INNOVATIVE JOINING OF AIRCRAFT PROFILES WITH BRAIDED HOLES

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Abstract:
Within this paper a new method for creating holes in composite materials is numerically investigated. The focus here is to use the braiding technology and create holes without destroying the fibres. Because of the highly varying material properties of braided holes an analytical approach for calculating the local material parameters is developed. The base for that approach is the process simulation of the braiding process. A method implemented in Matlab is investigated. The results are validated using classical laminate theory (CLT) method based tools.

1. Introduction

The use of fibre reinforced materials is increasing in several engineering areas due to their very high stiffness to weight ratio. In comparison to metal, thermoset plastics give fewer possibilities to assemble two separated parts. In addition to gluing, there is only the approach of drilling holes in the parts and joining with rivets, bolts or screws.
Fibre reinforced components manufactured with endless fibres reach high mechanical performance within the fact that the fibres are layed up continuously. Drilling holes in the component brake up those continuous fibres and can decrease the mechanical performance. Another well-known fact is that drilled holes increase the bearing performance of a hole because of the perpendicular fibres. It is possible, that cut fibres create a better absorption of compression brought in by bolts.

2. Braiding process, braided holes and simulation

2.1 Manufacturing of braided holes

A new way of creating holes is created to reach higher properties in the joining area. Braiding in common is preferred for profile geometries to create longish near-net-shape preforms. Here it is used to realize holes with continuous fibres.

A braiding machine is built up of moving bobbins with spools of rovings. These bobbins are moving circular around a braiding centre in plane - one half clockwise, the other half counter-clockwise. To this circular motion a sinusoidal motion out of plane is superposed (Fig. 1). In the braiding centre the rovings are pulled out of the braiding plane and create a sleeve. If a mandrel is moved through the braiding centre, the fibres lay down onto that mandrel and create a near-net-shape braid as long as the shape of the mandrel is convex and some boundary conditions are respected [1].

