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Design and Analysis of Discontinuous Long Fiber Reinforced Thermoplastic Structures for Car Seat Applications

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Abstract

Discontinuous long fiber reinforced polymers (DLFRP) with a remaining fiber length of 6 to 8 mm after processing reach up to 10 % higher mechanical properties compared to classical short fiber reinforced plastics. Fracture toughness was observed to be even three times higher. DLFRP is processed by injection or compression molding, applicable in mass production and so can lead to a reduction of the component number by a highly integrated design. The strongly computer aided investigations and the following component tests with prototypes for car seat structures showed that DLFRP can advantageously replace structural metal components. In appropriate applications they are capable to save weight and manufacturing costs.

1 Introduction

Cost saving and weight reduction are the key terms of new developments for todays transportation industry. This clearly indicates that economical and ecological aspects have significantly moved in the foreground of technical developments. Innovative technical solutions are required to combine additional functions and carry over further tasks which could either not be considered with a conservative solution or had to be represented by separate components. Innovative products also have to be equal or even more cost efficient than former ones.

One of the main factors to succeed in such an innovative product design is the material choice. Being in line with the demand for leight weight constructions in order to minimize energy consumption, polymer composites with fiber reinforcement are gaining more importance for structural car applications. Typical materials with a high degree of freedom in formability are short fiber reinforced polymers (SFRP) which are processed by injection molding for mass production applications. In automotive industry the majority of SFRP components is lowly stressed like panels or coverings which results from low mechanical properties of SFRP. In order to combine almost unrestricted formability of injection molding and acceptable mechanical properties, the material group of discontinuous long fiber reinforced polymers (DLFRP) was developed. Within this work the substitution potential of DLFRP for metal car seat structures was investigated.

2 Properties and special effects of DLFRP

2.1 DLFRP granulate

Most characteristic for DLFRP is its initial fiber length of 10 mm (injection molding) to 30 mm (compression molding) in contrast to SFRP compounds with only 0.5 mm fiber length or less. The granulate is obtained from thermoplast impregnated cut fiber rovings. When processed in a material adequate manner DLFRP show a residual fiber length of 6 to 8 mm. This results in a significant increase of the mechanical properties compared to SFRP in tensile strength (>10 %), elastic modulus (>10 %) and in fracture toughness even at low temperatures (up to 300 %) (Harmia[1]). Further advantages for DLFRP structural parts are better surface quality, higher fatigue strength and lower creeping and shrinkage. Table 1 shows important mechanical properties of DLFRP compared with competitive metals. Todays DLFRP PA6.6 LGF60 granulate costs are about 5.2 US $/kg.

2.2 Material adequate component design and processing

The property and design advantages of DLFRP mentioned above can only be applicated if the initial fiber length is preserved. Then, the fibers build up a rather stiff skeleton where each fiber is intermingled randomly with its neighbors. This explains why a minimum fiber fraction of about 35 % by volume is required to observe a significant property increase compared

Table 1. Properties of glass fiber reinforced DLFRP compared to SFRP and relevant metals (Source: A. SCHULMAN GMBH, HOECHST AG, KEIPER GMBH).

	Spec.	**Unit**	**DLFRP**	**SFRP**	**St**	**Al**	**Mg**
			PA6.6-LGF60	**PA6.6-KGF40**	**ZStE 550**	**AlMg 4,5**	**AM 60**
Fiber Content		wt.-%	60	40			
Density		g/cm^3	1.69	1.5	7.85	2.7	1.79
Shrinkage	longi.	%	0.1-0.3	0.8			
	perp.	%	0.2-0.6	1.2			
Tensile Strength	23 °C	MPa	202	110	550	280	220
	80 °C	MPa	140				
Tensile Modulus	23 °C	MPa	15,200	8,000	210,000	70,000	45,000
	80 °C	MPa	11,900				
Fracture Toughness (Izod ISO 180)	23 °C	J/m	520	220			

to SFRP. Thus, mold and component design has to follow material adequate design rules which consider the main fiber damage mechanisms as they have been discussed by Schmid[2]. Refering to injection molding, Lücke[3] presents a variety of precautions how fiber fracture can effectively be prevented. Own experiences in material adequate component design and processing conditions were obtained with a test structure (Steffens[4]). DLFRP components should not be injected perpendicular to the surface, because it locally results in an abrupt deflection of the melt and a corresponding fiber damage. Injecting parallel to a rib reduces fiber fracture. Holes within the structure should be avoided as they are responsible for welding lines. Only a single, large cross-section bar gate should be prefered.

