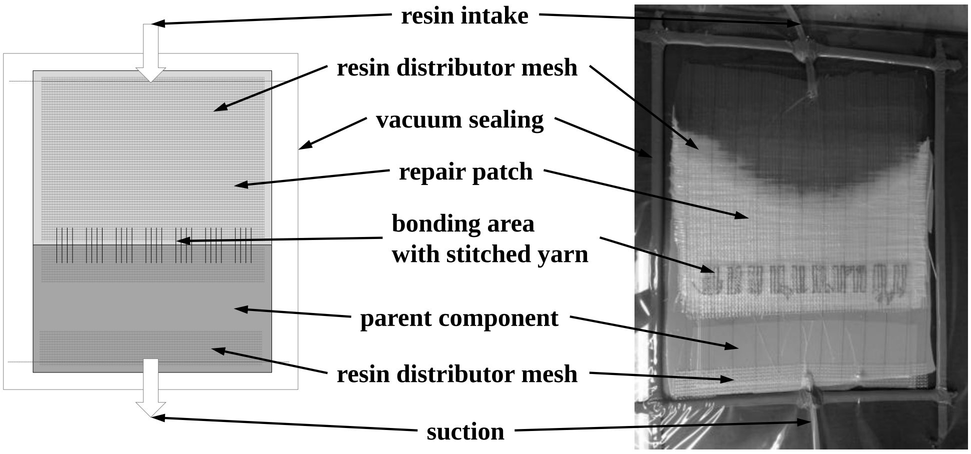

Figure 3: Resin infusion process for impregnation and co-bonding of hybrid patch repair with additional stitched yarn.

3. Specimens Definition

The specimen definition for tensile testing of the repair is given more detailed in [5]. Here, the main characteristics are outlined for clarity reasons for a GFRP laminate as parent component. Its layer and

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repair set-up are shown in Figure 4. In general, three different types of specimens are considered here. An undamaged parent component (called reference), a conventional co-bonded stepped single lap joint (co-bonded repair) and a single lap joint reinforced with carbon yarns (CF-reinforced) are investigated. The bonding area is cleaned with acetone. No further surface treatment is applied.

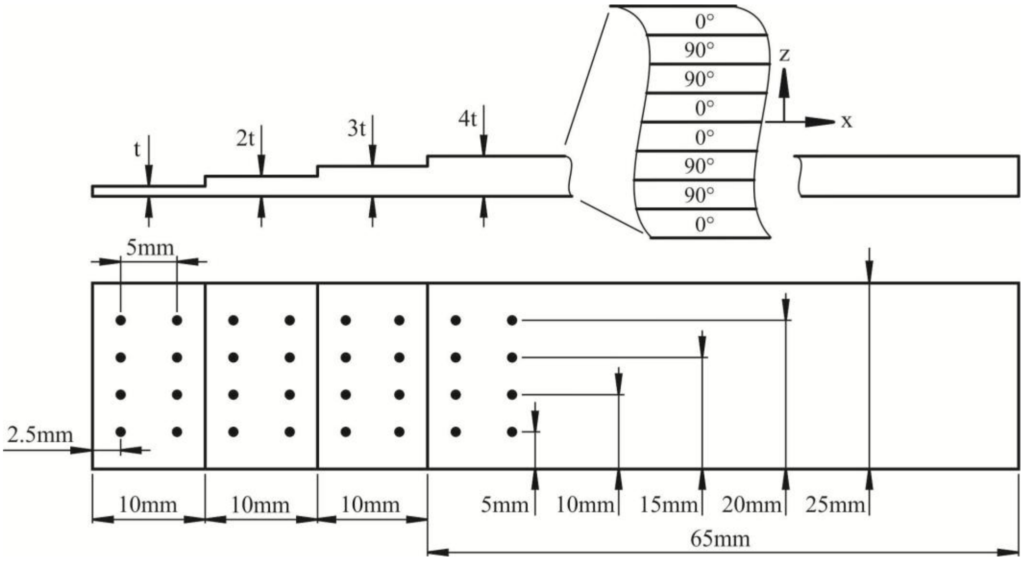
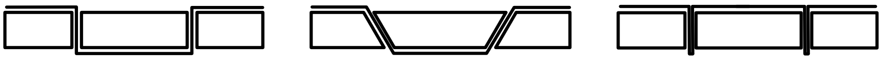


Figure 4: Geometry of single lap joint made of GFRP parent material [5].

