DIMENSIONING AND SIMULATION OF A CFRP – TRAILING LINK FOR THE REAR AXLE OF COMMERCIAL VEHICLES

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Abstract

Many currently available concepts for high-loaded tension and compression rods made of fibre composite are often only suitable for production in a large series under certain conditions, while remaining compliant with requirements inherent to commercial vehicles. The following investigation shows the entire development of a trailing link concept in carbon fibre reinforced plastic/aluminium differential construction for the rear axle of a MAN TGX long-haul transport vehicle. Design aspects with regard to cost-effective production as well as the design by means of classical laminate theory and FE simulation are described in detail. One of the most significant challenges that transpired from the study was the load transfer between the fibre-plastic composite rod and the bearing element made of aluminium, in which production tolerances have a significant effect. The proposed solution constitutes a clamping connection with tolerance equalisation and adaptability across components in order to make the component usable even for other applications. In addition, the geometry of the composite component allows for continuous production and therefore high profitability. Comparison with current standard production trailing links shows a considerable weight saving. Functional integration of the rubber bushing offers further potential for lightweight construction.

1 Introduction

The commercial vehicle as an investment item is used for transporting goods & people and therefore has different requirements for lightweight construction applications than private cars. The customer's decision to make a purchase is decisively affected by the maximum possible payload, fuel consumption, price and robustness of the vehicle.

This argument results in the demand in commercial vehicles for the reduction of the unloaded weight of the vehicle and therefore an increase in the load capacity that is paid for, i.e. the payload. Apart from structural lightweight design, lightweight material construction with modern materials provides further primary approaches to weight savings.

The focus of the present study lies on reviewing the usage of fibre plastic composites for selected structural components in the chassis of a commercial vehicle. The use of lightweight fibre-reinforced materials in this area of the vehicle particularly contributes to the reduction of unsuspended masses and thus simultaneously increases driving comfort and driving safety [1]. Furthermore, the reduced weight of individual components may enable secondary lightweight construction due to the reduced component group loads. In turn, the reduced wear results in longer maintenance intervals or lower maintenance costs.

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Despite the above reasons that promote the use of fibre-reinforced plastics, there are currently only few applications known in truck chassis. The reason for this lies in both the previously mentioned market-specific requirements, such as robustness and the cost-efficiency of components, as well as in the notion that the employment in commercial vehicles results in high component loads. The material also requires a substantial testing effort in order to obtain a certification and life cycle forecasting.

2 The trailing link for the rear axle of long-distance vehicles

In the context of a preliminary investigation, the trailing link, also called two-point link, has been selected as a suitable chassis component for the usage of lightweight materials. It is used in rear axles with air suspension of MAN long-haul transport vehicles (Figure 1) of the heavy and medium-weight series with different wheelbases.

The main task of the link consists of the lower longitudinal guidance of the rear axle by transferring drive and braking forces. For the complete guidance of the axle in longitudinal direction, either a three-point link or a four-point link developed by MAN themselves is used above the axle, which also has a stabilising effect with respect to rolling and transverse acceleration.