3 Component specifications and selection criteria

The basic capability of DLFRP to replace structural metal components was investigated on a metal car seat structure (Figure 1). The structural task of each seat component was systematically analysed by selection cri-

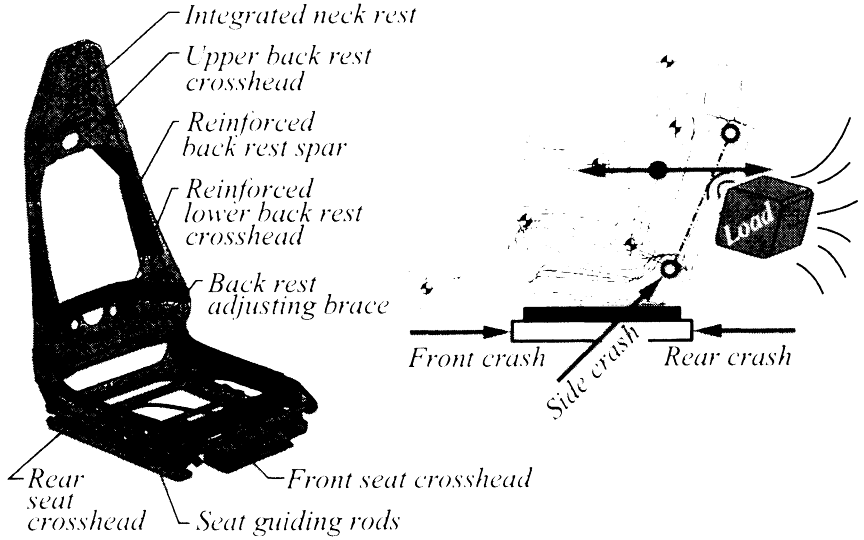

Figure 1. Metal frame structure of KEIPER's „Seat 2000" (left, Kußmann[5]), main load cases to be considered for design and analysis (right).

teria which mainly resulted from passive car safety specifications to be fullfiled for the load cases illustrated above. The seat structure also has to guarantee sufficient remaining space for the passenger and to show a good „fail-safe" behavior (e.g. Muntzinger[6]). Additionally, the back rest shall protect the passenger from flying about load. Further specifications are a low weight, economical manufacturing and both easy assembly/disassembly and recyclability. The major selection criteria applied were the possible degree of integration and the relation between structural load level and resulting stress in a material adequate DLFRP construction.

4 Results and discussion

4.1 Lower back rest crosshead

After a thorough analysis of the metal car seat structure, the lower back rest crosshead was selected first for a substitution by DLFRP. As illustrated in Figure 1, the original lower back rest crosshead consists of two steel components. One is a thin walled standard part which protects the back rest adjusting shaft from contact with the seat upholstery. The second

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lower crosshead element is a thick walled steel section which primarily takes up the side load of up to 30 kN and additionally the bending load when the passenger is pressed into the back rest in the case of a rear crash. Both components are welded into the steel back rest frame and show a weight of about 555 g. The predesigned lower DLFRP crosshead (Figure 2) integrates both steel parts and weighs about 500 g (PA6.6 LGF60) only.

