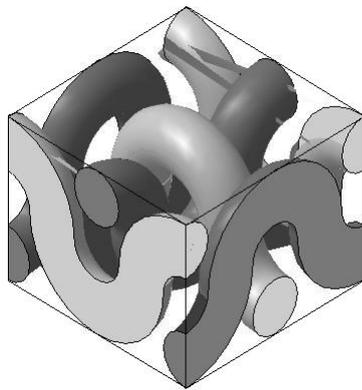




Executive summary

A new experiment procedure to predict the mechanical properties of composites reinforced by braided fiber bundles

Part 1: Model description and experiment definition



Problem area

Using the Resin Transfer Moulding (RTM) manufacturing technique, it has become possible to produce thick composite components in a cost-effective way. These components are more and more applied in aerospace structures. A reinforcement method of these composites is done by means of large tow-size braids.

Insufficient knowledge is available on the stiffness and strength behaviour of thick composite structures reinforced by large tow-sized braids (referred to as braids). The objective of this program is to develop a model that predicts the stiffness and strength of braided composite materials using large tow-size as a function of braiding angle.

The investigation was financed by the NIVR and for 25% by Stork SP Aerospace.

Description of work

In the framework of the NIVR Strategic Research Programmes, an investigation to the mechanical properties of braided composite materials using large tow-size carbon fibers was started.

This report will be used at a, to be determined, conference.

Results and conclusions

A testing procedure on braids in order to obtain these properties has been defined, as well as how the results from these experiments must be interpreted.

Report no.

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Author(s)

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Knowledge area(s)

Aerospace Materials
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Descriptor(s)

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Failure Criterion
Strength

A new experiment procedure to predict the mechanical properties of composites reinforced by braided fiber bundles

Part 1: Model description and experiment definition

The fact that large tow-size braids are concerned resulted in an adjustment of the size of the test coupons.

Applicability

The test specifications on the geometry of the test coupons applied in this project can be used as guidelines when mechanical properties of any composite

material (braid or fabric) have to be determined in future research projects.

The resulting computational model of the mechanical properties in this NIVR-SRP programme can be used for the design and analysis of structural components made of braids.



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Part 1: Model description and experiment definition

S. van den Berg

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The contents of this report may be cited on condition that full credit is given to NLR and the author.

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Summary

A model to predict failure of composite braids is described. The mechanical properties of the separate constituents and the braid geometry are input for the model.

Experiments - and the interpretation of their results - to obtain the input are defined. The geometry description is based on Naik's [1] model.

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Nomenclature

Abbreviations:

CLPT	classical laminate plate theory
FEM	finite element method
NLR	national aerospace laboratory
RTM	resin transfer moulding
RUC	repetitive unit cell
UD	uni-directional

Mathematical Symbols:

Roman

a	half bundle width	[m]
b	half bundle height	[m]
c	space between bundles	[m]
E	Young's modulus	[Pa]
F	stress allowable	$[N/m^2]$
h	braid ply thickness	[m]
k	$\cdot 10^3$	[-]
x	index	[-]
w	RUC width	[m]
y	index	[-]

Greek

α	rotation angle	[$^\circ$]
γ	shear	[-]
ε	strain	[-]
θ	braid angle	[$^\circ$]
ζ	bundle path	[-]
σ	stress	$[N \cdot m^{-2}]$
τ	shear	$[N \cdot m^{-2}]$

Subscript

c	compression
f	fibre
m	matrix
t	tension



x	global direction
y	global direction
xy	global direction
1	local direction
2	local direction
12	local direction
Superscript	
c	compression
t	tension

A NEW EXPERIMENT PROCEDURE TO PREDICT THE MECHANICAL PROPERTIES OF COMPOSITES REINFORCED BY BRAIDED FIBER BUNDLES

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ABSTRACT

A model to predict the failure of composite braids is described and applied to obtain the mechanical properties of the separate constituents in a composite material reinforced by braided fiber bundles. The results of tension and compression experiments on coupons and the braid geometry are input for the model. The required experiments – and the interpretation of their results – to obtain the input are defined. The geometry description is based on Naik's [1] model. This project showed that the non-linear material behavior of the matrix material points to using - similar to metals - σ_y at limit load during the design process. The width of the test coupon should exceed the width of the repetitive unit cell of the braid in order to obtain proper experiment results. This is required to properly load the fiber bundles in the coupon.