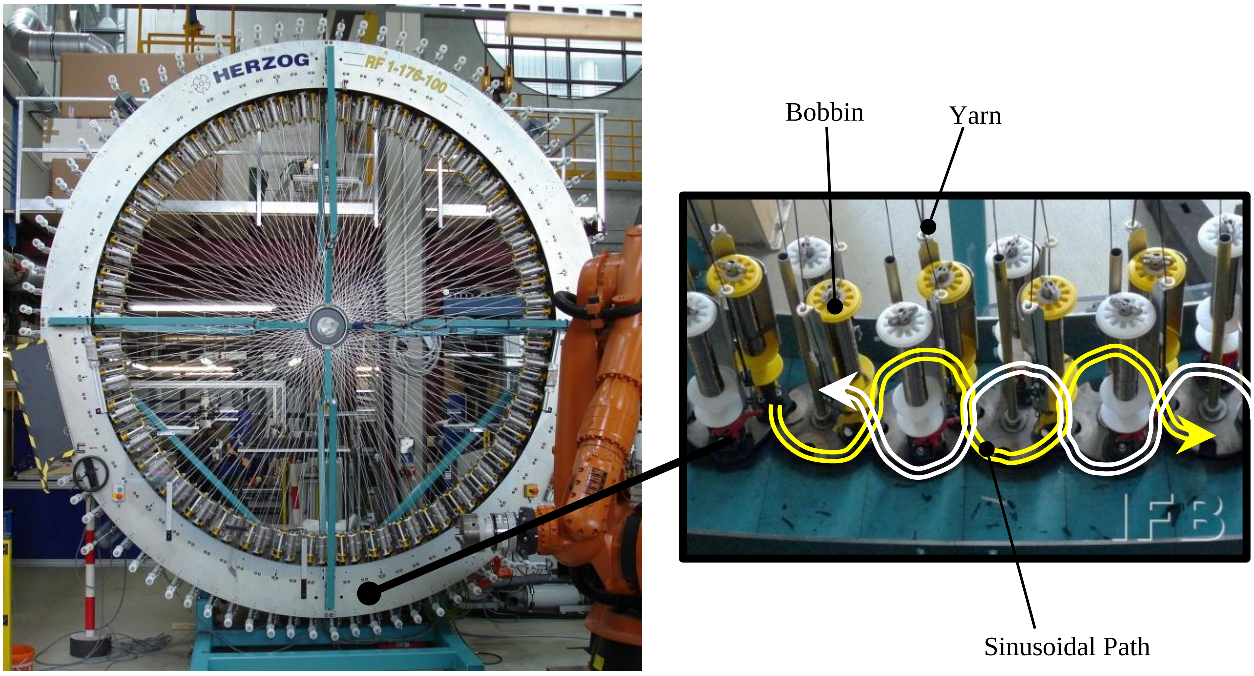

Figure 1. Braiding machine at the IFB

The fibre architecture of the braid depends on various parameters such as diameter and velocity of the mandrel, amount and size of fibres or parameters of the machine.
Another advantage next to the possibility to create near-net-shape preforms mentioned above is the fact, that it is possible to influence the local fibre architecture. This possibility is used here to create integrated holes.
Therefore a tubular shaped mandrel with small conical pins is developed. The tensioned fibres contact the surface of that pin and slide down next to it creating a hole (Fig 2.).

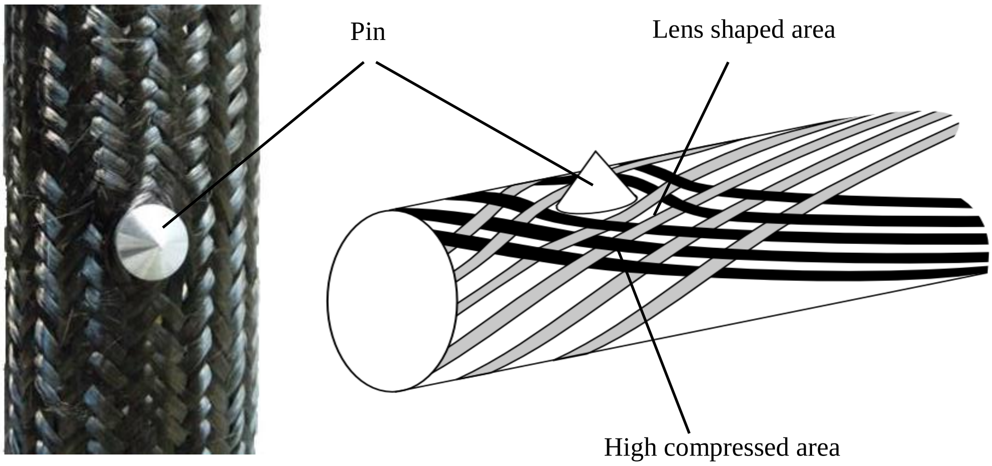

Figure 2. Braided holes

Due to that, no fibres are damaged but the fibre distribution is inhomogeneous. Next to the pin a higher amount of fibres is appearing whereas in fibre direction a lens shaped area with fewer fibres is developing.

2.2 Braiding simulation and simulation of braided holes

As explained in the former chapter, the braiding process is addicted to several machine parameters which influence the quality of the preform. The correlations between the parameters and the textile structure itself make it difficult to predict the fibre architecture of those complex braids.

For any exact calculation of the material properties the fibre architecture (fibre angle, undulation, fibre thickness and width) is needed. Using only fibre measurement methods on dry preforms to get the necessary parameters will not lead to good results because it is not possible to get the 3-dimensional fibre path. The only way of calculating the real local material properties is to know the exact fibre architecture at every place of the component. To get this information a braiding simulation is performed.

A modelling approach of the braiding process was developed for over-braided mandrels by Pickett et al. [2]. The bobbins and their motions are modelled as well as the braiding ring or the yarns.

To get acceptable calculation time the yarns are represented by bar elements. The problem is simplified by the following assumptions:

- No change in cross-section of the rovings
- No friction between the rovings

For the modelling of braided holes, a pin is added to the cylindrical mandrel as in reality (Fig. 3). A hole is created as soon as the yarns get in contact with the pin and lay down next to it.