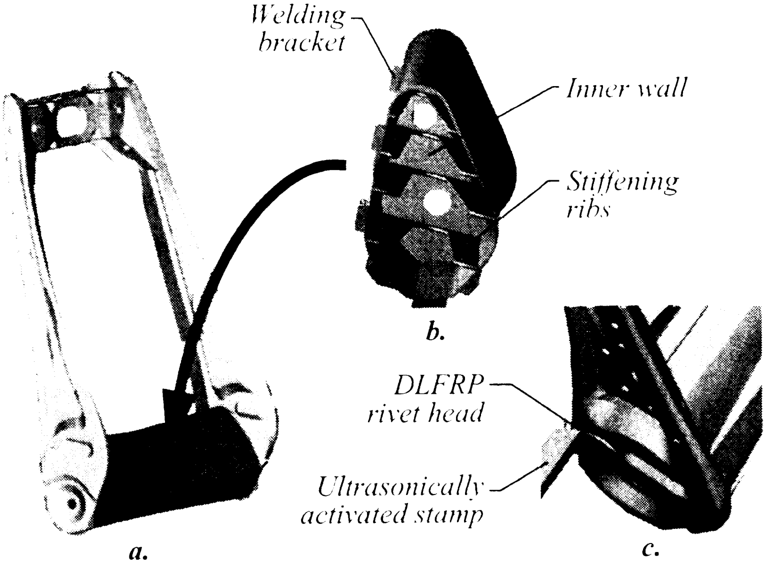

Figure 2. a., b.: Assembled back rest structure with tube like lower DLFRP crosshead, c.: rivet welding joining procedure .

The joining to the metal structure was achieved by rivet welding (Figure 2 c.). Shear tests of ultrasonically welded DLFRP rivet heads (PA6.6 LGF60) resulted to a shear strength of about 9 MPa which exceeds the calculated average shear stress of the welding brackets of about 5 MPa. The finite element analysis showed that the DLFRP component takes up a side load of about 30.7 kN.

4.2 Upper back rest crosshead

The second structural seat component investigated was the upper back rest crosshead. It has to take up a maximum rear crash load of 1.2 kN (in contrast to 960 N for the metal component) when the head of the passenger hits the neck rest in its most extended position. Future upper crosshead constructions additionally will have to take up the same side load as the lower crosshead of 30 kN. Therefore, this criterion was also considered with the new component. Figure 3 shows the final design of the upper DLFRP back rest crosshead with a separate neck rest. It integrates the metal U-sectioned steel crosshead welded into the seat structure and also two separately inserted plastic guide bushes for the neck rest rods. The composite component additionally enables a 20 ° rotation of the upper crosshead which allows a separate or an integrated neck rest to be moved close to the passenger's head substantially reducing neck injuries ([7]). The rotation was realized by an innovative joining technique, where the cross head is simply slipped onto the back rest spars. A plugged-in bolt fastens the component and at the same time serves as a joint. Bending and torsional stiffness was achieved by an I-cross-section and ribs in ±45 °-direction. Due to the increased neck rest load and side load requirements and the additionally demanded rotation, the upper DLFRP crosshead with an average wall thickness of 1.5 mm weighs about 440 g (PA6.6 LGF60) which is 150 g above the replaced steel and plastic parts.

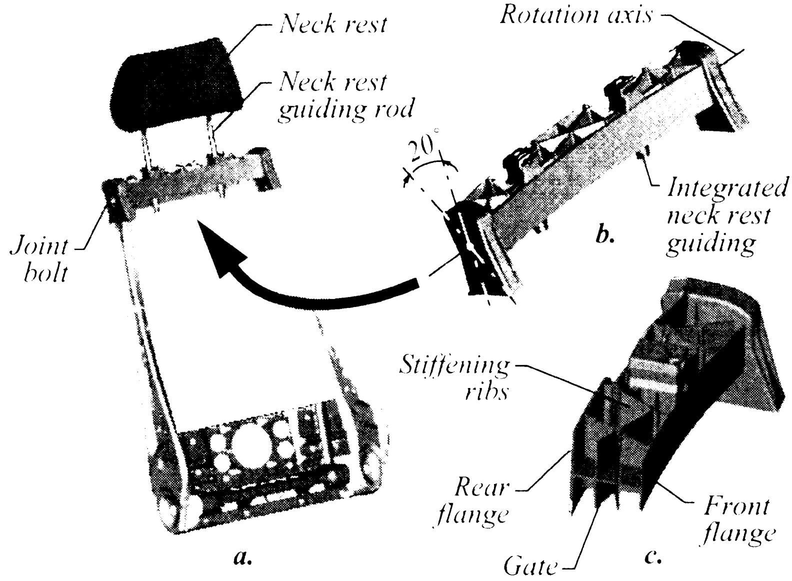

Figure 3. a.: Assembled back rest seat structure, b., c.: design details of upper DLFRP cross head.

