STRATEGIES TO INCREASE THE MECHANICAL PERFORMANCE OF LONG FIBER PATCH PREFORMS

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Keywords: Curvilinear load path, Long fiber reinforcement, Fiber patch placement,

Abstract
Load path optimized design comes typically with the aim to use as less carbon fiber as possible but still has optimal mechanical properties. Different placement technologies exist which are facing problems when it comes to small radii of curvature. The use of patch placement gives a high flexibility for layup design and therefore offers a high potential in this field. Compared to laminates with continuous fiber, patched laminates suffer from peeling forces in the outer plies under tension force. This leads to premature failure. Since this effect becomes more and more important for laminates with fewer layers a study is presented which investigated the influence of different amount of layers on the mechanical properties and failure behavior. This study shows that for specimens with fewer layers this effect leads to a catastrophic failure while specimens with increasing amount of layers are failing gradually while constantly peeling off plies towards the center of the specimen. To reduce this peeling effect two different overlap designs for the outer plies were investigated. The results show that an overlap of 3 mm already leads to an increase in tensile strength by 5.5 % and therefor is an effective way to increase the performance of patched laminates.

1. Introduction

Since the potential of cost reduction for carbon fiber is limited the overall aim to reduce the manufacturing cost of composite structures is to lower the consumption of carbon fiber with near net-shape preforms and load optimized design [1]. One promising way to achieve this goal is to build up preforms sequentially with fiber patches using the fiber patch placement technology (FPP) [2][3]. Therefore a high flexibility in terms of fiber orientation is achievable which leads to a better use of the potential of carbon fiber. Those patches are typically cut of unidirectional fiber spread tape but can also be made of scrap material produced by kit cutting and thus having a positive impact on the recycling loop [4]. The design of patched laminates differs from the traditional design of composite laminates. Since no continuous fibers are used the patches have to be positioned in a way that the applied loads can be transfered between the patches by shear forces. Each ply of a laminate consists of a specific amount of patches with predefined length which are laid up so they butt up against each other and in consequence form a ply of aligned fibers with a grid of distributed discontinuities. The next ply has to be positioned with an offset to the previous ply to avoid that two discontinuities are stacked directly on top of each other. Furthermore the discontinuities have to be distributed equally in the laminate to have homogeneous mechanical properties since every discontinuity lowers the stiffness locally due to the interrupted fiber course. Therefore this offset between two bordering plies is dependent on the patch length chosen to assure a homogeneous distribution of the discontinuities. Based on those prerequisites a specific patch pattern is resulting to

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

enable high mechanical properties. The influence of patch pattern on tensile strength is sketched on figure 1. On this illustration one patch of each layer is illustrated by a line, the discontinuity by a gap. For example one all discontinuities are positioned on top of each other. The maximum tensile strength is thereby defined by the one of the resin system which is the weakest part of the laminate. On the other hand in example four the stacking sequence is optimized to maximize the distance between two discontinuities which results in higher tensile strength.

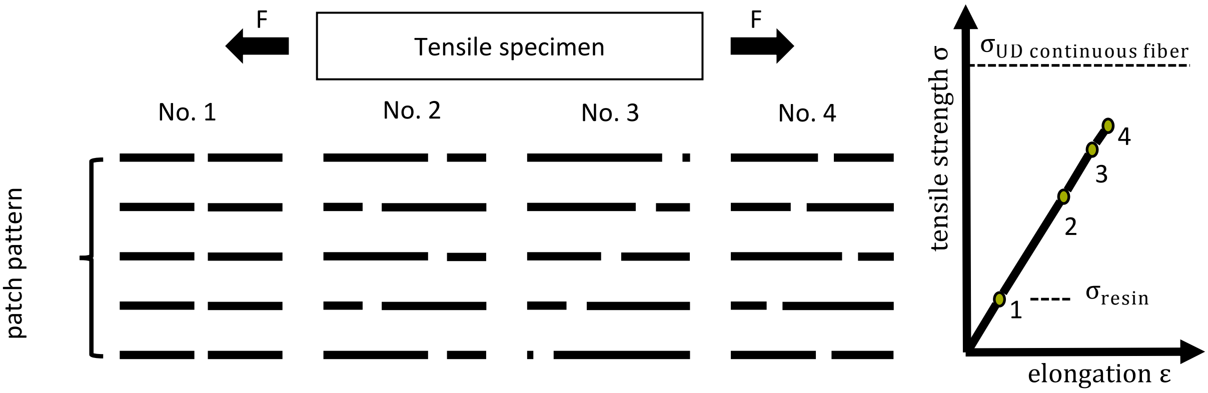

Figure 1. Influence of patch pattern on tensile strength (modified from [3])

