Development of a multifunctional truck cross member made of continuous fiber reinforced plastics

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Abstract: *Lightweight design of trucks enables to increase the payload and represents a way to reduce the fuel consumption per transported weight. Many engineers around the world are focusing on this topic. One idea to handle this issue is to combine several vehicle parts or functions in an integrated module.*

This contribution shows the development of a cross member made of a combination of continuous fiber reinforced plastic and steel. Beside the function as an important structure of the truck main frame, the part represents a liquid/CNG reservoir at the same time. The management of design issues, the assessment regarding stiffness and strength was the major focus of the project.

By means of FE analysis, performed with Abaqus the structure was optimized regarding manufacturing possibilities in combination with the other essential properties like stiffness and strength. Many activities were started to find an appropriate combination of the plastic part and the steel brackets, which enable the fixing within the truck main frame structure. Due to the fact that the function integrated structure is much stiffer (resulting from the bigger size and cylindrical shape) than the original cross member, the specific decoupling of the truck main frame and the new developed module was challenging. After solving the main design problems the development team focused on the optimized layout of the plies with respect to stiffness and durability. Finally the verification of the analysis results will be done regarding stiffness and fatigue results at a frame test rig.

Keywords: Composites, Stiffness & Strength, Optimization, Commercial Vehicles

1. Introduction

Composites are already used in a wide range of technical fields: aviation, wind turbines, passenger cars …. The composite material is used there already for system relevant parts which are high loaded. With the increasing importance of composite parts driven by light weight ideas and statutory fuel consumptions, new production methods and improved matrix systems were innovated in the last years. Also the production capacity, units per year, increased during new developments. Commercial vehicle developers follow the trend and use continuous fiber reinforced plastics for chassis parts.

This paper will give a practical overview about the development process which was undertaken for a commercial vehicle cross member (CM). Starting with a method for assessing how suitable the chosen part is for a continuous fiber reinforced plastic (CFRP) design. Followed by the modelling and assessing of the results using Abaqus as FE solver.

As production method for the CM composite braiding was chosen. The individual plies generated by this production method include carbon and/or glass fiber yarns, which are interlaced with each other, comparable to woven lamina. In the analyses strength and stiffness reduction due to the waviness of interlacing fibers, which depends on the braiding angle, should be considered. Finally the optimum braiding angle, depending on the loading of the structure and on the material strength and stiffness reduction due to waviness, should be determined.

2. CFRP Cross Member structure

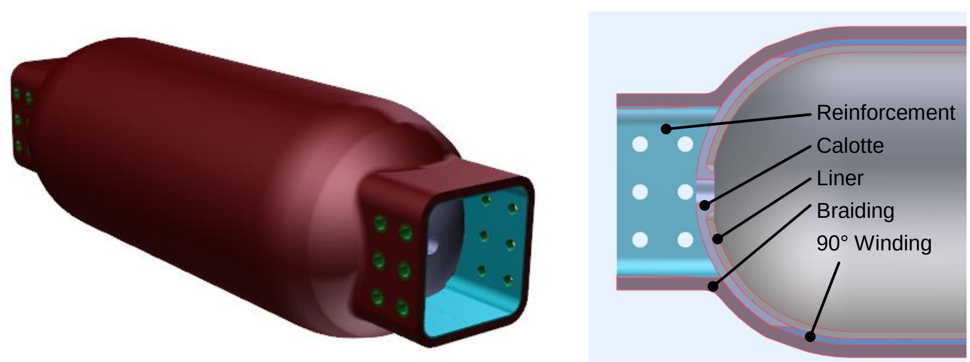


Figure 1: Cross member cross section and

The composite CM has the following structure.

- **Liner:** This is the most inner part. His function is to make the vessel airtight. The material is high-density polyethylene (HDPE). During the production the outline of this volume has an additional function. It is used as core for the 90° winding and for the braiding process.
- **90° Winding:** This layer carries the main pressure load which acts at the inside. The operation pressure for a compressed natural gas (CNG) tank is 200 bar. The burst pressure is 450 bar. The material is a CFRP.
- **Steel Calotte:** At both ends a steel spherical cap takes over the operation pressure.
- **Braiding:** The longitudinal force from the two calottes and the forces from the cross member function are taken over by these layers. The material is CFRP.
- **Reinforcement:** At both ends of the CM the braiding is reinforced with a steel plate. The reinforcements are form-closed connected with the braiding using metal pins (T-IGEL® concept from company Teufelberger Composite), see Figure 6. As for conventional steel cross members, the construction is mounted to the side rails via gussets. During the production the outline of the reinforcement is the core for the braiding process

