Composite Structures 152 (2016) 840–849

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Experimental investigation of hybrid material systems consisting of advanced composites and sheet metal

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ARTICLE INFO

Article history:
Received 1 March 2016
Revised 20 May 2016
Accepted 13 June 2016
Available online 14 June 2016

Keywords:
FRP–metal-hybrid systems
Experimental characterization
Analytical modeling

ABSTRACT

Previous studies have identified composite-metal hybrid material systems in automotive crash structural applications as a possible solution to meet the demands of both ambitious efficiency goals and increasingly strict vehicle safety requirements. The purpose of this study is to experimentally identify basic principles, which define the material systems' properties such as the stiffness and strength as well as major parameter effects on a coupon scale. A further aim is to compare these findings to common approaches such as the rule-of-mixture theory and define analytical models able to predict these properties based on a set of parameter values. While there is a strong dominance of the steel phase, the experiments generally confirm the rule-of-mixture theory. Some effects might have to be considered when designing hybrid material systems for technical applications, such as the shift of the special neutral plane in asymmetric layups or a changed failure mode for different loading directions. The analytical models presented do match the experimental results, although the complex interaction between the material phases is not fully analyzed.

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1. Introduction

In the course of establishing more sustainable mobility solutions, lightweight design plays an increasingly important role in automotive engineering. While stringent CO_2-emission regulations lead to efficient lightweight design concepts, growingly demanding crash safety requirements are a driving force towards increasingly reinforced, thus crashworthy but heavy-weight vehicle bodies [1]. Since the body-in-white (BIW) accounts for roughly 26% of the total vehicle mass, effective lightweight design in load carrying structures, including the exploration and application of novel materials, are a promising way to overcome this contradiction [2]. In accordance with an increasing complexity of requirements for engineering structures, especially in crash applications, the latest developments in research concerning lightweight materials identified so called hybrid material systems as one very promising way to realize advanced lightweight structures [3,4]. Hybrid material systems consist of two or more materials or material systems in discreet phases which can be arranged in a multitude of architectural designs. The hybrid material systems studied here consist of one sheet metal phase and one glass- or carbon fiber reinforced polymer (GFRP/CFRP) phase adhesively bonded to each other. Applying those in automotive structural applications subjected to crash loads is one solution to benefit from (a) significant weight saving potential inherent to composites under crash loads [5–7] and (b) stable, well studied crashworthiness characteristics of metals at competitive costs [8].

Research and feasibility studies on the mechanical behavior of hybrid material systems consisting of advanced composites and metals (such as published by Koch, Feraboli, Eckstein etc. [9–13]) so far mostly originated from direct applications in complex engineering systems rather than in the field of fundamental material research. As a general result, those hybrid structures could be identified as feasible solutions in the respective fields of application with the possibility of moderate to high weight savings, higher integration levels and/or enhanced mechanical properties compared to conventional solutions. Focusing on the mechanics and the crashworthiness of hybrid structures in automotive crash applications Costas et al. [14], Wang et al. [15], Bouchet et al. [16], Shin et al. [17], Kim at al. [18] and Bambach et al. [19–25] studied crash energy absorbing components that generally consist of one steel or aluminum base structure externally reinforced with GFRP or CFRP. Given the limited comparability between the above-mentioned studies, general results are weight saving potentials of up to 38% with a strong dependency on the individual specimen

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http://dx.doi.org/10.1016/j.compstruct.2016.06.029
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design, constituent parent materials and application. A more general analysis has been published by Uriayer [26], who tested CFRP laminates sandwiched between two strips of steel sheets under tension and found a bilinear response in the stress–strain curve of the specimens due to reaching the steel's yield stress before the maximum stress at failure of the CFRP phase. After the fracture of the CFRP component the specimens exhibited a ductile behavior of the still intact steel strips until total failure. A rather comprehensive study of hybrid materials on a coupon level was conducted by Mildner [27]. Specimens composed of aluminum or steel adhesively bonded to GFRP- or CFRP-laminates of different fiber layups were tested under quasistatic tension and 3-point-bending conditions. Although the vast majority of tension tests were aborted directly after laminate fracture due to a failure of the clamping mechanism, several interesting observations were made. According to predictions based on rule-of-mixture calculations for non-unidirectional fiber orientations in the laminates the stiffness of hybrid specimens did not reach the levels of pure steel. The hybrids' stress–strain curve also showed a bilinear behavior except for unidirectional CFRP-steel specimens, which reached laminate fracture before reaching the yield stress of the steel. Hybrid specimens with laminates with mostly longitudinal (0°) fiber orientations outperformed pure steel specimens in terms of strength while predominantly transversally reinforced hybrid specimens did not.