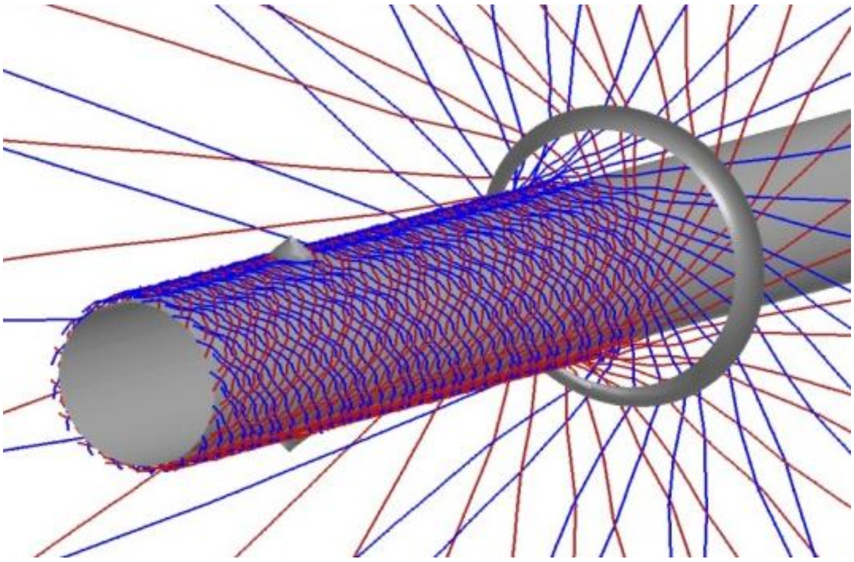

Figure 3. Braiding simulation of integrated holes

The testing in reality and in simulation will be conducted with flat specimens in order to compare. Therefore a draping process of the braided preform to flat pattern is added (Fig.4). Draping was performed using PAM-Crash explicit from braiding process simulation results.

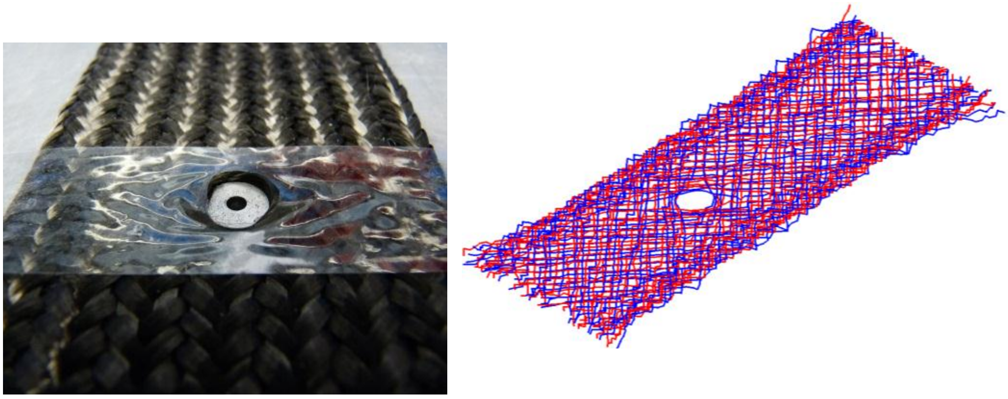

Figure 4. Draping of braided structure to flat specimen

3. Calculation of local material parameters

In every engineering process, the possibility of calculating the material properties is very important in order to be able to design a structure, e.g. for aircrafts. The braiding simulation as explained above is able to give the fibre architecture represented by bar-elements. For the calculation of the material properties this architecture is necessary because of its very high influence to the material behaviour [3].

A Matlab tool is developed to calculate the material properties using this fibre architecture as a basis.

The tool separates the flat specimen into a discrete amount of areas called discrete zones shown in Fig 5.