3. Layout

Whether a part is suitable for a CFRP design and which fibers and matrix material should be chosen depends on several conditions. Some of the criteria are:

- Environmental conditions: area of operations, temperature range, weight
- Manufacturer influence: production method, costs, availability
- Mechanical condition: stiffness, type of loading

For an analyst, the first focus should be the mechanical condition depending on the peculiarity of the composite material. The mechanical properties of FRP are anisotropic. The stiffness and the strength of a unidirectional (UD) layer depend on the orientation of the fibers which are embedded in the matrix. Depending on the type of material the fibers exhibit strength and stiffness values which are certainly higher than for conventional steel, see Table 1.

Material	**Strength [N/mm²]**	**Young Modulus [N/mm²]**	**Density [g/cm³]**
Steel	400 – 1000	210 000	7.85
Aluminum	100 – 450	70 000	2.7
CFRP (HT fiber, Epoxide, φ=0.6)	$R_{\parallel}^{+}$: 1450 $R_{\perp}^{+}$: 32	$E_{\parallel}$: 139 360 $E_{\perp}$: 8 800	1.7
Carbon fiber (HT fiber – HM fiber)	$R_{\parallel}^{+}$: 4530 – 2450	$E_{\parallel}$: 230 000 – 400 000	1.74

Table 1: Material Data, HT fiber … High Tenacity Fiber, HM fiber … High Modulus fiber, $R_{\parallel}^{+}$ … strength parallel to fiber tension, $R_{\perp}^{+}$ … strength normal to fiber tension

The composite material is optimal used when the direction of the maximum principal stress is equivalent to the fiber direction. In the work of K. Durst 2008, a method is explained how parts can systematically assessed weather they are suitable for a CFRP design or not. Based on this work an article in the NAFEMS Magazine with further extensions is issued (Klein 2014). The base is that in an early phase of the project the potential of a part, of different designs, should be assessed considering the specialty of anisotropy of composite material. Therefor a simple method is to generate a FE- model with an isotropic material. Looking at the maximum and minimum principal stresses for each load case gives not only a first impression about the main orientation of the fibers (maximum principle direction) it also show whether the part is suitable for a composite material design or not (variation of principal stress direction).

At the chassis of a commercial vehicle the usage of CFRP material isn't very common till now. Nevertheless for commercial vehicle cabs, short fiber reinforced plastic is already used by MAN Truck & Bus AG (H. Häberle 2013). The article contains further examples where composite materials are used. Successful examples for a rigid beam axle or a cross members (trailer world 2012) exist also on the market. That was also a stimulus for us to start this investigation on a braided cross member with an integrated CNG vessel function.

4. FE- Modelling

At first generating a mesh of a composite part is as easy as generating a shell mesh for a structural steel sheet part. Furthermore the element orientation needs to be uniform and the laminate property is filled with the composition of the plies.

Abaqus offers the possibility to use different modelling technics.

1. A shell element plus a composite property
2. A continuum shell element with a composite property
3. A continuum shell element (stacked) with a usual shell property (anisotropic material is oriented via element coordination system)
4. A solid element with a composite property
5. A solid element (stacked) with a usual solid property (anisotropic material is oriented via element coordination system)

If the classical laminate theory (CLT) should be used and only the in plane stresses of each ply should be evaluated the first option fits well. If delamination or transverse shear stresses should be assessed, a more detailed FE- model with stacked elements is necessary.

For the CM a shell FE- model with composite property is used. But deviant from the conventional used reference surface the mesh isn't placed at the mid surface. The shell mesh reference surface is defined at the bottom side with an offset, see Figure 2. This type of modelling has an advantage when the laminate thickness isn't constant due to local reinforcements. The reference surface is flat and the mid surface in the natural axis is handled by Abaqus.