1. INTRODUCTION

Using the Resin Transfer Molding (RTM) manufacturing technique, it has become possible to produce thick composite components in a cost-effective way. These components are more and more applied in aerospace structures, e.g., to replace metal forgings like landing gears. A reinforcement method of these composites is done by means of braids with large tow sizes. Insufficient knowledge is available on the stiffness and strength behavior (mechanical behavior) of thick composite structures reinforced by braids (referred to as braids). The objective of this research is to develop a model that predicts the stiffness and strength of braided composite materials as a function of the braiding angle.

In the framework of several technology programmes the Structures Technology Department of NLR developed a computational model to predict failure in a composite braid. In contrast to other research on braids, this research has as its focus the prediction of failure of the braid or, in other words, to predict the strength of a braid. This programme has been carried out in close collaboration with Stork SP aerospace, and was partly funded by the Netherlands Agency for Aerospace Programmes (NIVR). An extensive literature survey on methods to compute a braid's strength and elasticity showed that an analytical approach is most effective for the purpose of the predictive model. The purpose of the proposed model is to be applied in a finite element model of a composite product where, e.g., as a result of the production process, the braid angle varies. Stresses and failure in the braid is predicted using the braid angle at each integration point of the FEM model.

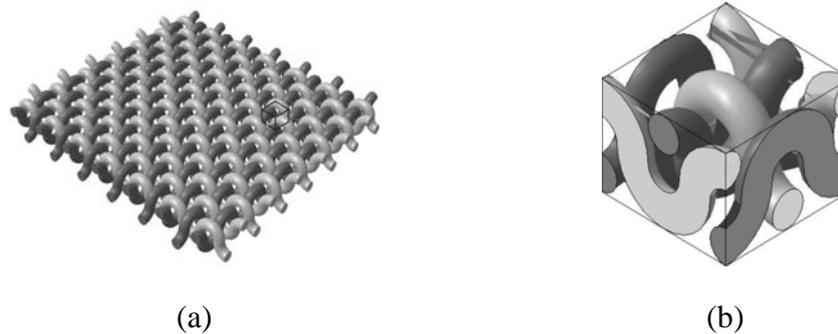


Figure 1: Obtaining the RUC: a) An illustration of a simple fabric; b) A repeating unit of the simplified fabric.

The fundamental theory of the predictive model is based on the assumption that the undulation of the fiber bundles causes the mechanical properties to decrease. The stresses in the braid are predicted using the braid angle and the undulation of a fiber bundle in combination with the classical laminate plate theory (CLPT). Rotation occurs in braid and therefore in undulation angle; in this way a somewhat 3D CLPT procedure emerges which is necessary to take the fiber's undulation into account. Distinction in the CLPT procedure between tensile and compressive stresses is implemented as well.

2. GEOMETRICAL MODEL

The model requires geometrical properties of the braid in order to obtain the undulation path of the fiber bundles. These geometrical properties are obtained using simple measurements in a Repetitive Unit Cell (RUC) of the braid; see Figure 1 for an example of a RUC of a plain weave fabric.

The focus of this research is not to describe a braid's geometry in elaborate detail, as a very refined geometry is not necessary for the proposed predictive model. A description of the bundle path, denoted by $\zeta(x)$, is required. Therefore, some assumptions on the bundle path have been made to keep the model simple and straightforward: 1) the bundle height, $2b$, is half the braid ply thickness h ; 2) the warping bundle perfectly follows the shape of the fill bundle; 3) the shape of the fill bundle is described by an ellipse.