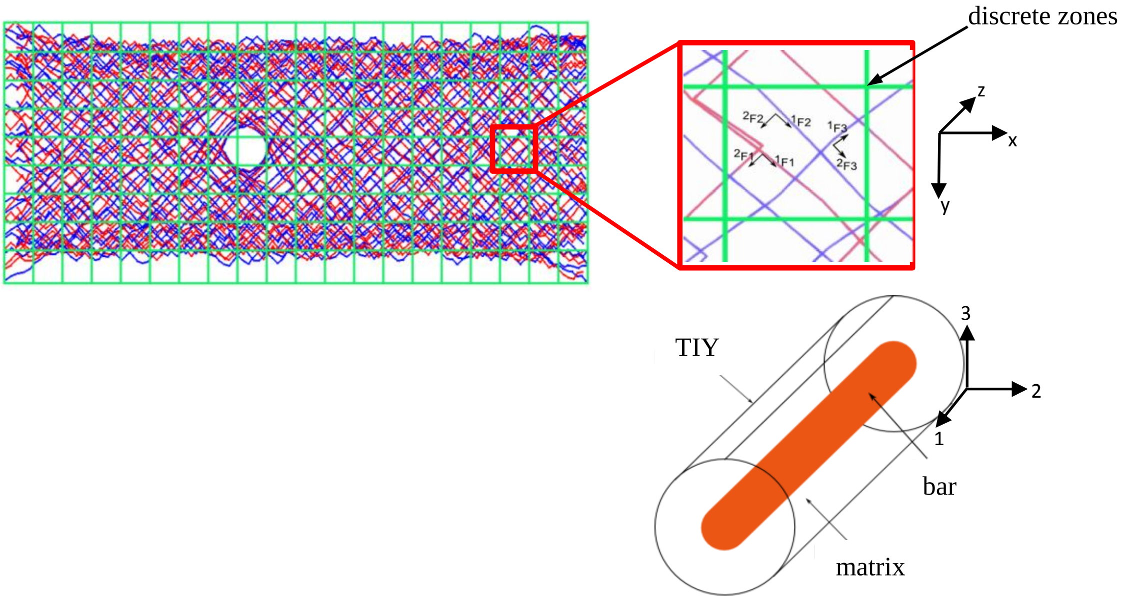

Figure 5. Discrete elements with bar elements

For every area the material properties are calculated. Therefore the coordinates of every bar element is imported and a comparison between these bar-coordinates and the coordinates of the discrete zones is performed. In this way the tool is able to decide whether a bar-element belongs to that area or not. There are several possibilities how a bar could lay in an area. The simplest way is that the bar is complete in the regarded zone. Another possibility is that only

one end belongs to that area. All in all there are 23 different possibilities which have to be considered only for the 2-dimensional case of a flat specimen.
Each bar element is considered as homogenized transversal isotropic yarn-element (TIY) (Fig. 5) and the elastic stiffness in fibre direction is calculated using the rule of mixture [4]:

$$E_{TIY,1} = E_F \cdot \varphi_F + E_M \cdot (1 - \varphi_F) \qquad (1)$$

In equation (1) E_F defines the Young's-Modulus of the fibre, E_M is the Young's-Modulus of the matrix whereas φ_F is the fibre volume ratio.
Perpendicular to the fibre direction there are different approaches to calculate the transversal modulus. Due to the simplification of the TIYs the stiffness in 2- and 3-directions is considered as equal [4]:

$$E_{TIY,2} = \frac{E_M}{1-\nu_M^2} \cdot \frac{1}{(1-\varphi_F)+\frac{E_M}{(1-\nu_M^2)\cdot E_F}\cdot\varphi_F} \qquad (2)$$

In (2) ν_M defines the poisons ratio of the matrix.
The shear moduli in 12-, 13-direction is defined by equation (3) whereas G_{23} is calculated by poisons law (4):

$$G_{TIY,12} = G_{TIY,13} = G_M \cdot \frac{1}{(1-\varphi_F)+\frac{G_M}{G_F}\cdot\varphi_F} \qquad (3)$$

$$G_{TIY,23} = \frac{E_2}{(1+\nu_{23})} \qquad (4)$$

The fibre volume ratio of each TIY can be assigned in different ways. The first approach is to determine it as constant for the whole specimen. This leads to a good calculation time but does not consider the varying fibre distribution mentioned above and local compaction.
Another approach is to calculate a volume ratio for each discrete element *i* by using the volume of all bar-elements V_{Fi} in this area. Therefore the length of the bars l_{Fi} is needed as well as the fibre cross section area A_F which has to be defined by the user and is regarded as constant. The thickness t_i of each discrete element is determined by using the z-coordinates of the bar elements.
With that approach the fibre volume ratio is defined as:

$$\varphi_{Fi} = \frac{V_{Fi}}{V_i} = \frac{l_{Fi}\cdot A_F}{t_i\cdot A_i} \qquad (5)$$

With these approvals the calculation of the elastic properties of each discrete area can be performed using transformation of the continuum stiffness like for the classical laminate theory.
The 6x6 stiffness matrix for each TIY is simplified to:

$$[C_{TIY}] = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{66} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \qquad (6)$$

The entries of the matrix can be found in [4] and are addicted to the parameters defined above.
The matrix for the compliance can be calculated with the simple relationship:

$$[S_{TIY}] = [C_{TIY}]^{-1} \qquad (7)$$

Since every bar element has its local coordinate system 123, the property-matrices has to be transformed into the global coordinate system xyz (Fig. 5). Therefore three different transformation matrices are needed for the rotation around the three coordinate axes x, y, z with the angles α, β, γ.
The transformed stiffness matrix is then

$$[\tilde{C}_{TIY}] = \left[T^{\sigma}_{123\rightarrow xyz}(\alpha,\beta,\gamma)\right]^{\prime -1} \cdot [C_{TIY}] \cdot \left[T^{\sigma}_{123\rightarrow xyz}(\alpha,\beta,\gamma)\right]^{T} = [\tilde{S}_{TIY}]^{-1} \quad (8)$$

with

$$\left[T^{\sigma}_{123\rightarrow xyz}(\alpha,\beta,\gamma)\right] = \left[T^{\sigma}_{123\rightarrow xyz}(\alpha)\right] \cdot \left[T^{\sigma}_{123\rightarrow xyz}(\beta)\right] \cdot \left[T^{\sigma}_{123\rightarrow xyz}(\gamma)\right] \qquad (9)$$