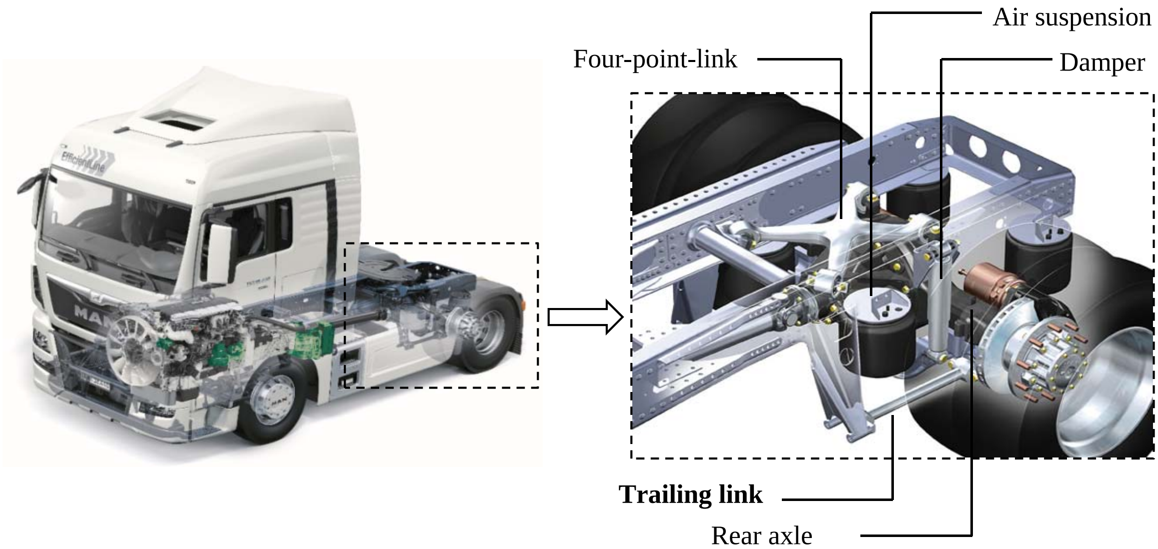

Figure 1. MAN TGX long-haul transport vehicle – component illustration of the rear axle

The two-point link is attached on the vehicle body and rear axle by means of a rubber bushing for acoustic decoupling. Due to its rod-like geometry and the predominant load resulting from axial tension and compression forces, the component is suitable for the targeted utilisation of anisotropic materials. As well as the axial load resulting from acceleration and deceleration, the torsional stiffness and the cardanic stiffness during body rolling and compression and rebound respectively also cause torsion & bending loads (Table 1).

Table 1. Load cases of the trailing link

Load case	Axial force (tension/compression)	Rolling (torsion)	Compres-sion/rebound (bending)
1: Maximum compression load	-130 kN	-	-
2: Maximum tension load	75 kN	-	-
3: Combined load	± 45 kN	± 4,3°	± 90 mm

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3 The development of a concept for the trailing link

In the development of components made of fibre-reinforced plastics, there is a close connection between geometry, material, a laminate and the manufacturing process (Figure 2). The main challenge lies in achieving an economic production in accordance with the production volume, which consists of at least 50,000 items per year in the case of the trailing link.