Previous studies showed that peel forces which arise at the discontinuities on the outer plies lead to premature peeling off of the outer plies and can therefore influence the mechanical properties of the specimen [5]. This effect can become crucial for specimens with fewer plies since the outer plies have a higher percentage of the total amount of plies. Different strategies have already been developed to decrease this influence. Czél for example proposes to halve the thickness of the outer layer of the specimen to lower this influence [6]. Based on this approach a strategy could be to build a laminate with thicker patches for the inner layers and to use thinner patches for the outer layers. By now the FPP machinery can only use one type of material which has to be defined before start of manufacturing and then has to stick to this predefined areal weight and can not vary it for the outer plies. This leads to a demand for new strategies to reduce the peeling stresses in the outer plies and thus increase the mechanical performance of patched laminates without varying the thickness of the patches. In this study two overlapping designs for the outer plies are investigated and compared to a reference concept without gap or overlap. The strain field of the coupons has been recorded with a digital image correlation system (DIC-system) to reveal differences in failing for each concept. To define a suitable amount of layers for the specimens a pre-study with specimens of different amount of layers has been conducted to reveal a possible influence of the number of layers on the mechanical properties.

2. Materials and Method

For investigating the influence of different stacking sequences on tensile strength and Young's modulus the tensile test is chosen. The specimens are prepared according to EN ISO 527-4 type 2 with 150 mm of free length [7]. The width of the specimens has been changed to 15 mm due to manufacturing restrictions. As mentioned above a patched laminate needs a specific patch pattern which influences its mechanical behavior strongly. Therefore every specimen has been manufactured using the same patch pattern consisting of five layers based on a patch length of 60 mm. To calculate the shift between two layers and to assure that the discontinuities are distributed homogeneously the patch length has to be divided by the amount of layers per patch pattern. Here this leads to one discontinuity in thickness direc-

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tion per 12 mm for every patch pattern. The pattern used also maximizes the total distance between the discontinuities which therefore increases the overlapping area between the layers. The pattern is shown in figure 2. Compared to a pattern using symmetric or equal shifting between two layers this asymmetric approach shows higher tensile strength. If a specimen is build up patch with a length of 60 mm, this would also lead to discontinuities close to the cap strips. This can have negative effect on the failing behavior of the specimen or lead to a failure outside of the view of the DIC system. To force the specimen to fail in an area around the center of the coupon every layer consists of only one discontinuity. Therefore a specimen is resulting which is patched around its center and has continuous fibers around the area of the cap strips.

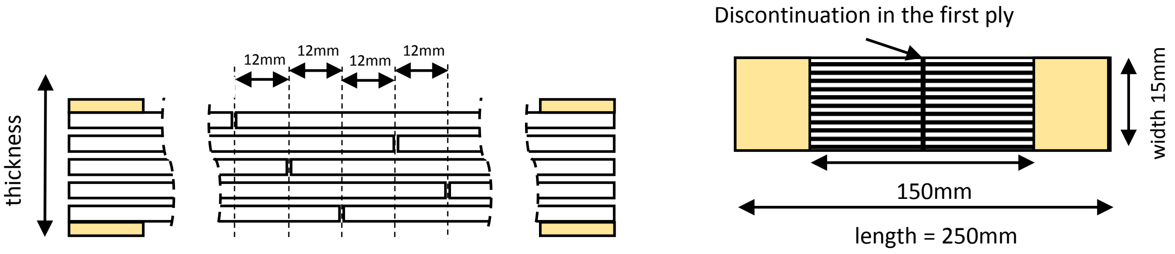

Figure 2. Patch pattern (left) and specimen dimensions (right)

For the investigation of the influence of coupon thickness on the mechanical properties three specimens with 5, 10, 20 and 30 layers have been manufactured. This increments have been chosen according to the fact that the basic patch pattern consists of five layers and is then multiplied to form thicker specimens. To prevent the outer plies to peel off before failing of the coupon two stagging sequences are evaluated to identify their influence on the mechanical properties. Specimen with ten layers were chosen for this study. A design with an overlap of 12 mm and a design with a 3 mm overlap is used. Those results are then compared to a reference design made of bordering patches without gap or overlap. The different designs for the outer plies are shown in figure 3.