Figure 4 a. shows the result of the finite element stress analysis at a

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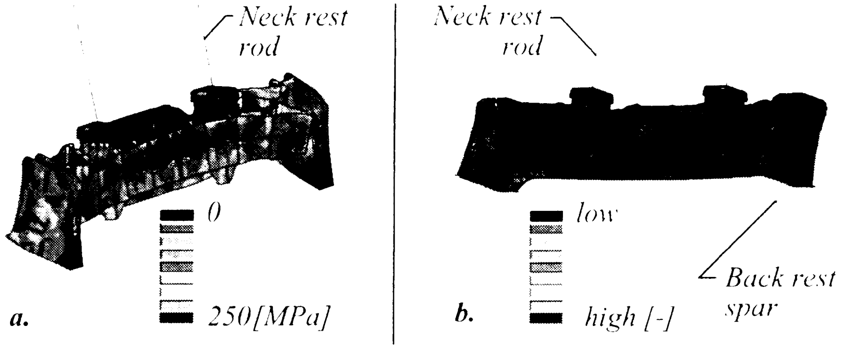

Figure 4. a.: Von-Mises stress of the deformed DLFRP structure at maximum quasi-static rear crash load (3 x deformation magnification), b.: fatigue damage distribution.

neck rest load of 1.2 kN applied to both neck rest guiding rods in opposite driving direction. The calculation assumed quasi-isotropic and linear elastic material properties. For component design, a Von-Mises stress allowable of 200 MPa was applied. Some local areas show maximum stresses of 250 MPa which is due to an insufficient number of finite elements. The specification demands a sufficient back rest structure fatigue strength for a 400 N cyclic load perpendicular to driving direction combined with 1000 N in driving direction. The fatigue life simulation of 10^6 combined load cycles showed that the fatigue strength allowable of 40 MPa is not exceeded. Figure 4 b. illustrates the calculated fatigue damage distribution above 10^6 combined load cycles. This analysis is based on crack growth and damage accumulation models validated for metals. As processed DLFRP show outstanding quasi-isotropic properties this assumption is valid for a first approach.

4.3 Prototype manufacturing and quasi-static component testing

Due to a higher degree of innovation refering to the number of integrated parts and additional functions, the upper DLFRP crosshead was selected for prototype manufacturing. Figure 5 a. shows the mold filling simulation which was performed in advance of the tool construction. As the rheological data for DLFRP PA6.6 LGF60 were not available, only a simulation based on SFRP PA6.6 KGF40 data was performed as a reference point.

The DLFRP prototypes were manufactured using a standard injection molding machine with PA6.6 LGF50 and LGF60. Figure 5 b. illustrates the long glass fiber skeleton obtained after the burning out of the PA6.6

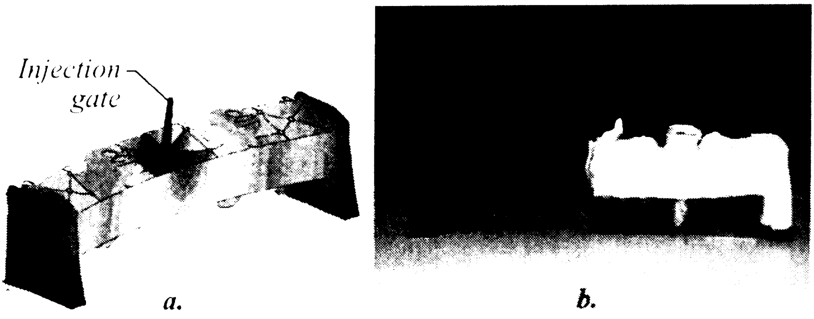

Figure 5. a.: Mold filling simulation, b.: DLFRP prototype (left half) and long glass fiber skeleton after burning out the polymer matrix (right half).