In addition, the stitching configuration is varied as shown in Figure 5Figure 5. The U-shaped and the V-shaped stitching form are achieved by an alternation in the drilling angle only (90°, 60°, 45°) and the amount of reinforcement fibre is kept constant as a single thread is used. In an additional configuration, the amount of fibres in the through-the-thickness-direction is doubled for the 90° drilling angle. For this configuration the diameter of the drilled holes has been increased from 1,0 to 1,5 mm. For the double thread configuration, a T-shaped stitch has been applied that can also be performed when the repair area is accessible from one side only.



single thread
U-shaped (90°)

single thread
V-shaped (<90°)

double thread
T-shaped (90°)

Figure 5: Stitching configurations under consideration

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4. Finite Element Modelling and Validation

The Finite Element Method (FEM-) code Abaqus/Explicit Version 6-11.2 (Dassault Systèmes SA, France) is used. The FEM idealization is described in [5]. For the sake of clarity, the major modeling characteristics are outlined in the following.

The laminates of the repair are modelled using a unidirectional (UD-) layer formulation where each layer is idealized based on a quadrilateral solid shell. Failure of the UD-layers is considered using Hashin's composite model with respect to [8].

The reinforcing yarns are modelled by 8-node linear brick elements with an ideal elastic-plastic stress-strain relationship using v. Mises equivalent stress formulation. Compared to the real yarn, the stiffness as well as the in-plane damage behavior of the yarn in are consequently overestimated.

Furthermore, as simulations indicate that the yarn on the surface of the specimen is neglectable for the overall behavior, only the yarn within the holes is idealised for simplicity reasons.

The co-bonded area between the mating partners is idealised with 8-node three-dimensional cohesive elements (element type COH3D8 according to [9]). It is a cohesive element formulation using a traction-separation response. The damage is initiated based on a maximum nominal stress criterion. Due to the highly dynamic fracture process, an automated mass scaling approach is used for these elements. The applicability of the mass scaling is checked considering occuring energy levels.

The FEM idealizations show very good agreement with experimental results. In Figure 6, one example for a GFRP parent component is illustrated (see [5] for further validation data).

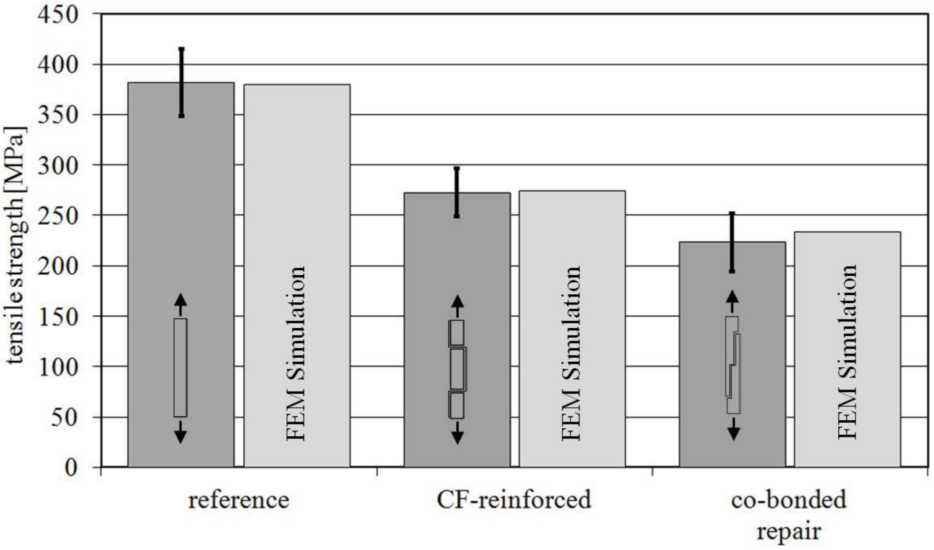

Figure 6: Tensile joint strength of GFRP-laminates (cp. [5]).

5. Experimental and Numerical Results

In order to estimate the potential to restore the tensile strength, we first investigate the influence of bore holes on the parent structure. I.e. the strength reduction due to the introduction of drilled holes is determined based on the described Finite Element modeling. In comparison to the yarn idealization according to section before, the yarn is modeled here as ideal-elastic orthotropic continuum without any failure behaviour. In Figure 7, the parent material is indicated as reference with no holes. This reference is compared to two different parent materials, first, to one which has the same layer set-up but different hole combinations (dark grey) and secondly to a parent material which is doubled by the overlap that occurs in the repair (cp. Figure 1). The latter one is consequently thicker by t = 0.53 mm than the parent component of the repair. The hole combinations comprise parent material with holes that are not filled, holes filled with resin as well as with carbon fibre (CF) yarn. Figure 7 clearly indicates that the strength reduction due to the drilling of bore holes can be compensated to a certain value by filling the hole by CF yarns. If the parent material is not doubled in thickness by the overlap, the limit is possibly about 90-92 % of the strength of the parent material. If a thickness enlargement is allowed as possible by the repair under investigation here, then a strength restoration of up to 100 % seems likely.