An arbitrary braid using these assumptions is illustrated in Figure 2, which shows that $\zeta(x)$ can be described by easily obtained geometric properties of a fabric. These geometric properties are the bundle height $2b$, the bundle width $2a$ along cross-section A-A, the RUC width w , the space between the bundles c , and the braid angle θ . Figure 2 shows an overview of these variables in a schematic representation of a braid. Many other models also try to implement variables such as the fiber content and the nesting factor which take complex considerations to implement into a geometric model.

3. PREDICTION OF THE MECHANICAL PROPERTIES

Important input parameters for many predictive models, e.g. CLPT, to obtain the mechanical properties of a laminate are the mechanical properties of the separate constituents; this is also the

case for the current model. These properties are obtained by experiments described by several ASTM standards [2-4].

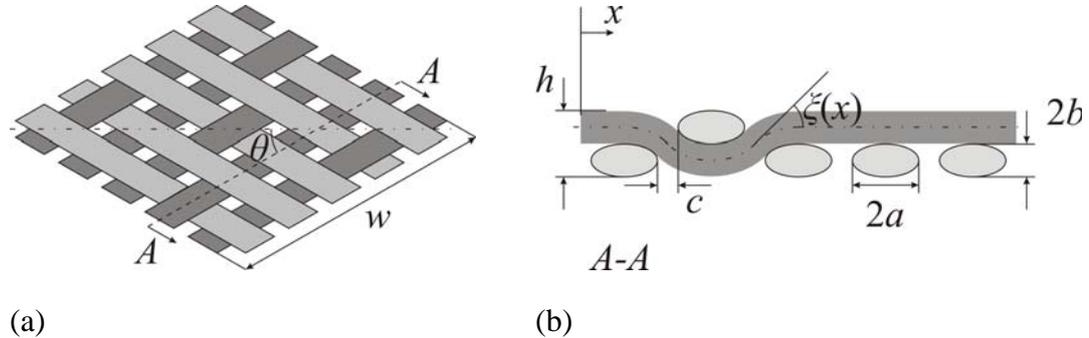


Figure 2: RUC Analysis: a) Top view of the RUC; w denotes the width of the RUC, θ denotes the braid angle. b) Side view of the RUC; h denotes the height of the braid ply, a denotes half the bundle width along cross-section A-A, b denotes half the bundle height and $\zeta(x)$ denotes the variable undulation angle along the bundle. The dark grey area represents the warp bundle; the light grey area represents the fill bundle.

At this point, it is very important to realize that the properties of the separate constituents obtained by these experiments are not pure dry fiber/bundle properties or matrix properties. The mechanical properties are a combination of several occurring interactions. These interactions include the combining of the elastic properties of both constituents, the interactions between the constituents and between the bundles in the fabric. The current model makes use of these interactions during the experiments, which mean that they do not have to be implemented separately.

The material properties of braids are usually assigned by means of the material directions. However, these directions are not in accordance with the material directions as for UD-ply and fabrics. The material directions for UD-ply and fabrics are aligned or perpendicular with the fiber directions (warp-direction is usually referred by the 1-direction) while this is usually not the case for braids (see Figure 3). From this consideration it may be clear that it is not straightforward to separate the mechanical properties of the different 'UD-braid' properties. Therefore a procedure is proposed to separate the desired mechanical properties of the constituents in a braid.

3.1 Experiment Definition

As mentioned above, it is not straightforward to separate the mechanical properties of the constituents in a braid. This can be explained by the fact that the mechanical properties in these directions do not represent properties of the separate constituents but a combination of them (see Figure 3).

For example, consider a multi-axial load resulting in a load case where mainly the fibers are loaded. The allowables based on uni-axial load cases where failure is governed by a combination of the material properties of the separate constituents, fibers and matrix, will result in a much

smaller prediction of the maximum allowable stress than the fibers can handle in this case. This example is shown in Figure 4.