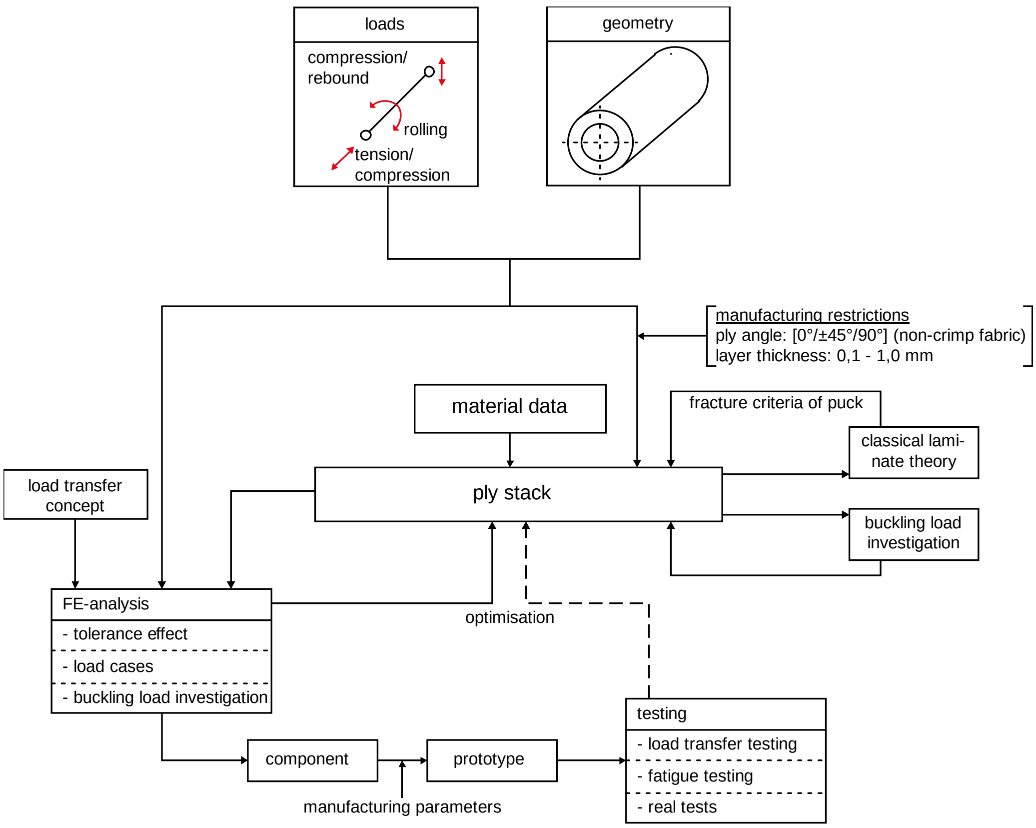

Figure 2. Development steps of the trailing link

To reduce the complexity in the area of load transfer, the two-point strut is designed in differential construction, consisting of two aluminium bearing elements and a tubular connection made of fibre-reinforced plastic. Due to the mechanical advantages of a closed cross-section in the event of torsion and the rotational symmetry, a circular tube was selected as cross-section. An analysis of the available design space sets the maximum external diameter to 50 mm. Decisive for this are the spaces between the trailing link and tyre and/or silencer at maximum rebound and rolling. The tube length is derived from the distance of the attachment points in connection with the bearing element geometry at 450 mm (Figure 3). This enables continuous manufacturing by means of pultrusion, as it is called for polymers (Figure 4).

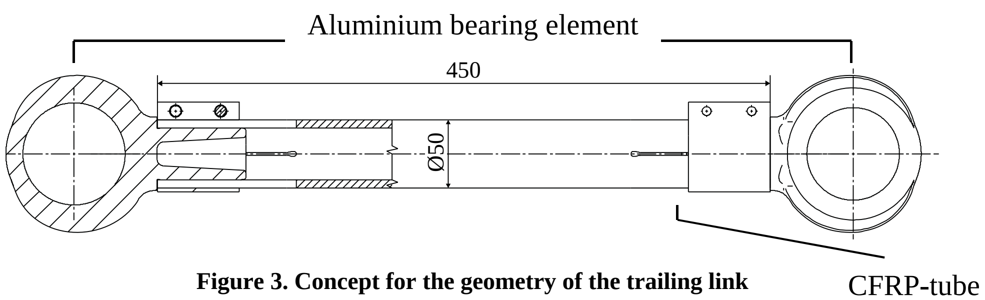

Figure 3. Concept for the geometry of the trailing link

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In addition to the possibility of high manufacturing volume, this kind of manufacturing method also has additional essential advantages. Both the construction of a laminate from unidirectional layers with high fibre volume content (over 60 %), and the use of thermoplastic or thermoset resin systems are possible. Furthermore, low tolerances in the range of ± 0.05 mm are achieved.