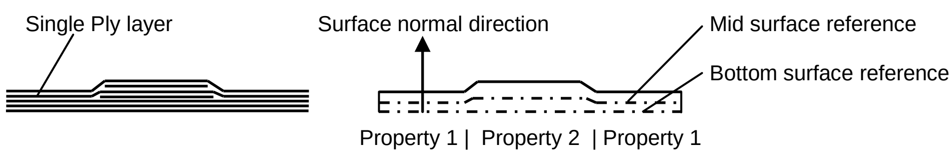


Figure 2: Shell mesh mid surface vs. bottom surface modelling

The following option is used to define an offset:

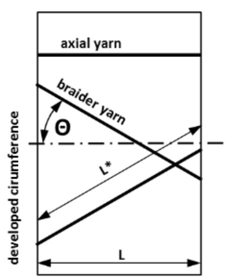
```
**
*SHELL SECTION, ELSET=set_comp, COMPOSITE, ORIENTATION=rect_lam,
OFFSET=SNEG
   0.30,      , composit_material,     0., layer_01
   0.30,      , composit_material,    45., layer_02
```

5. Material Properties Definition

The result of the braiding process is a fabric that follows exactly the shape of the mandrel. The yarn orientation is determined by braiding machine parameters and by the mandrel shape. Two different types of fabrics are possible, a tri-axial fabric which is used for the CM or a bi-axial fabric. The tri-axial fabric consists of braided yarns and yarns in CM longitudinal axis.

Material data for 3 different braided tri-axial fabrics and for the processed components (yarn and matrix) are available. The angle between the braided yarns in this case is 30°, 45° and 60°. The data include stiffness and strength values in axial yarn direction and perpendicular to the axial yarn.

Modelling the laminate with a composite shell section the tri-axial fabric is split in its unidirectional (UD) yarn components instead of using the averaged engineering characteristics. E.g. the symmetric structure for the 30° yarn angle fabric is (30, 0, -30, 0, 30). The center layer is twice as thick as the other layers. The reason for this proceeding is that here a more detailed assessment of the fiber and the matrix is possible. For optimization purpose material data for in-between braiding angles are also required. With the available data an approximation of the stiffness should be done, considering the different yarn content of the three yarn directions and of the waviness depending on the yarn angle. Depending on the used braiding machine, the bobbin number is fixed and the packing density depends on the yarn angle and the fiber deposition width. The following procedure was developed to fit the analyzed materials to the test data. From the yarn and matrix data the UD stiffness is calculated (H. Schürmann 2007). At the test specimen all three yarns have the same raw material (=UD material). But depending on the braiding angle the braiding yarns are longer than the axial yarn, see Figure 3. This circumstance is considered with an adjustment of the UD ply thickness.



$$t_a : t_{-\Theta} : t_{+\Theta} = 1 : \frac{1}{\cos(\Theta)} : \frac{1}{\cos(\Theta)} \qquad \text{Equation 1}$$

t_a ... UD axial yarn ply thickness

$t_{-\Theta}, t_{+\Theta}$ ... UD braider yarn ply thickness

Θ ... yarn angle

Figure 3: Length difference between axial and braider yarn and relation of UD thickness

The braiding yarn is wounded around the axial yarn. The waviness influence is considered by the waviness factor which reduces the original UD stiffness. It is assumed that the axial yarn has no waviness. The braiding yarn waviness factor is optimized in such a way that the engineering characteristic of the composite fits the test values. The process is displayed in a flow chart, see Figure 4.

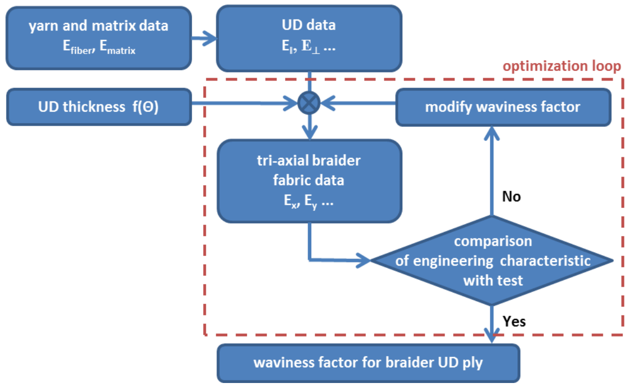


Figure 4: Process for adjusting the FE model stiffness with test data

Figure 5 shows the normalized stiffness's for the 3 test data in comparison with the analyzed one. With the described process and only two parameters it was possible to get a good match. The gained waviness factor must not be seen as an absolute figure. Because also the 45° the braider yarns are interlaced too. But the fabric is less distorted at 45° than for 30° or 60°. This is cause by the symmetrical decrease of the waviness factor for angles differing form 45°. The waviness factor for reducing the braider yarns is nearly 1 for 45° and around 0.75 for 15° degree deviation from the 45°. The adjusted composite shell property has the following appearance. The thickness of the UD plies is weighted with the UD thickness influence. The axial yarn UD ply material is the original material and the braided yarn UD plies material have the original material with a modified $E_{\|}$ stiffness.