matrix. The component tests were performed with quasi-static rear crash load at a crosshead speed of 500 mm/min (Figure 6). The crosshead load-displacement curve in Figure 6 indicates the expected fail-safe behavior of the structure after passing the maximum load at about 3.2 kN. First cracks were observed at a tensile load of about 2.1 kN. This is 0.9 kN above the numerically predicted crack initiation which is mainly caused by a partly larger prototype wall thickness compared to the analysis and insufficient knowledge on the local material properties within the component.

An economical analysis of a series production with a capacity of 500,000 upper DLFRP crossheads per year showed that about 75 % of the product costs are material costs. Considering manufacturing and assembly costs, a cost reduction compared to the metal solution was achieved. Further cost reduction can be expected by new granulate production techniques.

5 Conclusions

It has been shown that a substitution of structural metal components in cars by DLFRP constructions is advantageous if a high degree of integration and innovation refering to the number of parts and functions is realized. As a precondition, the product development has to follow material specific design and processing rules. The key factor for a successful replacement is a load, material and assembly/disassembly adequate design with an appropriate joining technique. Economical advantages in mass production applications will be achieved if the DLFRP granulate costs are redu-

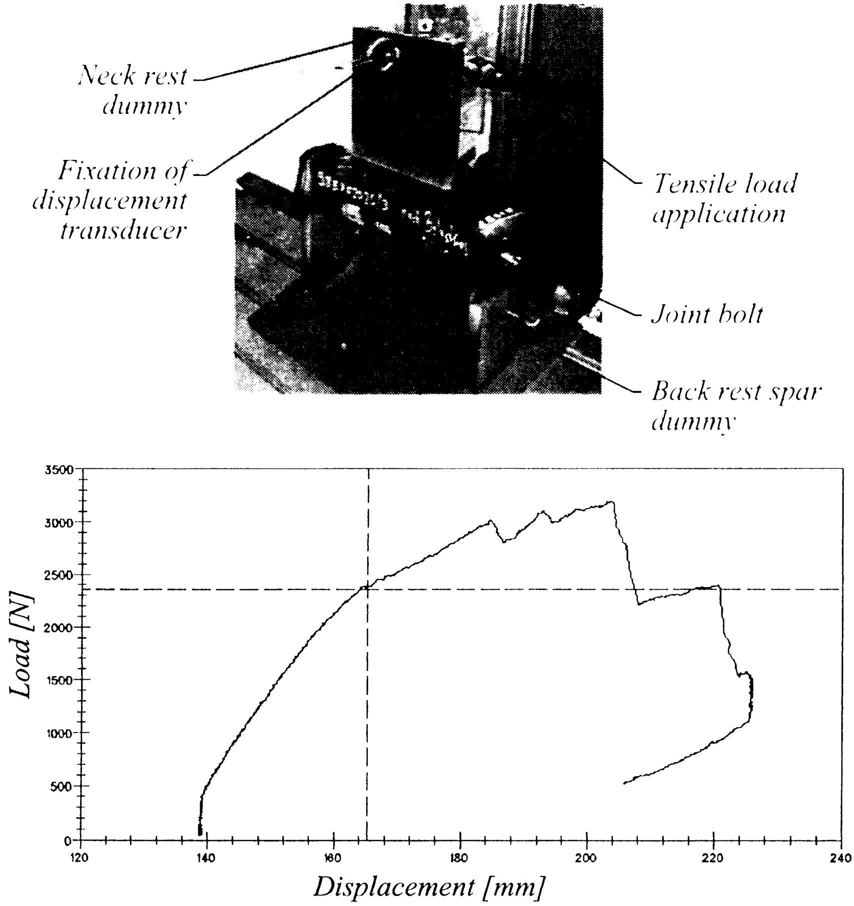

Figure 6. Component test set up for quasi-static loading (top), corresponding crosshead load-displacement curve (bottom).

ced by already prepared new granulate production techniques.

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