Analytical approaches to model the behavior of hybrid material systems consisting of FRPs and metal on a coupon level have primarily been discussed by Liedtke [28]. He customized the rule-of-mixture theory to model the stiffness and strength of symmetrically sandwiched hybrid specimens with respect to their cross-sectional share of FRP. Since there was no comparison to real experiments, a transferability to nonsymmetrical specimens or a general assessment of the validity was not possible.

The aim of this study is to establish a systematic approach to the mechanical characterization of hybrid material systems consisting of advanced composites and metals and to extend the scientific foundation in this area of research on hybrid material systems. The central idea is to identify basic principles which determine the qualitative mechanical behavior of those hybrid systems up to failure such as the rule-of-mixtures or the effects of major design parameters. As opposed to previous research activities, an experimental parametric study comprising parent material systems typically applied in automotive crash structures is presented – including a variation of the steel-to-FRP-ratio. The principles observed are then processed in analytical approaches to model the stiffness and strength in different loading conditions also comprising asymmetric designs and an experimental validation. Based on this, a second goal of this study was to fundamentally assess the potential of different hybrid systems for the application in automotive structures particularly when subjected to crash loads. This in turn implies a novel approach also considering post failure effects and mechanisms in the experiments.

Hybrid specimens consisting of sheet metals adhesively bonded to advanced composite laminates are tested in bending and tension up to failure under quasi-static conditions. In order to isolate the material effects and to rule out geometric or architectural factors flat coupon specimens were chosen in this study.

2. Specimen design, testing and evaluation procedures

2.1. Materials selection

2.1.1. Metals

With the aim of qualifying hybrid material systems for automotive lightweight structures subject to crash loads the selection of materials referred to materials already used for crash relevant structures in current vehicle designs. Two significantly different types of automotive steel – a dual phase steel named "HCT600X +Z100" [29] often applied in deforming, energy absorbing structures and a hardened manganese-boron-steel named "22MnB5" [30] widely used in deformation resisting structural areas - were chosen for the manufacturing of the test specimens. Both steels are abbreviated as "DPS" (dual-phase steel) and "MnB", respectively.

2.1.2. Composites

Key factors for the composite materials selection were the anticipated mechanical performance, the manufacturability and costs. The composite layups were manufactured using semi-manufactured products (prepregs) consisting of unidirectional glass or carbon fiber mats pre-impregnated with epoxy resin. Both the carbon fiber prepreg "PREDO PR-UD CS 300/600 FT 102 38" [31] and the glass fiber prepreg "PREDO PR-UD EST 300/300 FT 102 35" [32] were produced by SGL epo GmbH. To ensure comparability both prepregs contained the same epoxy resin matrix "FT102" [33] and had a fiber areal weight of 300 g/m^2. The fiber mass fractions were 62% and 65% for the carbon and the glass fiber prepreg, respectively. The types of reinforcing fibers used in this study were 50 k filaments industrial grade carbon fibers and standard E-glass fibers, which are commonly used in engineering applications such as automotive or aircraft systems.

2.1.3. Adhesive

Joining of the constituents was achieved through a layer of "BETAMATE 2096" [34], a two-component epoxy structural adhesive widely used in the automotive sector for crash, structural and repair applications. This type of adhesive has proven to be suitable for joining composites and metals in previous test series [35].

2.2. Specimen design and manufacturing

For the 3-point-bending and tension tests, simple flat coupon specimens were designed as a two-layer thin plate consisting of a steel sheet of 1.5 mm constant thickness adhesively bonded to a cured layup of composite prepregs. As to be seen in Fig. 1 and Table 1, the dimensions of the specimens were 190 mm in length, 15 mm in width with a varying total thickness in the range of 2.8–6.8 mm depending on the type and the number of FRP layers.

The parameters varied in this study were the types of steel and reinforcing fibers, the fiber or ply orientations as well as the thickness of the composite layups within the hybrid specimen. Table 2 shows the full list of the parameters of variation and their levels. As mentioned above, the types of steel are referred to as "DPS" and "MnB", the layups as "[0/90]", "[±45]" and "[ISO]", respectively. Since industrial manufacturing and production processes limit the applicability of unidirectional laminates in automotive structures, a selection of commonly applied multi-directional laminates were chosen in this study.

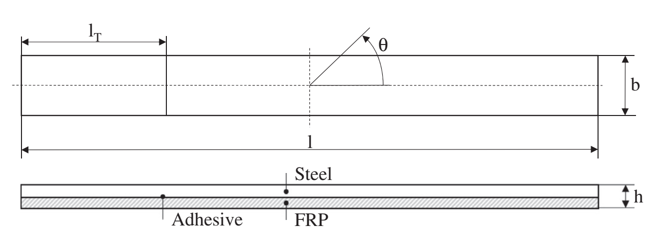

Fig. 1. Specimen design for the tensile and 3-point-bending tests.

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