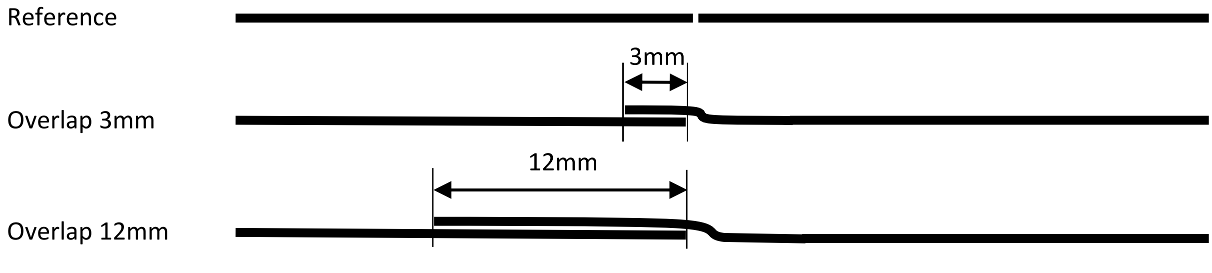

Figure 3. Specimen design of the outer plies

The material used in this study is Oxeon Textreme HTS45 unidirectional carbon fiber tape with a width of 20 mm. This tape already has an epoxy binder applied on one side. SIKA CR80 resin and CH10 hardener is used as epoxy resin system. The areal weight of the tape is 80 g/m^2. Since the FPP machine currently only supports patches with a fixed length the patches are cut by hand and preformed using a heating iron. Material data is shown on table 1.

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Table 1. Material data

Material	Type	Manufacturer	Tensile Strength (MPa)	Youngs Modulus (GPa)	Density g/cm^3
Textreme HTS 40	Spread tow tape	Oxeon	4300	240	1,77
CR 80 - CH 10	Resin and hardener	Sika	69	3,3	1,16

All specimens have been infiltrated at room temperature using the vacuum assisted process (VAP). After curing, a tempering cycle of 16 h at 55 °C has been applied to increase the material properties of the resin system according to material data sheet. The tensile tests are executed at the chair for carbon composites with a Hegewald & Peschke inspect 250 universal testing machine and a movement speed of 1.5 mm/min. To determine the strain and stresses of the coupon a DIC system (ARAMIS by GOM, picture rate: 1 fps) is used and positioned in front of the coupon. The specimens are tested until final failure.

3. Results and Discussion

The results of the study on the influence of different amount of layers on tensile strength and Youngs modulus are shown in figure 4. It can be seen that with an increasing amount of layers the specimens can suffer a slightly higher tension before failing. Youngs modulus is not affected by the variation of the amount of layers.