In Figure 8, the tensile strength is compared between repair specimens with different bore hole angles of the reinforcing yarn. A carbon fibre yarn is used to reinforce the bonding area. The experimental investigations as well as the Finite Element simulations do not show a clear influence pattern as well as a clear performance improvement. This is possibly due to the highly nonlinear impact of the bore

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hole angle on the mechanical behavior. The nonlinear influence is caused by the selected layer set-up, the number of steps in the repair, the material of the reinforcing yarn and the position of the bore holes among others. Due to this complexity, only bore hole angles of 90° (U-shaped and T-shaped) are considered in the following.

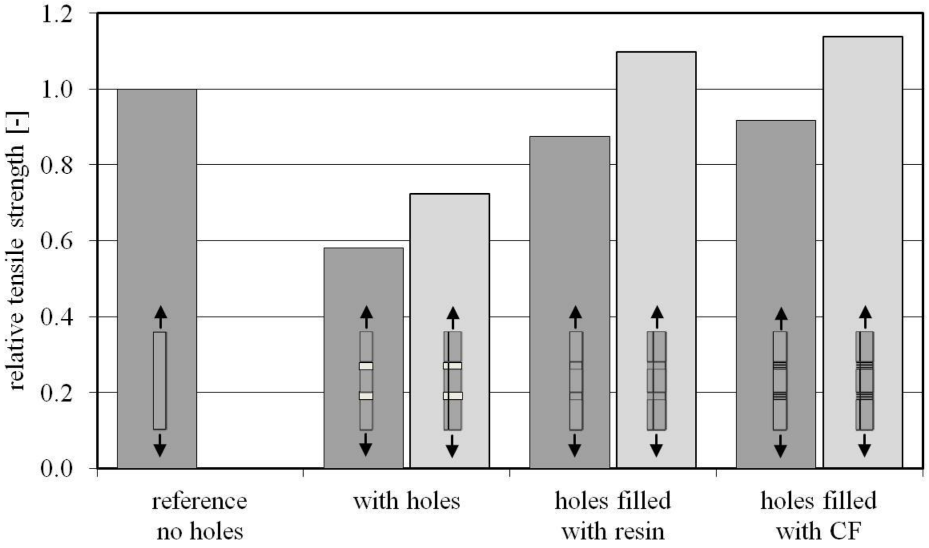

Figure 7: Strength of parent material (reference) compared to parent materials weakened by bore holes filled differently based on simulations.

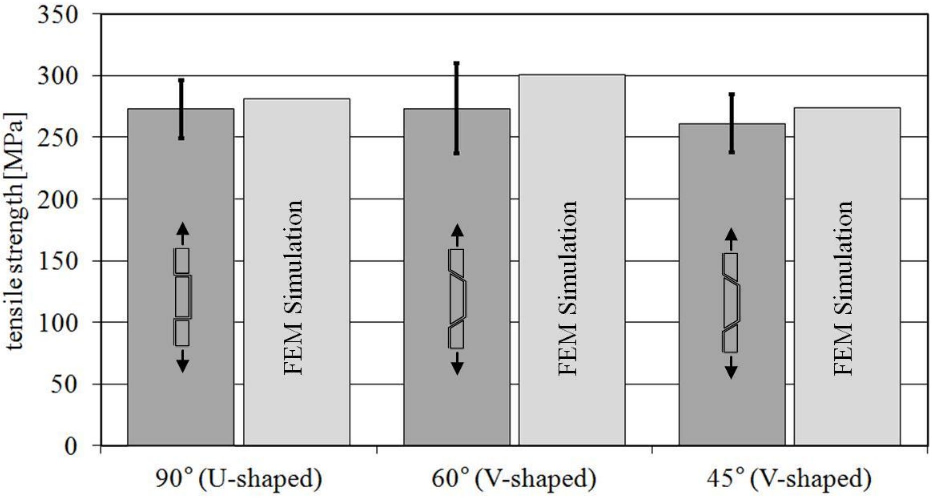

Figure 8: Strength of specimens with different bore hole angles (bonding area is reinforced with carbon fibre yarn) based on experiments and FEM simulations.

In Figure 9, the effects of hole diameter as well as the fibre volume content of the reinforcing yarn on the strength are shown. The experimental result is shown in the middle in dark grey. The values to the left and right are simulation results. To the left, the hole diameter is decreased leading to an increased fibre volume content of the yarn. The diameter is decreased in such a way that, first, the yarn is twice as strong as the original one (28 % original fibre volume content). Then, the simulation results for theoretically possible fibre volume contents for quadratic as well as hexagonal fibre packing (≈79 % resp. 91 %) are given. To the right, the same fibre volume contents are set but now by adding additional fibre material into the unchanged hole, i.e. with constant diameter. The simulation results suggest that a reinforcement of the yarn in the holes that is twice as strong as the one used in the experiments can improve the tensile strength by about 20 % points. To summarize, as much yarn

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material should be introduced into the drilled bore holes as possible. And simultaneously, the bore holes should be as small as possible.