The transformed TIY stiffness matrices of the *n* bar elements has to be summed up to calculate the homogenous stiffness matrix of each complete discrete zone *i* weighted with the ratio of fibre volume V_{Fk} to volume of the discrete zone V_i:

$$[A]_i = \sum_{k=1}^{n} [\tilde{C}_{TIY}]_k \cdot \frac{V_{Fk}}{V_i} \qquad (10)$$

The Young's- and shear-moduli for the compound can be calculated with:

$$E_{x,i} = \frac{1}{([A]^{-1})_{11,i}} \qquad E_{y,i} = \frac{1}{([A]^{-1})_{22,i}} \qquad E_{z,i} = \frac{1}{([A]^{-1})_{33,i}} \qquad (11)$$

$$G_{xy,i} = \frac{1}{([A]^{-1})_{66,i}} \qquad G_{xz,i} = \frac{1}{([A]^{-1})_{44,i}} \qquad G_{yz,i} = \frac{1}{([A]^{-1})_{55,i}} \qquad (12)$$

4. Validation and application

4.1 Numerical Validation for UD-material

The developed Matlab tool is validated by comparing it to calculation tools using the CLT. Therefore a model of only one discrete zone with unidirectional fibres is built up. The fibre volume ratio is set constant to 58%. With these boundary conditions a polar coordinate plot of the Young's-Modulus in 1-direction is created (Fig. 6) including the results of the Matlab tool (black curve) and the results of CLT (red curve).

The difference of the curves is almost zero so that the calculation method of the developed tool can be considered as correct.
For the final validation it is necessary to compare the calculated elastic behaviour for a UD material with experimental testing. The stiffness in reality should be determined using a digital image correlation system.

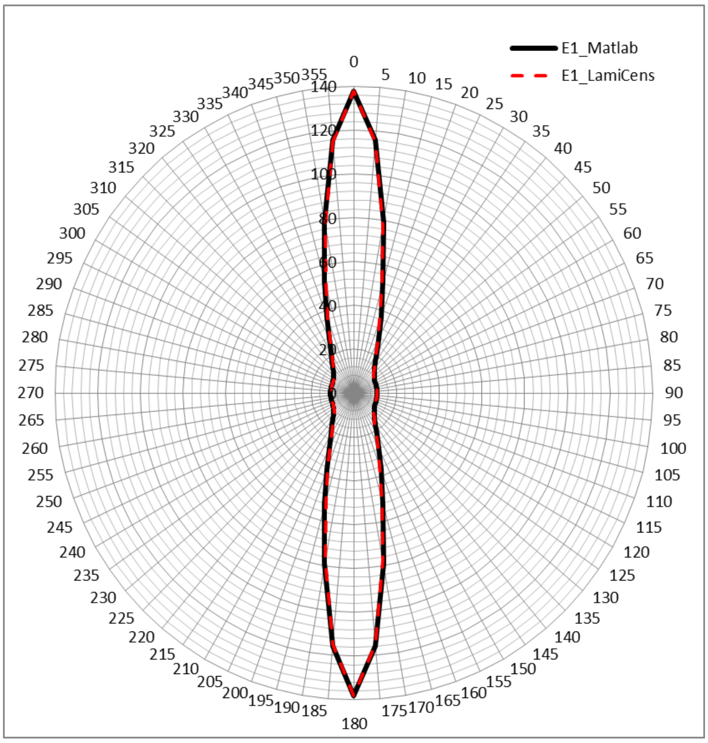

Figure 6. Polar coordinate plot of stiffness comparing the developed tool and LamiCens

4.2 Validation with braided structure on Coupon-Level

The calculated stiffness properties of a braid are evaluated with results of mechanical tests (Fig. 7). Therefore biaxial and triaxial braids with a braiding angle of 45° are examined. Birkefeld et al. has performed the experimental testing for the Young's-Modulus in 1- and 2-direction [3].