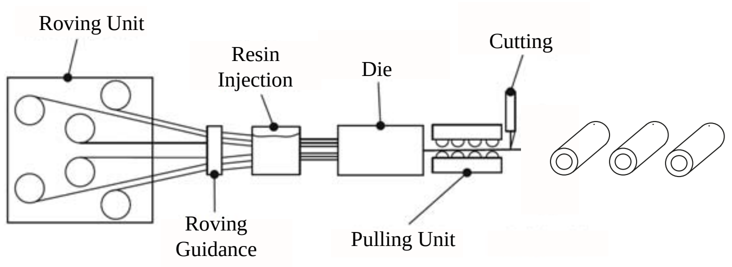

Figure 4. Pultrusion process for continuous manufacturing of profiles [3]

Contrary to the widespread usage of epoxy resin as a matrix material for high-loaded components, polyurethane (PUR) shall be employed as a test in case of the trailing link. This thermoset material provides many advantages with respect to manufacturing and material behaviour. Due to the chemical composition, process parameters such as viscosity and reactivity can be varied and adapted in a wide range to minimise cycle times [5]. The mechanical statically properties of the composite (Table 2) nearly reach those of a laminate made with epoxy resin. In contrast to the brittle behaviour of epoxy resin, however, the higher toughness of the PUR has a positive effect, particularly on the fatigue behaviour. The occurrence of micro-damage is observed at higher load cycles, which reduces the degradation of properties and increases the fracture load cycle criterion.

Table 2. Material properties for glass-fibre (GF) and carbon-fibre (CF) reinforced materials with polyurethane matrix (PUR)

Stiffness						
laminate	E_{11} [GPa]	E_{22}/E_{33} [GPa]	G_{12}/G_{13} [GPa]	G_{23} [GPa]	ν_{12}/ν_{13} [-]	ν_{23} [-]
CF-PUR	144,0	8,6	4,9	3,8	0,26	0,40
GF-PUR	51,2	11,5	5,2	5,4	0,28	0,38
Strength						
laminate	R^t_{11} [MPa]	R^c_{11} [MPa]	R^t_{22}/ R^t_{33} [MPa]	R^c_{22}/ R^c_{33} [MPa]	R_{12} [MPa]	R_{ILSS} [MPa]
CF-PUR	2110	1377	58	180	92	80
GF-PUR	1200	900	50	170	70	-

To minimise the optimisation loops of the component, the initial build-up sequence was first determined by means of netting theory. This design method determines the optimum ply angle and the thickness of the layers and ensures that the load can theoretically be supported by the fibres alone, without considering the matrix [4]. However, the applicability of this theory is restricted to membrane loads (tension/compression, shear), plate loads (e.g. bending) cannot be considered. As input parameters for the netting theory and hereafter also for the classical laminate theory (CLT) width-related internal force flows are needed, which are derived from the geometry in connection with the load. Together with the static and dynamic loads from Table 1, the input parameters for determining the initial ply stack are therefore known.

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Before the laminate can be finely dimensioned by means of CLT, the result of the netting theory regarding the existing manufacturing restrictions for the pultrusion process must be adapted. In consultation with the manufacturer, restrictions for layer thickness, minimum fibre angle for the prevention of fibre slippage and layer arrangement for the use of non-crimp fabrics (NCF) are established. Under consideration of the required factors of safety, a $[90°/+45°/0°/-45°/0_2°]_S$ laminate with 6 mm wall thickness is initially stipulated. Furthermore, thin layers of GF-PUR laminate are applied as innermost and outermost plies of the tube to prevent electrochemical corrosion between the carbon fibres and aluminium bearing element. After stipulating the lay-up of the laminate, optimisation is made using the CLT and the Puck fracture criterion. The result of this process is summarised in Table 3.

Based on the geometry and the ply stack, the buckling load can be calculated according to Euler buckling load case 2. A factor of safety *j* is achieved against load case 1 (“clutch drop”) with a maximum compression-axial force of 130 kN of *j* = 4.5. The fibre-reinforced polymer tube then provides sufficient safety against buckling.