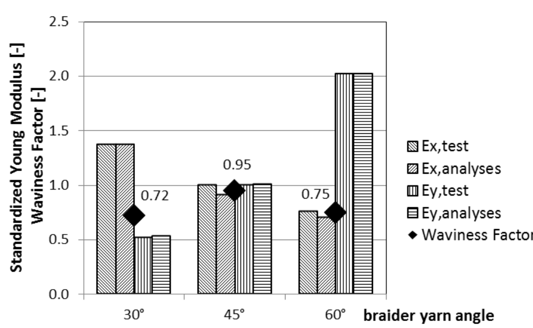


Figure 5: The diagram shows a comparison between test and analysis standardized young modulus values for the three braiding yarn angles. Additional the waviness factor for the braiding yarn is shown. Ex … Young modulus x direction, Ey … Young modulus y direction

6. Optimization of the Pined Surface

For the connection between metal reinforcement and braided composite a tie contact is chosen. But for a detail analysis the interaction there is investigated more detailed. The tie contact is converted into a contact pair. Additional the pins are realized with beams which are connected to the shell mesh on both sides with distributing couplings.

Figure 6: T-IGEL® pins at the FE- model and at the prototype parts

The detail analyses shows that the interrupted pin rows close to the calotte are higher loaded than the rest of the pins. When these pins are removed the local stresses at the reinforcement decrease significantly and at the braided composite slightly.

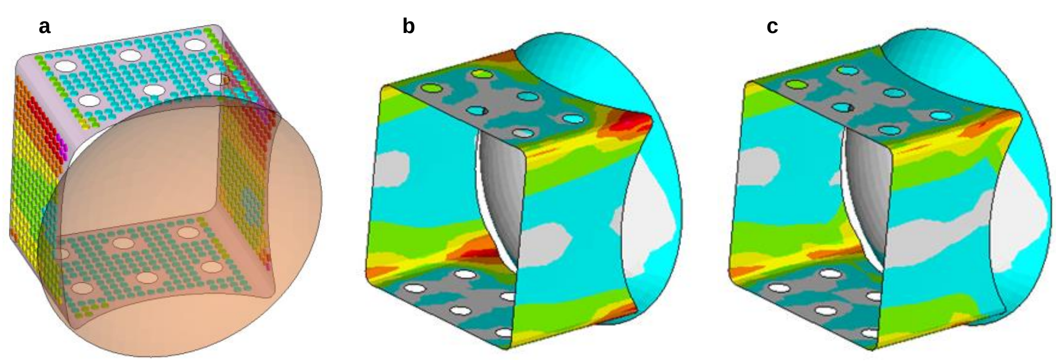


Figure 7: Results with and without optimized pin area, (a) pin shear force distribution for frame torsion load, Von Misses stress distribution without (b) and with (c) pin area optimization

7. Stiffness Analysis

The stiffness analysis was first hand performed with an idealized setup where three loads are applied to determine the stiffness. A bending, a shear and a torsion load are investigated. Reference values from standard CM profiles are also determined, see Table 2.

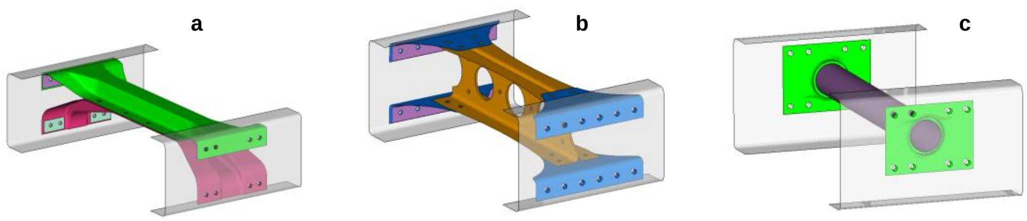


Figure 8: Conventional steel reference cross member, (a) light truck alligator CM, (b) double-C CM, (c) tube CM

	Bending [Nm/°]	Shear [N/mm]	Torsion [Nm/°]
Light truck alligator CM	4500	240	920
Double-C CM	36000	4300	635
Tube CM	7300	1280	4930
CFRP CM (incl. gussets)	17300	2070	4300

Table 2: Stiffness values for reference steel and CFRP CM

The torsional stiffness of the CFRP CM is very high. The large diameter plays a main role in this case. A soft gusset to achieve a smooth transition between tank and side rail is necessary.