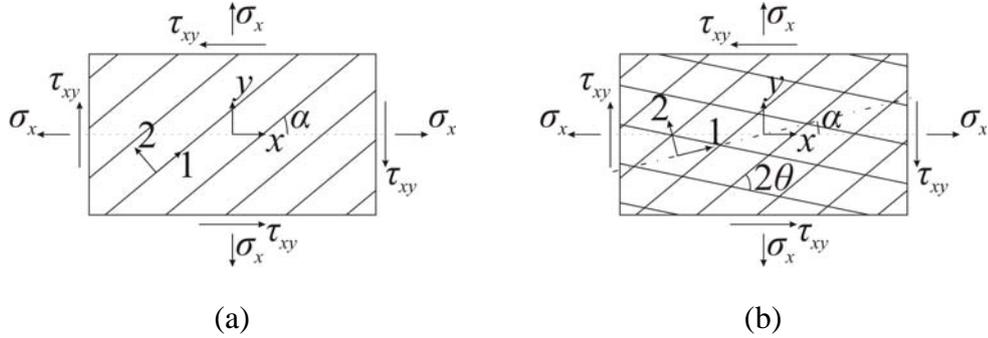


Figure 3: A composite ply under an arbitrary load with its material directions, the solid lines are representing the fiber bundles and the striped line shows the braid’s direction. The ply rotation is represented by α a) UD-ply; b) braid-ply, the braid angle is represented by θ .

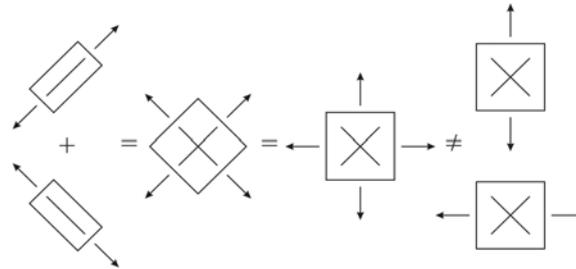


Figure 4: Multi-axial load-case in a braid.

A theoretical study combining CLPT and two failure criteria, namely the Puck [5] and the Hashin [6] failure criterion, have been executed to determine which experiments should be executed on test coupons. These failure criteria both consist of a separate fiber failure prediction and a matrix failure prediction from an arbitrary stress state on a UD-ply. Equation 1a describes fiber failure, $f > 1$, according to Hashin where superscript c represents compression and superscript t represents tension. Equations 1b and 1c describe matrix failure, $m > 1$, according to Hashin in tension and compression respectively. Equation 2a describes fiber failure in tension or compression according to Puck. Equation 2b describes matrix failure in tension or compression according to Puck.

$$\left(\frac{\sigma_1}{F_1^{t/c}} \right) = f^{t/c} \tag{1a}$$

$$\left(\frac{\sigma_2}{F_2^t} \right)^2 + \left(\frac{\tau_{12}}{F_{12}} \right)^2 = m^t \tag{1b}$$

$$\left(\frac{\sigma_2}{2F_{12}}\right)^2 + \left(\left(\frac{F_2^c}{2F_{12}}\right) - 1\right)\frac{\sigma_2}{2F_2^c} + \left(\frac{\tau_{12}}{F_{12}}\right)^2 = m^c \quad (1c)$$

$$\left|\frac{\sigma_1}{F_1^{t/c}}\right| = f^{t/c} \quad (2a)$$

$$\left(\frac{\sigma_2}{F_2^{t/c}}\right)^2 + \left(\frac{\tau_{12}}{F_{12}}\right)^2 = m^{t/c} \quad (2b)$$

In these equations, the maximum allowable stress in fiber-direction is denoted by F_1 , the maximum allowable stress perpendicular to the fiber-direction is denoted by F_2 and the maximum allowable shear stress is denoted by F_{12} .

It is assumed that the resulting experiments are also suitable to determine the stiffness properties of each of the constituents using the corresponding experiment.