Table 3. Ply stack of the tube (GF – glass-fibre, CF – carbon-fibre, PUR – polyurethan, NCF – non-crimp fabric, UD – unidirectional)

ply stack of the tube (symmetrical in relation to layer 6)				
layer *n*	angle [°]	thickness [mm]	material	semi-finished product
1	90	0,60	GF-PUR	NCF
2	+ 45	0,30	CF-PUR	
3	0	0,60	CF-PUR	
4	- 45	0,30	CF-PUR	
5	0	0,60	CF-PUR	UD
6	0	0,60	CF-PUR	UD
n_{sum} = 12		**t_{sum} = 6,0 mm**		

A consequence of the differential construction of the trailing link is the need of a reliable connection between the tube and the bearing element. Most multiaxial stress conditions in the area of load transfer lead to high stresses at low interlaminar strength. Furthermore, production tolerances and design space restrictions have a considerable effect on the design. Firstly, an adhesive connection between the tube and the supporting element is checked. This is based on the theory of Volkersen [2].

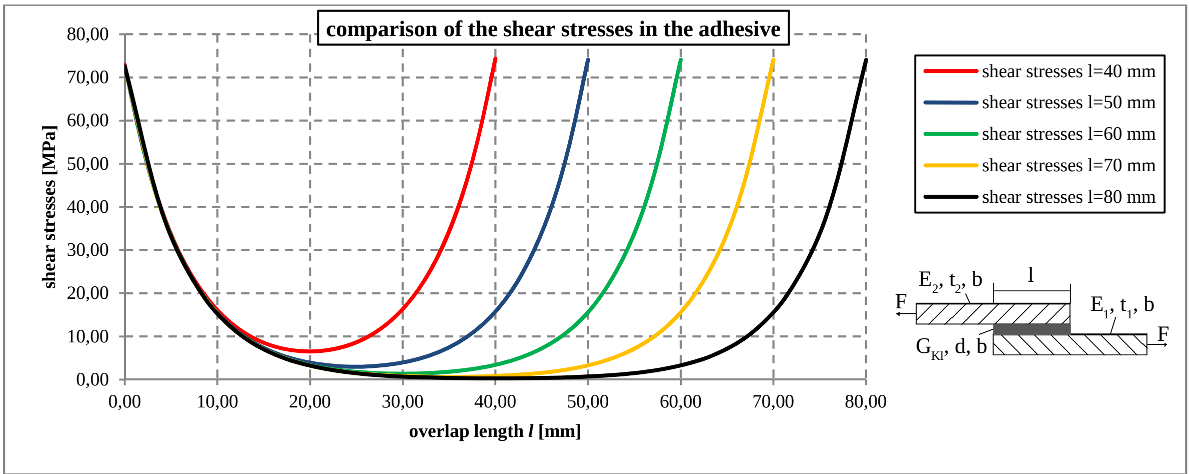

Figure 5: Shear stresses in the adhesive for various overlaps *l*

In Figure 5 the curves of shear stress in the adhesive for various overlap lengths are illustrated. The comparison shows that the maximum shear stresses on the edges of the purely adhesive-bonded connections are too high for industrial adhesives. In addition, there are various effects from media (e.g. water, fuel), temperature and cyclic stress. Increasing the size of the circumference of the tube is not permitted due to the restricted design space, meaning that this connection does not represent a solution.

After an extensive market analysis, it became evident that currently only few mass-producible connections of this type with component tolerance compensation are available. A widespread example of the transfer of high longitudinal forces is the interference fit [4]. However, the oversize required for the pressing process in connection with tolerances leads to the destruction of the laminate by joining both parts.

The following investigated type of load transfer is based on applications in racing bicycles. In this case, the carbon fibre reinforced frame is slotted in the region of the clamp and the tubes fitted by means of a steel clamp. The advantage of the slot is the lower susceptibility to the interference and clearance fits that inevitably result from production tolerances. Furthermore, a defined pre-load can be applied via the clamp and relaxation of the material can be compensated for.