This configuration is used to analyze different versions of the CFRP CM and the results are compared. Two previous versions are displayed in Figure 9. In design (a) the mounting to the side rail is similar to the steel tube CM version. Basically the size of a premounted gusset is limited by the braiding machine. On the other side welding after the braiding process is challenging. Because the heat from the welding process will damages the composite material. The advantage of this solution is that a conventional bolt hole pattern can be used. The second shown design (b) has no diameter reduction across the CM length. Therefore the calotte has to be larger, which increases the total weight. The bolts are not accessible when the CM is mounted and the bolt hole pattern isn't conform with any usual side rail hole pattern.

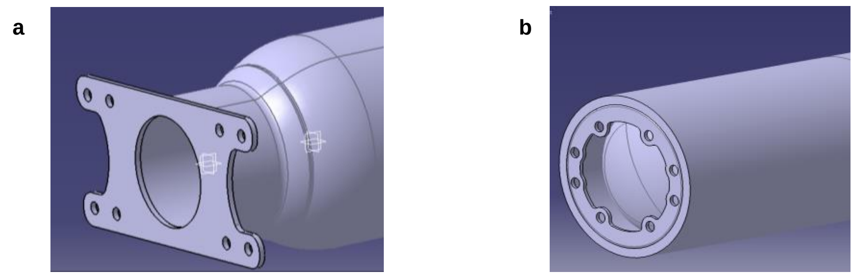


Figure 9: Previous CM versions, (a) CM with a round reinforcement which is welded to a mounting plate, (b) CM with large diameter reinforcement equal to the mandrel and bolts inside the circumference

8. Strength Analysis

For the strength analysis the CFRP CM is integrated in a commercial truck frame. To guarantee that the CM is high loaded, the add on parts: fuel tank, battery box and muffler are arranged very close to the CM, see Figure 10. The FE- model shown is a 4x2 tractor truck. The suspension is modeled with an auxiliary beam structure representing the correct stiffness.

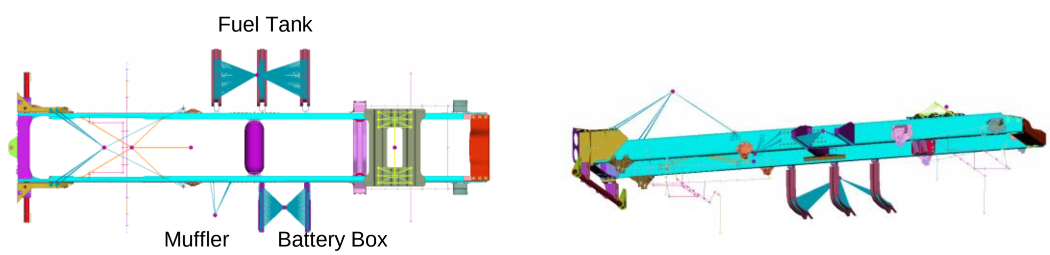


Figure 10: Truck frame for strength analysis. The add on parts surrounding the CM are named.

The analyzed load cases are misuse load cases (MLC):

- **MLC 1, vertical bending:** The add on parts mounted at the main rails burden the CM with a bending moment. The frame itself is symmetrical and the global bending has no influence on the CM.
- **MLC 2, lateral force:** A curve driving maneuver is simulated with this load case. The side bending of the main rails causes a shear loading of the CM.
- **MLC 3, twist:** Driving over an obstacle or over a slope, the frame is burden with a twist. This maneuver is most serious for the frame and CM. The CM has a combined load of bending and of a torsion moment. The stiffness of the frame and of the truck suspension

cooperates. A torsion stiffness change of the frame will lead to a higher deflection of the suspension.

- **MLC 4, internal pressure 450 bar:** The operating pressure of the CNG tank is 200bar. For safety reason the tank has to resist a burst pressure of 450 bar.

The assessment was done according to the VDI regulation (VDI- Regulation Part 3, 2014). The regulation favored the Puck criterion which is mainly used for UD plies. The main focus is the fiber fracture (FF) stretch factor. The inter fiber fracture (IFF) stretch factor is secondary, because of the used braiding process no distinct matrix direction exist in one ply. Some post processor tools have implemented subroutines which determine the stretch factors or the stress exposure values (the stretch factor is the reciprocal value of the stress exposure). For Abaqus is a subroutine available called VDI2014_v2, which is a free software from Tobias Kremer (Kremer, 2009).

9. Results

The critical point of the CM is the transition from the round cross section to the quadratic. At first hand the cross section is here smaller and for the torsion load the stresses are increased. Furthermore the connection to the gussets on only two sides concentrates the load flow further. The minimum fiber fracture stretch factor is above 3.5, see Figure 11. The braiding yarn angle has only a minimal influence at the fiber fracture stretch factor.

