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Manufacturing and crashworthiness of fabric-reinforced thermoplastic composites

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ABSTRACT

In the present paper, the crashworthiness of fabric-reinforced thermoplastic composites is experimentally and numerically investigated under axial impact loading. Main aim of this article is the qualification of large-scale producible structures for energy absorbing applications. For this reason, the considerable steps of thermoforming as well as relevant process parameters are identified. This includes the development of an appropriate handling system for production on lab-scale. Formed three-dimensional profiles are tested under axial impact loading in a drop tower to initiate a continuous progressive crushing mode. Experimental results are analysed and evaluated regarding specific energy absorption (SEA). Numerical analysis by the explicit finite element code LS-Dyna is based on the orthotropic material model MAT54 and a four-layered shell model to implement crushing failure. Investigations show, that energy absorbing structures made of bidirectional organic sheets are suitable for automotive lightweight design.

1. Introduction

Lightweight design becomes increasingly important in numerous applications across almost every industrial sector. Mainly, this development is a result of economical and ecological constraints on the one hand and increasing safety and comfort requirements on the other hand. In terms of automotive lightweight design, fibre-reinforced plastics (FRP) have proven their potential for several (semi-) structural applications [1,2]. An important example for energy absorbing structures in the vehicle front-end is the crashbox. Especially in case of moderate crash velocities, the crashbox is the vehicle's most important component for an effective limitation of the resulting accelerations and the absorption of kinetic energy.

Additionally to high values of stiffness and strength combined with a low density, FRP can offer high energy absorption capacities under axial loading. A characteristic value in terms of energy absorbing structures is the (weight-) specific energy absorption. Due to high SEA values of 60–80 kJ/kg [3–5], thermosets reinforced by unidirectional endless carbon fibres exhibit a significant weight saving potential of up to 50% compared to metals. Steels are often limited to 20 kJ/kg or less for example in case of hat and double hat sections [6–8]. Anyway, aluminium tubes reach specific energy absorption of up to 30 kJ/kg [5]. The limited specific energy absorption capacity of these materials results from a deviating collapse behaviour compared to composites under compressive loading. With its ductility the axial compression of metals is characterised by fold formation. The resulting discontinuous energy consumption is described and analysed in numerous experimental and theoretical studies, e.g. [8]. Another substantial disadvantage of metallic structures is the formation of a blocking length, which does not contribute to energy absorption. In case of composite structures, however, axial loading can initiate crushing failure if local and global instabilities are excluded. Crushing is characterised by a continuous absorption of energy by means of fragmentation and destruction, which results from a complex interaction of multiple failure modes. Namely these are fibre breakage under tension, fibre compressive kinking, delamination of layers, matrix fractures and (elastic) bending [9]. In case of a stable and continuous failure, a high peak force in the beginning and a distinct mean force level following denotes the resulting force-displacement curve [10]. A local structural weakening of the component, as investigated in [11], favours the initiation of a progressive failure.

Despite the numerous advantageous properties compared to conventional construction materials, the use of FRP is limited to a few industrial applications. Among other reasons, this is due to the cost-intensive production of the fibres and fibre semi-finished products as well as long cycle times for the production of composite components in medium and large quantities. A promising approach is the use of fully impregnated and consolidated glass fibre-reinforced thermoplastics, so-called organic sheets. Substantial reasons for the use of organic sheets are economically driven, by reason of low material and processing costs

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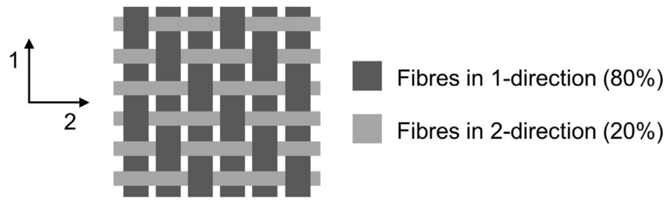

Fig. 1. Schematic in-plane representation of the investigated twill weave fabric.

Table 1
Mechanical properties of investigated thermoplastic GFRP.

Main fibre orientation:	0°	45°	90°
Young's modulus [MPa]:	28,813	1553	10,146
Max. stress [MPa]:	618	58	153
Max. strain [%]:	2.2	29.9	2.0
Poisson's ratio:	0.120	–	0.013
Shear stress (γ = 5%) [MPa]:	–	27	–

compared to other FRP. Due to the composition of the starting materials and a lower thermal effort for manufacturing, glass fibres are less expensive than carbon fibres. In addition, thermoplastics are meltable by heat supply and gain shape stability by cooling in contrast to thermosetting resin systems, which undergo irreversible crosslinking connections during curing. Thus, fibre semi-finished products with thermoplastic resin offer considerable potential for reducing processing costs in serial production through shorter cycle times. For the same reasons, thermoplastic composites exhibit an advantageous recycling feasibility [12,13].