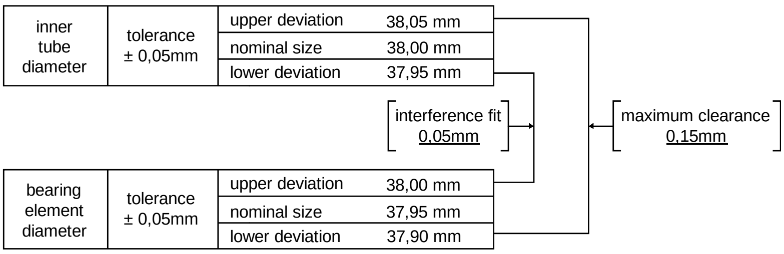

Figure 6. Selection of the tolerance field for the tube and the bearing

For the simulation of the concept with the aid of the Finite Element Method (FEM) the software Abaqus/CAE 6.14-1 was used. In separate models, all three tolerance combinations (maximum tolerance, nominal size, maximum oversize) are taken into consideration to investigate the varying effect on the stresses. The trailing link is modelled as a half model and simplifying the rubber bushing by springs. In doing so, all components are discretised with continuum elements (C3D6/C3D8R) to record the multiaxial stress states in the area of the load transfer and the notch. To simulate the composite tube, two finite elements for each layer are used to evaluate the interlaminar shear stresses. The analysis is carried out in several steps, in which the initially required pre-load is applied by a temperature difference on the clamp. The load is then applied in the form of a displacement or force and/or torque. To evaluate the failure according to the Puck fracture criteria, the subroutine UVARM of TU Darmstadt is used.

The evaluation of the analyses of the trailing link shows that four slots across the circumference in the region of the clamping gives a compromise between manufacturing cost and strain. Further parameters derived from the analyses are length and geometry (width, length, base geometry) of the slot. In addition, the stresses occurring in the laminate can be reduced by a proper selection of the tolerance field. This is defined in such a way that, in order to apply interlaminar compression stress, the tube is compressed by the pre-load of the ring (Figure 6).

The summary of the laminate failure indexes (Table 4) shows that the load cases 1 & 2 are decisive for dimensioning the tube. The stresses induced by the rubber bushing as a result of rolling and suspension are below these. Furthermore, the longitudinal load cases 1 and 2 (Table 1) occur quite rarely in the entire lifetime of the component.

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Table 4. Maximum failure indexes for all load cases and tolerance combinations (FF – fibre fracture, IFF – inter-fibre fracture, *j* – safety factor)

		maximum clearance z = 0,15 mm		**nominal dimension** z = 0 mm		**interference fit** z = -0,05 mm	
load case \ failure mode		FF	IFF	FF	IFF	FF	IFF
1	axial compression (j = 1,1)	0,69	0,89	0,63	0,83	0,62	0,93
2	axial tension (j = 1,5)	0,24	0,68	0,63	0,83	0,32	0,98
3.1	compression/rebound (j = 1,0)	0,23	0,34	0,15	0,29	0,07	0,22
3.2	rolling (j = 1,0)	0,48	0,52	0,42	0,50	0,35	0,66

The location of the maximum stresses in the tube is at the end of the slot in all load cases (Figure 7). In the undisturbed area, these correspond to the result obtained by the CLT. Furthermore the maximum failure indexes in the tolerance field “maximum clearance” were considerably reduced in comparison with “interference fit” due to the compression of the ring. As a result of a production tolerance as a normally-distributed random parameter, the stresses are in the middle between “nominal size” and “maximum clearance”.