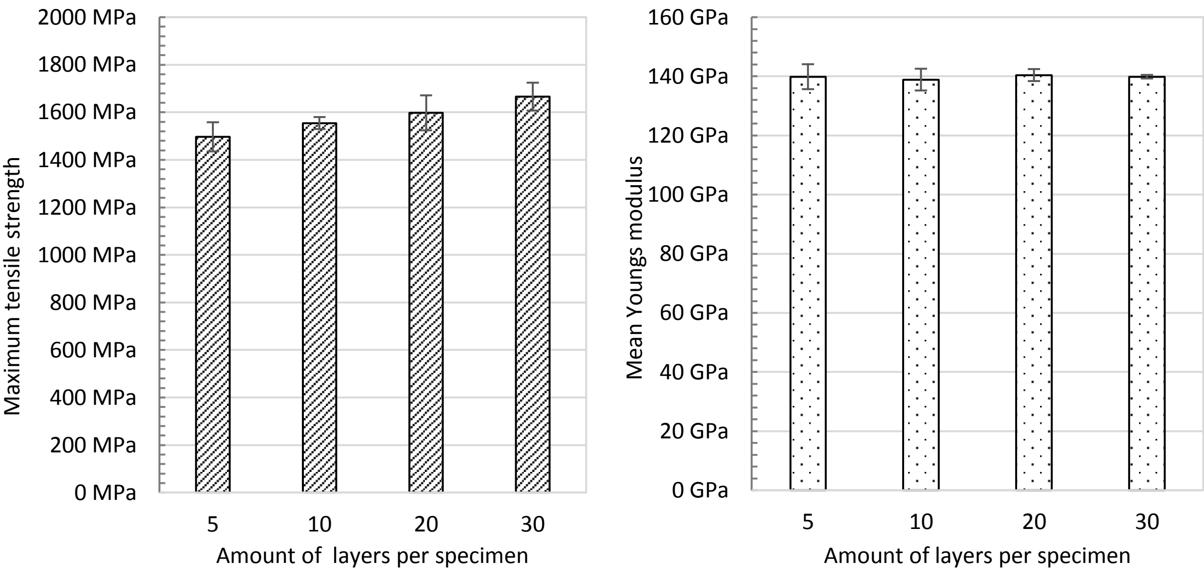

Figure 4. Maximume tensile strength (left) and Youngs modulus (right) for specimens with different amount of layer

This results for Youngs modulus is not surprising since the peel off of the outer plies happens close to the final failure of the specimens while the modulus is measured at lower strains. The mean value of Youngs modulus for the different specimens is approximately 140 GPa which is very similar to the theoretical value of 145 GPa which can be calculated using the mixture rule, a fiber volume fraction of 60 % and the data provided in table 1. This calculated value could also be reproduced with tests of specimens of

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the same materials and a continuous fiber course instead of a patched approach. This shows that the use of patches does not influence the stiffness of a laminate negatively. While the mechanical properties do not differ much between the different types of specimens, the failure behavior is strongly affected by the amount of plies. The failure of the specimen starts with a peel away of patches on the outer plies. With increasing load the outer patch peels off up to the cap strip and reveals discontinuations in the lower plies. The lower plies for there part start to peel and therefore continue to reduce the cross section of the specimen. For specimens with a less amount of layers this leads to a catastrophic failure since the outer plies have a high percentage of the total amount of plies. With increasing amount of layers the failure occurs gradually starting in the outer plies and moves towards the middle with constantly peeled off plies. As an example the stress / displacement curve of a specimen with 5 and 30 layers is shown on figure 5. While the specimen with 5 layers show a catastrophic failure the specimens with 30 layers has a pseudo ductile behavior before finale failure.

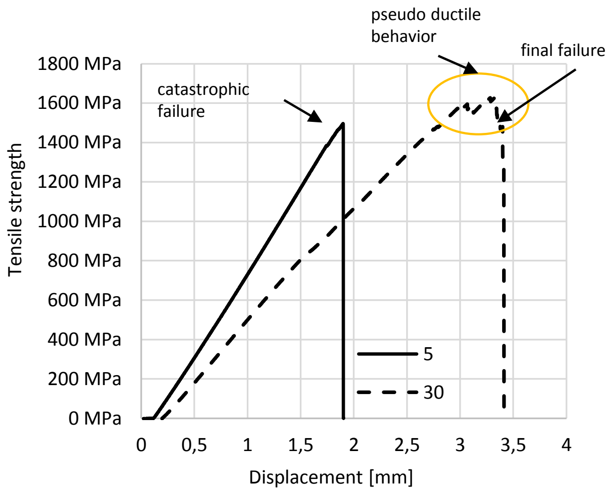

Figure 5. Stress / displacement curve of a specimen with 5 and 30 layer

The results for different stagging designs of the outer plies are shown on figure 6. Compared to the reference concept an overlap of 3 mm leads to an increase in tensile strength by 5.5 %. A larger overlap can increase the mean tensile strength by additional 2.5 % but due to the standard deviation a significant difference can not be identified between the different overlap concepts. Youngs modulus is not affected by different overlaps.