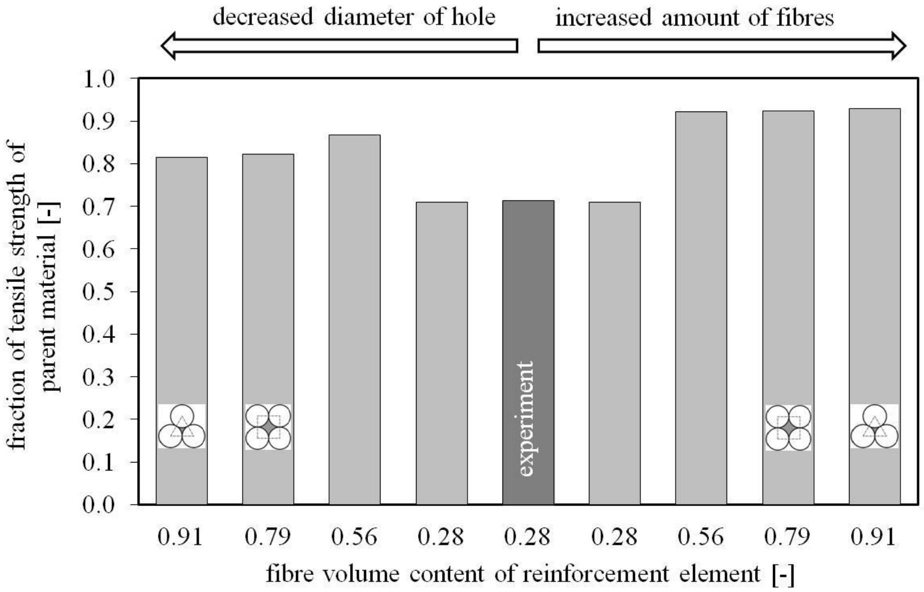

Figure 9: Influence of fibre volume content of carbon fibre yarn reinforment on tensile strength.

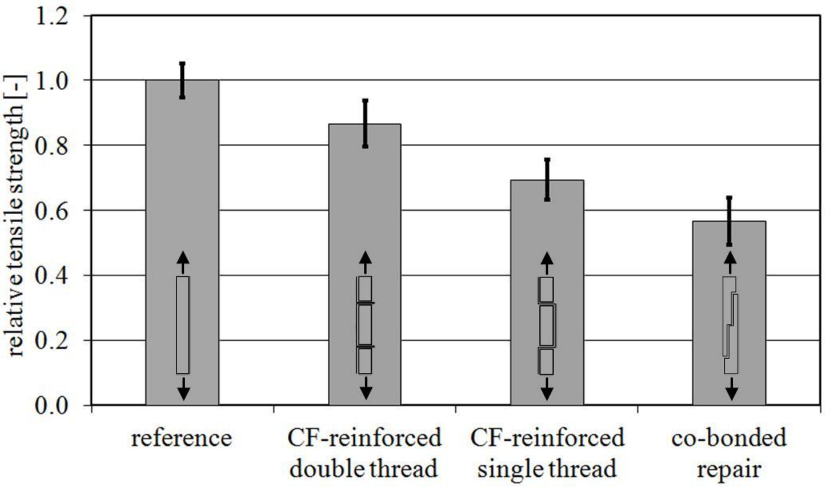

Figure 10: Influence of double thread in bore hole on tensile strength based on experiments.

In Figure 10, experimental results are given where the fibre volume content in the holes with constant diameter is increased using tufting technology. As a result, we obtain a double thread in the hole. The tensile strength is increased compared to the single thread by about 17 % points to about 87 % of the tensile strength of the parent material.

6. Conclusion

A hybrid repair technique for composite components made of GFRP specimens where the bonding area is reinforced with high performance multifilament yarns is investigated. The tensile strength of such repairs can likely be restored to about 90 % of the undamaged specimens without any specific surface treatments. This is due to the fact that the reinforcing influence of the yarns on the bonding can

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clearly outperform the weakening effect of the drilled holes which are needed for the connection between parent part and repair patch. As a consequence, the proposed hybrid repair technique shows a high potential to be applied in repair problems where unfavourable environmental conditions strongly endanger the bonding effect of adhesives or where very limiting geometric constraints reduce the bonding area to unrealistic values for pure bonding joints.

Acknowledgement

The authors gratefully acknowledge the financial support through the project „StructRepair+ - Reparatur struktureller Bauteile aus faserverstaerktem Kunststoff mit zusaetzlicher Vernaehung der Fuegestelle” (AiF grant no 17972 N) within the framework of the research funding programme of the Cooperative Industrial Research Association promoted by the German Federal Ministry of Economic Affairs and Energy.

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