Due to the above arguments, this paper deals with the manufacturing of large-scale producible structures made of glass fibre-reinforced plastics (GFRP) for energy absorbing applications. Therefore, relevant process steps of thermo-forming are identified and an appropriate handling system for production on lab-scale is developed. Produced three-dimensional structures are attached to composite closing plates, subdivided and tested under axial impact loading in a drop tower. In addition to the experimental assessment of crashworthiness of fabric GFRP, numerical analyses in LS-Dyna are carried out. Therefore, a four-layered shell model is implemented for the numerical analysis of crushing behaviour. The applied material model MAT54 rests on basic material investigations.

2. Experimental investigation

Experimental investigations in this study concern the characterisation, forming and testing of fabric-reinforced composites. First, quasi-static tension and compression tests are performed to describe the investigated material in numerical simulations. Furthermore, energy absorption characteristics of formed hat profiles are determined under axial impact in drop tower tests. As a conclusion of the experimental section, SEA of the composite structures as well as failure characteristics are evaluated.

2.1. Material characteristics

The material in this study corresponds to an impregnated and consolidated composite consisting of bidirectional twill weave glass fabric and polyamide 6 (PA6). Fibre volume fraction of the 0.5 mm thick layers amounts to 47%. Main fibre orientation (1-direction) of the weave fabric contains 80% of all fibres, which implies an amount of 20% in orthogonal (2-) direction (Fig. 1). Approximately, the investigated material shows orthotropic characteristics.

Prior to the manufacturing and testing of energy absorbing structures, material characteristics are determined for the numerical material model MAT54 in LS-Dyna. Investigations contain quasi-static tension and compression tests with 2 mm/min rate of loading. These tests are defined by the standards DIN EN ISO 527-4, DIN EN ISO 14126 and DIN EN ISO 14129 for FRP. Tests are carried out with a MTS-Criterion (Model 45) test stand. While strain is determined by an optical measurement system (GOM 5 M) and a stochastic high-contrast pattern, a 100 kN load cell measures the resulting force. For each of the considered tests, five valid trials are assumed. Average results in terms of stress-strain diagrams and characteristic mechanical properties of the considered GFRP are illustrated for 0°, 45° and 90° main fibre orientation in Fig. 2 and Table 1.

Under tensile load, the composite material exhibits a linear elastic behaviour in longitudinal direction and reaches a maximum stress of 618 MPa at 2.2% elongation. Laminates with a main fibre orientation of 90° achieves strength of 153 MPa and a maximum strain of 2.0%. The maximum shear stresses are determined by samples with +/−45° main fibre orientation. Stress-strain diagrams show a degressive course of these curves with a maximum strength of 58 MPa and a maximum shear deformation of 30%.

2.2. Thermo-forming process

For the production of fibre-reinforced thermoplastic components by means of thermo-forming, defined process conditions regarding the temperature of the mould and semi-finished product, the consolidation pressure as well as transfer times between process steps, must be adhered. As an example, the draping and forming ability of organic sheets directly derives from the temperature dependent matrix viscosity. Moreover, deformation mechanisms like fibre elongation and stretching, fibre gliding and shearing are decisive for the processibility of organic sheets. More detailed processing information of composites is

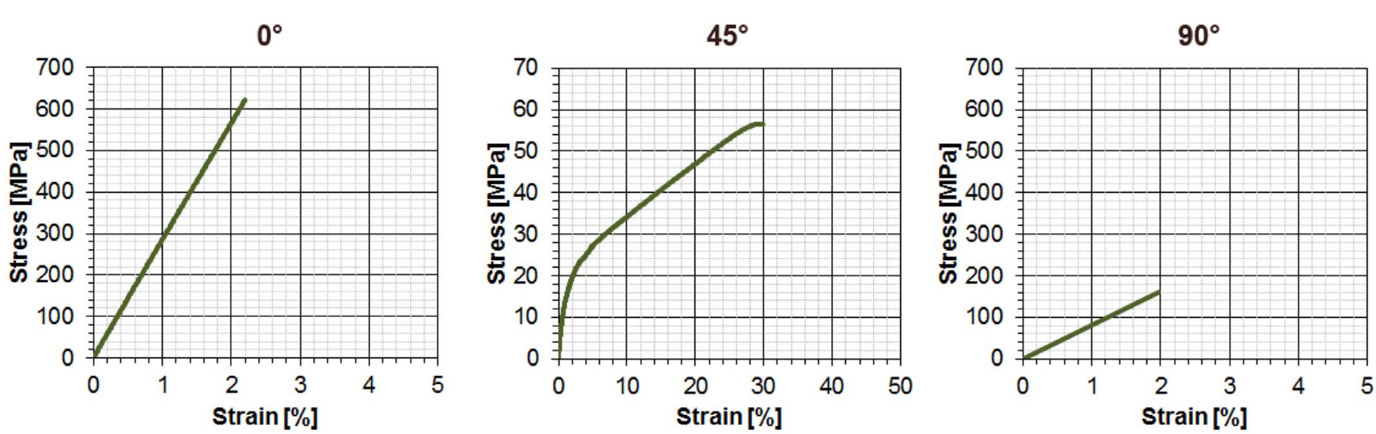

Fig. 2. Stress-strain curves of investigated thermoplastic GFRP.