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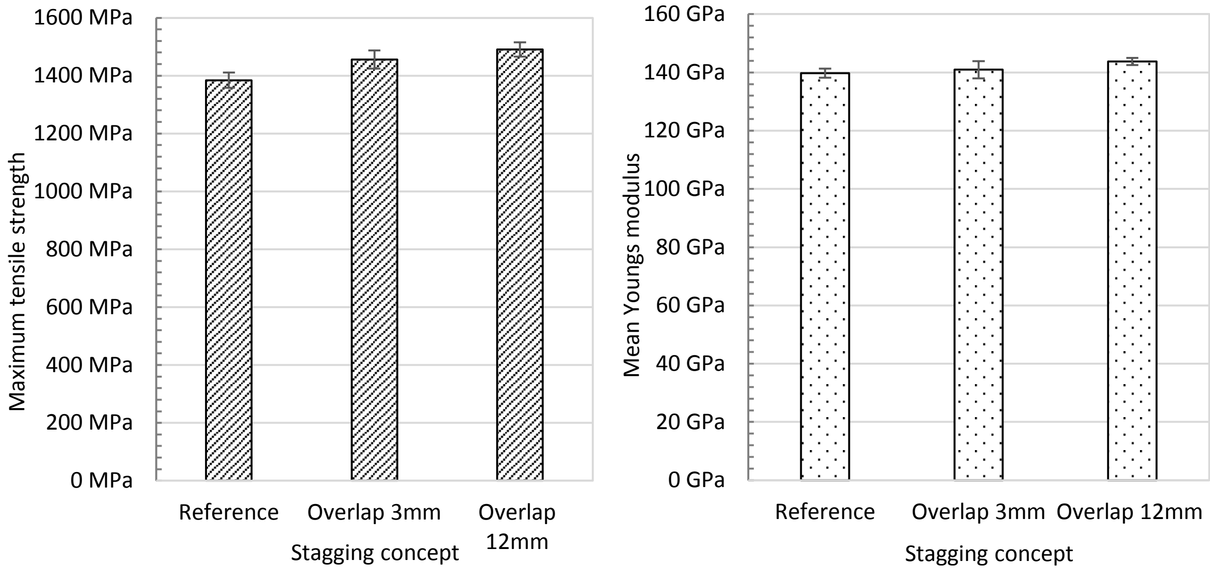

Figure 6. Maximume tensile strength (left) and Youngs modulus (right) for specimens with different overlap pattern in the outer plies

4. Conclusion

Load path optimized design mostly comes with the aim for a minimum use of fiber material. Therefore thin plies are used to achieve good mechanical properties with less material input. One approach in this direction is the use of fiber patch placement technology. Despite all advantages, patched laminates suffer from premature peeling off due to high peeling stresses in the outer plies under tension load. This effect becomes very important for laminates with a low amount of plies. In this case the outer plies have a high percentage on the total amount of plies. Once the outer plies are peeled off the cross section becomes a fraction of its initial size and therefore the specimen fails. Due to the fact that the peeling moves from the outer plies towards the middle, specimens with a large amount of plies show a state before failure where they constantly peel of plies while still be able to suffer maximum tension. This is an interesting finding since typically composite materials are failing catastrophic without any advance notice. In this case a structure made of patches would start to degrade which could be inspected visually while it would still be able to suffer the applied load. While peeling forces in the outer plies are a major reason for a premature failure of the specimens different concepts were evaluated to identify their influence on the mechanical properties. Since the study with specimens of different amount of layers showed that the amount of plies do not have a larger influence on tensile strength or Youngs modulus, the concepts were investigated using specimens with ten plies. Smaller specimens would have been too difficult to handle due to the very thin material used. Two different concepts with 12 mm and 3 mm overlap between two bordering patches in the outer plies have been evaluated. The results showed that with overlapping patches in the outer plies by 3 mm the maximum tensile strength could be increased by 5.5 % compared to a reference design where the outer plies were not overlapping. It is important to say that this increase comes with a higher material input needed. When regarding a laminate with ten layers and every layer has the same dimensions this would lead to an additional material input of 1 % of the total material needed. In this case an overlapping pattern is applied on the outer layers on both sides of the laminate. When using the concept with 12 mm overlap the amount of additional material would increase up to 4 % of the total amount of material. For this concept the mean tensile strength could be increased by additional 2 %. When comparing this increase of performance with the material needed it shows that this is not

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efficient. Since the overlaps come with additional material this can lead to an uneven surface and a local variation in fiber volume content. In this study material with 0.08 mm per layer was used. In this case this unevenness could not be identified. When using material with larger areal weight and in consequence a higher thickness per layer the surface might get uneven. Also the resin pockets which occur at the point where the overlapping layer initially overlaps the subjacend layer become larger. These spots promote an initial crack propagation and can therefore influence the mechanical properties in a negative way. Since the use of material with higher areal weight increases the productivity of fiber patch placement technology, these topics are subject for further investigations.

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