The load cases are restricted to those that can be translated into uni-axial load cases. The reason for this restriction is that these are the only cases that are really practical in a normal (industrial) test environment: $\pm 30^\circ$, $\pm 45^\circ$ and $\pm 60^\circ$ are the only braid angles considered. The study has been executed for an epoxy resin/high strength carbon fiber combination using in-house material data.

During the derivation of the experiments a distinction has been made between experiments to obtain the fiber properties, E_1 and F_1 , and the matrix properties, E_2 , G_{12} , F_2 and F_{12} . An experiment to obtain the fiber properties should result in a stress state where the m/f -ratio has a minimum value. This way, the properties of the matrix material has as little influence as possible on the result of the experiment. This resulted in an experiment on a $\pm 45^\circ$ -braid which has been rotated 45° (see Figure 5(a)).

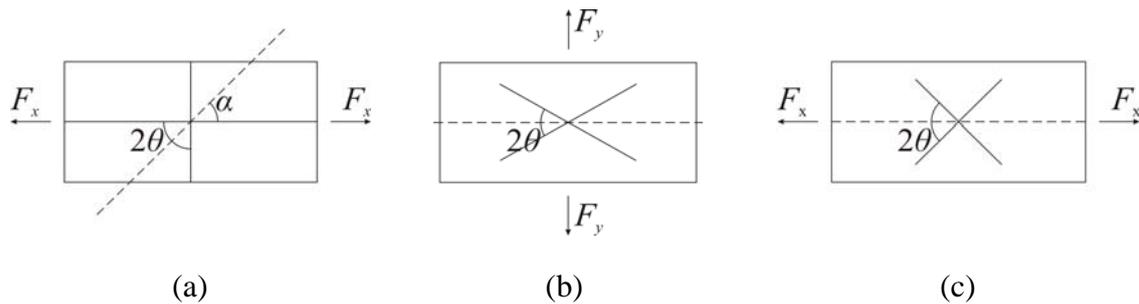


Figure 5: Experiments to obtain the material strength properties F_1 , F_2 and F_{12} for compression and tension; a) $\theta = \pm 45^\circ$, $\alpha = 45^\circ$ b) $\theta = \pm 30^\circ$, $\alpha = 0^\circ$ c) $\theta = \pm 45^\circ$, $\alpha = 0^\circ$.

The experiments to obtain the matrix properties (E_2 , G_{12} , F_2 and F_{12}) require a somewhat different consideration since the matrix material has properties in normal and shear direction. The f/m -ratio needs to be minimized to make sure that matrix failure is the main failure mode, and the load-case should result in the proper stress-state. To determine F_2 , the $[\tau_{12}/\sigma_2]$ -ratio should be as small as possible, which results in the experiment shown in Figure 5(b). To determine F_{12} , the $[\sigma_2/\tau_{12}]$ -ratio should be as small as possible, which results in the experiment

shown in Figure 5(c). However, it is not possible to obtain a pure normal stress σ_2 without any influence of the shear τ_{12} for braid angles limited by $\pm 30^\circ - \pm 60^\circ$. It is also not possible to find a load-case where only shear exists. To overcome this problem and to determine the proper material properties, a procedure is proposed. Consider Figure 6 where an arbitrary quadratic failure criterion is depicted by the black oval shaped line. The grey dots on this line represent the results of the experiments. These can be extrapolated to the vertical axis using the failure criterion to determine F_{12} and extrapolated to the horizontal axis to determine F_2 . This procedure is shown in the figure for tension as well as compression. In the determination of F_{12} , the assumption is made that failure occurs at the same amount of shear in positive or negative direction (see Figure 3 for the sign convention in this research). The striped line in Figure 6 shows this assumption.

This figure also makes clear why the σ_2/τ_{12} ratio to determine F_{12} and the τ_{12}/σ_2 ratio to determine F_{2c} and F_{2t} must be as small as possible. The reason is that the extrapolation becomes more accurate when these ratios are minimized.