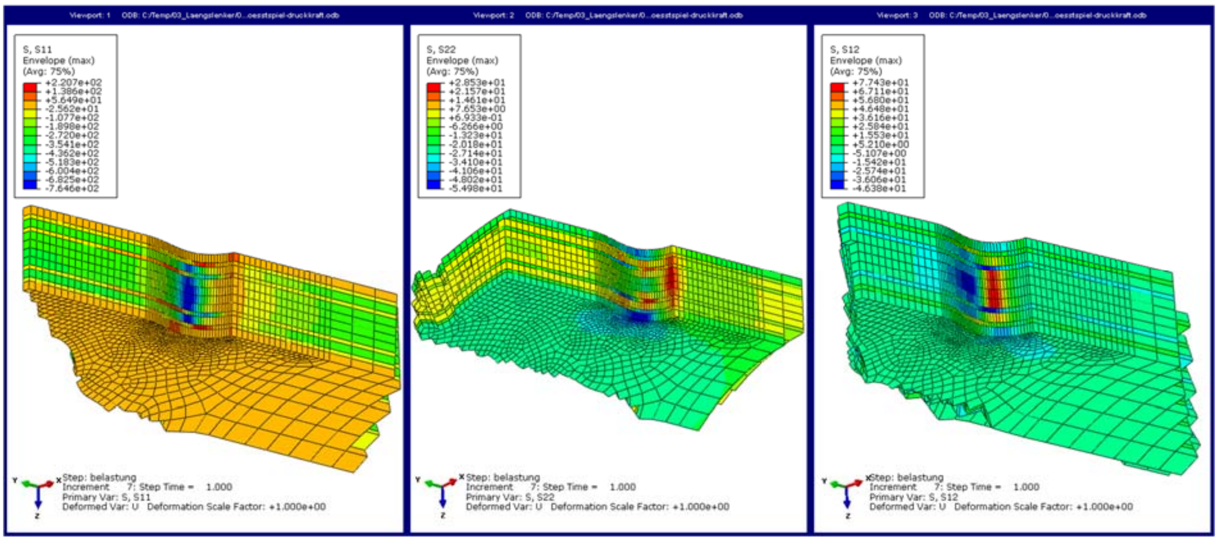

Figure 7. Stress components S11 (longitudinal stress), S22 (transverse stress) and S12 (shear stress) in the area at the end of the slot (load case 1: maximum compression load; tolerance field: interference fit)

After evaluation of all analyses, it became evident that the slotted clamping may be a possibility for overcoming the production tolerances (Figure 8). The selection of an even number of oppositely placed slots allows for machining by means of a diamond saw blade. On the boundary between the fibre-reinforced tube and the bearing element, an adhesive should also be applied. This reduces the friction during joining and supports the load transfer by friction by an additional adhesive bond. The concluding balance of component masses shows a saving of around 2.6 kg, which corresponds to 26 %. If the rubber bushing taken over from the series trailing link is not included in this calculation because it is a non-design area, a 43 % weight saving is made.

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Figure 8. Final concept of the trailing link

4 Summary

In the presented process of the design and dimensioning of a trailing link for a MAN TGX long-haul transport vehicle, it was possible to show which decisive effects are involved in the development of a high-loaded frictional bonding with respect to series production. After the approaches with conventional load transfer and limited design space did not lead to a solution of the problem, new considerations had to be made. The consideration of applications in other areas yielded the concept of a slotted tube, which meets the requirements regarding load and mass producibility. For this concept the ply stack of the composite tube is stipulated by using netting theory and CLT. The trailing link is then simulated with the aid of the finite-element method to evaluate failure indexes in the area of load transfer. As a result of this investigation stresses could be reduced by a proper selection of the tolerance field in addition to the number and the geometry of the slots. After all there is about 26 % of weight saving in comparison with series component.

This concept is set to be reviewed via the subsequent manufacture of a prototype, followed by component testing. In connection with further calculations, the existing simulations should be validated and the load transfer further optimised to reduce the failure indexes. Parameters for this include slot length, geometry and number. Furthermore, a variation of the overlap length of the clamp and bearing element is possible. The replacement of the series rubber bushing may provide additional potential for lightweight construction due to an optimised concept.

This possibility of highly loaded longitudinal force transfer in tension and compression leaves room for further applications, which are not only limited to the trailing link of the rear axle. Tension – compression – struts with high design space requirements may be applied in many areas both in trucks and in buses, within the group or across the industry.

Acknowledgements

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