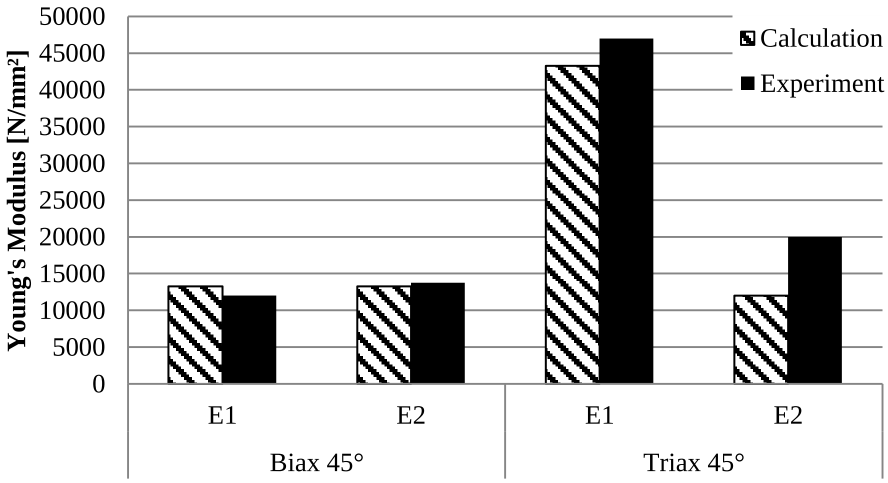

Figure 7. Comparison of calculation and experiment for braided structures

4.2 Application to braided structures with integrated holes

With the developed calculation method the properties of the flat specimen mentioned above are determined. In Figure 8 the distribution of the Young's-Modulus in 1-direction is plotted. The red coloured areas show a high stiffness value due to a high rate of fibres in 1-direction. The integrated hole is coloured deep blue. The lens shaped zones around the holes can be determined as well as the fibre-poor border areas. In this case, the fibre volume ratio is calculated by the tool using the local thickness of each discrete zone. The size of the flat pattern is 40mm to 50mm discretized by 900 elements.

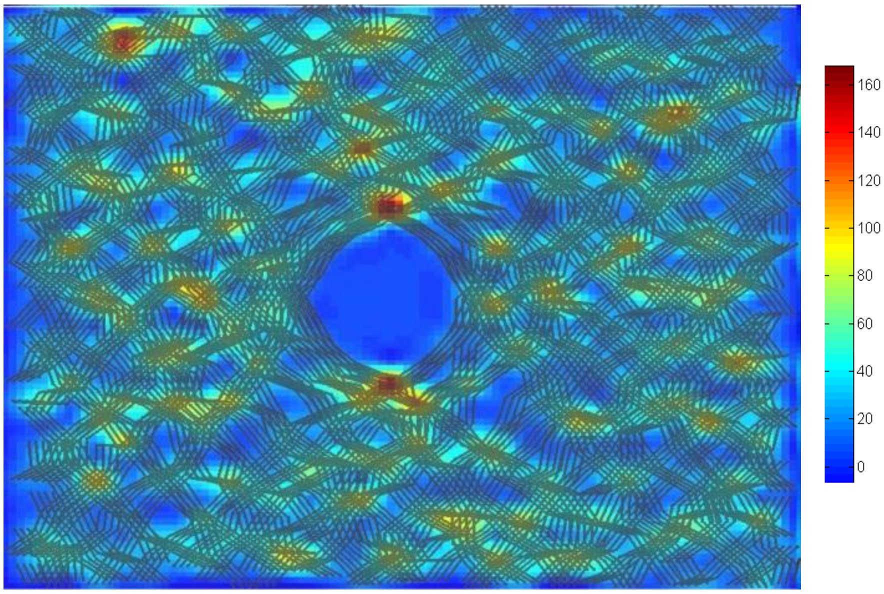

Figure 8. **S**tiffness distribution over flat test specimen including a braided hole (N/mm^2)

5. Conclusion

The investigated tool using an analytical calculation method introduced in this paper offers the possibility to calculate the local elastic properties in fibre reinforced materials. It is possible to estimate the stiffness distribution over an integrated braided hole considering the fibre architecture of the braiding-process simulation. With that information a homogenised model for the prediction of the behaviour of the structure can be performed. The first tests deliver suitable results. The validation of the braided hole with experimental tests will be performed within the next month and the approach will be evaluated.

Acknowledgements

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