3.2 Test Coupon Dimensions

The dimensions of the test coupons, especially the width of the coupons, are of importance in relation to the actual mechanical properties of the braid. This is also mentioned in the ASTM standards [2-4] but concrete statements regarding the width of a coupon are not made. Similar research on this phenomenon [7] has been done previously and one of the conclusions was that the scatter of the experiments as well as the stiffness properties can be related to the width and length of the strain gauges. This gives the idea that the dimensions of the test coupons can be related to the RUC dimensions. To verify this, a similar experiment on this subject is executed in this project. The test coupons were made of epoxy resin/high strength carbon fiber combination. All coupons had the same thickness and braid angle. The width of the coupons was varied. The details of the applied braid are given in Table 1. The results of the experiments are depicted in Figure 7.

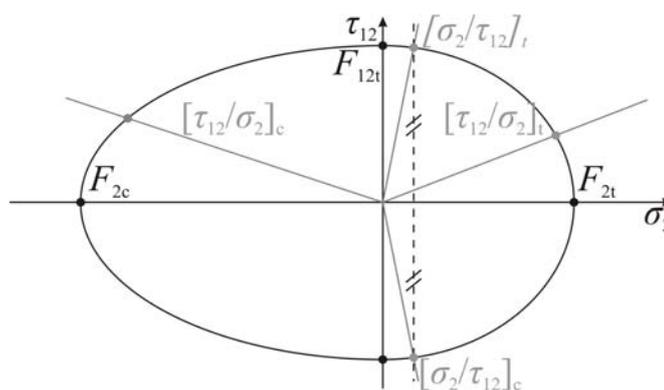


Figure 6: Determining the F_2 and F_{12} strength values of a braid. The grey lines represent the ply stress relations and the grey points on these lines represent when ultimate failure occurs in that stress situation. The black line represents the (quadratic) failure criterion and the black points at the axes represent the extrapolated strength values.

Table 1: Test Coupon Details

Material	epoxy resin/high strength carbon fiber
Bundle Thickness	24k
Braid Angle	30°
RUC Width	24 mm.
Coupon Thickness	4.08 mm.
Load Direction	x

Figure 7(a) shows the trend of the ultimate stresses σ_u against the width of the test coupons w_{coupon} . Figure 7(b) shows the trend of the yield stresses σ_y against w_{coupon} . One can see in Figure 7(a) that σ_u remains increasing after w_{coupon} exceeded the width of the RUC w_{RUC} while Figure 7(b) shows that σ_y is quickly converging after w_{coupon} has exceeded w_{RUC} . The large scatter for σ_y at $w_{\text{coupon}} = w_{\text{RUC}} = 2$ is caused by deviating braid angles in the test coupons.

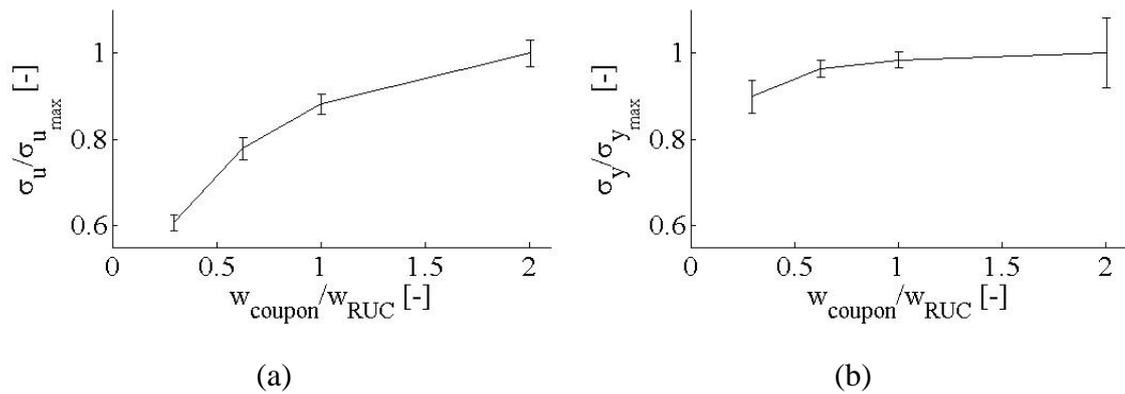


Figure 7: Experiment results: a) normalized ultimate stress, σ_u ; b) normalized yield stress, σ_y .