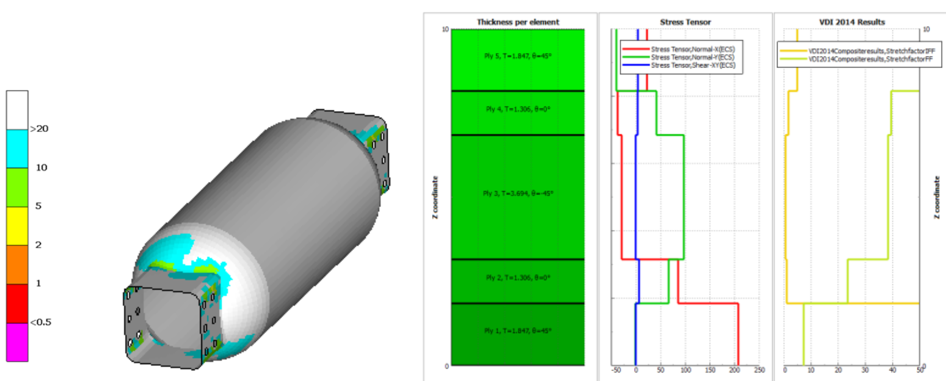


Figure 11: Minimum fiber fracture stretch factor for the torsion load case.

The IFF stretch factor is below 1. But for a fabric the Puck criterion isn't ideal. The following tests will show where the static and the fatigue limits are. A comparison between analysis and test will be the base for second optimisation loop.

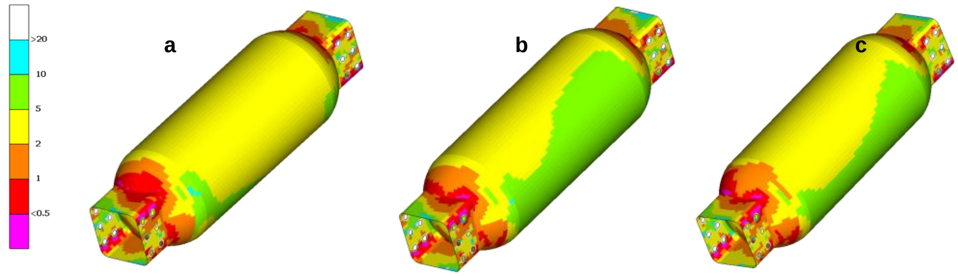


Figure 12: Minimum inter fiber fracture stretch factor for the torsion load case for (a) 30°, (b) 45° and (c) 60° braiding yarn angle.

Further the exact orientation of the yarn especailly at the transitons to the metal reinforcement wasn’t clear till the first prototyp parts were produced.

Figure 13: One of the first prototype without gussets.

The burst preassure misuse load case has a uniform stretch factor distribution. The inter fiber fracture stretch factor at the braiding part has a minium where the calotte ends and the 90° winding starts, see Figure 11.

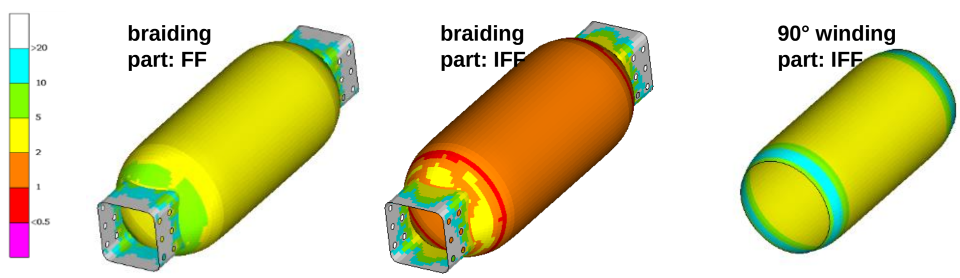


Figure 14: Minimum stretch factor for the misuse load case burst pressure 450 bar at braiding and 90° winding part. FF … fiber fracture, IFF inter fiber fracture

10. Conclusions

The development of a CFRP product with software tools available at the market is possible. During the project runtime, software implementation for assessing and displaying composite results were steadily improved and developed. The software companies recognized the trend, to light parts made out CFRP material and supporting the engineers with new implemented features for this topic.

6 CFRP CM were produced and 5 of them will be tested in the servo hydraulic laboratory of the Engineering Center Steyr. The stiffness and the strength of the CM should be compared with the analyzed results.

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