The Young's modulus, E , of the braid also shows a trend when the w_{coupon} is varied. The Young's modulus does not increase after w_{coupon} has exceeded w_{RUC} . This is depicted in Figure 8.

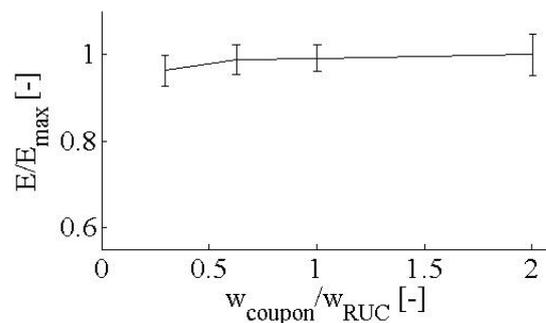


Figure 8: Experiment results: Young's modulus.

4. CONCLUSIONS AND RECOMMENDATIONS

The test coupons clearly showed matrix failure. This non-linear material behavior points to using - similar to metals - σ_y at limit load during the design process. As for failure stress, $\sigma_{0.2}$ has been applied from which the stress/strain components can be derived for the separate constituents using the 3D CLPT-procedure. Since $\sigma_u > 1.5\sigma_y$, σ_y at limit load becomes the design driver.

After investigating the test coupons the trends in Figures 7 and 8 can be explained. If the coupon width exceeds the RUC width, the fiber bundles can be properly loaded and the ultimate load becomes dominated by the strength of the fiber material. This is made clear in Figure 9. In Figures 9(a) and 9(b) it can be seen that besides matrix material, fibers have failed. In this figure, one can distinguish fiber pull-out and cracked fibers. The load cannot be properly transferred between crossing fiber bundles by the matrix material if the width of the test coupon is not larger than the RUC width. The ultimate load is in this case dominated by the strength of the matrix material. In Figure 9(c) and 9(d), a test coupon is displayed with a width smaller than the RUC width. Here can be seen that the fiber bundles are still intact and only matrix material has failed.

5. ACKNOWLEDGEMENTS

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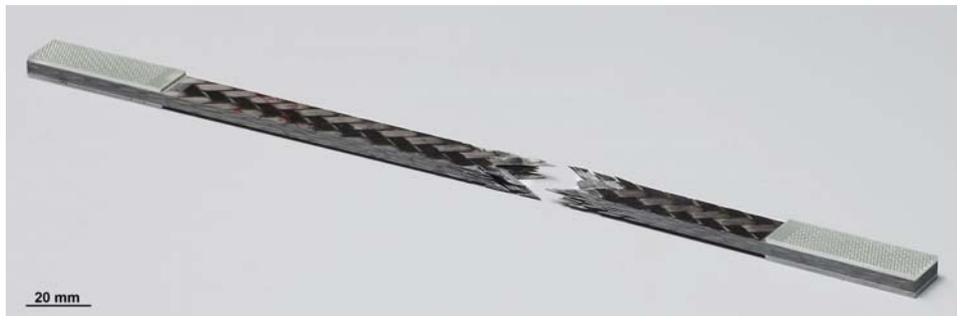
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(a)



(b)



(c)



(d)

Figure 9: Test Coupon Failure; a) overview of a testcoupon with $w_{coupon} > w_{RUC}$, b) detail of a testcoupon with $w_{coupon} > w_{RUC}$, c) overview of a testcoupon with $w_{RUC} > w_{coupon}$, d) detail of a testcoupon with $w_{RUC} > w_{coupon}$