Potentials of Optical Damage Assessment Techniques in Automotive Crash-Concepts composed of FRP-Steel Hybrid Material Systems

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Abstract. With car manufacturers simultaneously facing increasing passive safety and efficiency requirements, FRP-metal hybrid material systems are one way to design lightweight and crashworthy vehicle structures. Generic automotive hybrid structural concepts have been tested under crash loading conditions. In order to assess the state of overall damage and structural integrity, and primarily to validate simulation data, several NDT techniques have been assessed regarding their potential to detect common damage mechanisms in such hybrid systems. Significant potentials were found particularly in combining 3D-topography laser scanning and X-Ray imaging results. Ultrasonic testing proved to be limited by the signal coupling quality on damaged or curved surfaces.

1. Introduction

Hybrid material systems composed of advanced composite materials (CFRP / GFRP) and metals are one possible way to enhance multi material lightweight design by synergistically exploiting beneficial properties of the individual discrete material phases. Several authors have studied the crash behavior of such hybrid material systems on a component level with different specifications (see for example [1–3]). General results indicate, that hybrid material systems offer – although strongly dependent on the type and the architecture / arrangement of the parent materials – significant weight saving potentials of up to 38 % (compared to conventional materials) in energy absorbing structures [4] and advantages in other crashworthiness performance metrics such as the load uniformity [5]. However, the complexity and the interdependency of parametric effects strictly limit the comparability and transferability between the individual results.

Consequently, based on previous studies on coupon [6] and component [7] levels, the authors have tested composite-intensive hybrid material systems (ratio of cross sectional thicknesses of FRP to metal of higher than 1) in generic automotive structural subsystems under crash conditions as the final experimental program in a building block approach. Main goals of this program were to analyze the damage and failure mechanisms, to assess the potentials regarding performance and weight savings as well as to study the transferability of mechanisms from one stage to the next. Another aim was to generate a comprehensive set of data for the validation of numerical simulation models.

Critical to the performance of such material systems in vehicle-structural applications is the damage behavior of both constituent materials phases and the adhesive interface under crash loading conditions.
This behavior determines the overall crashworthiness of a structural concept composed of hybrid material systems, which in turn can be qualitatively assessed by evaluating the amount of brittle damage in the composite phase, interlaminar and interface delaminations, as well as the residual structural integrity. Non-destructive analysis techniques (NDTs) are commonly used in metal and composite structures for manufacturing and in-service quality or damage assessment [8, 9]. Since the increased research efforts on hybrid material systems such as the ones studied here are a quite recent development, NDT technologies have rarely been applied and evaluated with respect to the particular challenges inherent to such material systems. Droeder et al. have developed an automated ultrasonic device to test hybrid automotive structures for defects in the composite phase [10]. Although the architecture of the hybrid system is not clearly stated, they were able to detect dry areas and defects coupling the waves through an elastomer couplant and a medium to the FRP phase. Gieske and Rumsey used ultrasonic testing to assess the bonding quality in GFRP to metal adhesive interfaces in wind turbine applications [11]. When coupling the signal into the GFRP phase, the bond quality of the adhesive interface as well as defects within the composite phase were detectable. However, their approach using the through transmission technique (other techniques generated ambiguous results) limits the scope of applicability to structures that provide access to the relevant testing positions from both sides. Most studies focusing on X-Ray or computed tomography (CT) with hybrid material systems worked on highly integrative fiber-metal-laminates (FMLs). With composite-metal hybrid systems, the main challenge in X-Ray based analyses is to have enough energy for a total penetration of the metal layers and still obtain a reasonable contrast between the low density materials and defects / voids [12]. Further challenges in CT-analyses of such multi-material systems include severe artefacts stemming from beam hardening or scattering at the metallic parts [13].

In this study, the damage assessment approach is based on visual inspection, followed by a description and categorization of the individual damage mechanisms. In order to enhance this approach, different optical measurement technologies are applied and evaluated regarding their potential to provide deeper insights into the damage mechanisms, a more profound assessment of the overall performance and a larger scope of validation data. Eventually, understanding the damage mechanisms in such hybrid material systems could lead to improved structural designs with respect to crashworthiness and energy absorption.

2. Hybrid material vehicle subsystem crash tests

Chapter two intends to provide an overview of the experiments performed and the specimens tested. Additionally, a brief description of the damage mechanisms usually found in such hybrid structures is derived.

2.1. Subsystem design and crash test results

The test specimens contain three different components: one steel, one CFRP and one GFRP component. For the steel component a dual phase steel (DP-Steel) (“HCT600X+Z100” [14]) was chosen as it is commonly used for energy absorbing structures in BiW designs. For the manufacturing of the composite laminates fiber mats with an areal weight of 300 g/m² made of unidirectional 50k filament industrial grade carbon fiber and standard E-glass fiber, pre-impregnated with epoxy resin (“FT102” [15]) - so called prepregs - have been used. Both prepregs, the carbon fiber (“PREDO PR-UD CS 300/600 FT 102 38” [16]) and the glass fiber prepreg (“PREDO PR-UD EST 300/300 FT 102 35”) [17]) were obtained from SGL epo GmbH. They exhibit a stiffness in the 0°/fiber-direction of 120 GPa/40 GPa and strengths of 1409 MPa/1046 MPa. Joining of these three different material phases was achieved by using a layer of a two component epoxy adhesive (“BETAMATE 2096” [18]).

As shown in Figure 1, the specimen is composed of four beams all of which consist of varying cross sections and material systems. The sill (#4) is made of 12 layers GFRP [0°/±45°] and has a two-sided reinforcement made of 1.5 mm DP-Steel. The cross beam #3 consists of two 2.0 mm DP-Steel U-shaped profiles bonded by adhesive. The square hollow profiles in cross beam #2 is made of 12 layers and #1
is made of 8 layers with a [0°/±45°] layup. Both profiles feature single U-shaped 0.75 mm DP-Steel reinforcements as shown below.

Figure 1. Cross sectional view of the four base parts of the subsystem specimen.

The experiments have been carried out at the Component Crash Test Facility at the Fraunhofer EMI Crash Center. The explosive release of pressure stored in a vessel accelerates a push rod and a sled, guided on a rail system. As the push rod hits a damping device, the sled uncouples from the system and impacts the specimen with a defined speed. The impact energy of 23.9 kJ results of an impact speed of 8.6 m/s (∓0.1) and an impact mass of 647 kg. The displacement of the specimen and the speed of the sled were measured using a magnetostrictive measuring system. Three 3D-force sensors were installed under each crossbeam and were used to measure the impact force (on each section). Four high-speed video cameras were positioned at varying angles in order to document the damaging process.

Figure 2 shows the force-displacement plot of the central force sensor in impact direction (left) with the corresponding HS-video frames (right) at the indicated time steps.

Figure 2. Force-Displacement plot of the central force sensor in impact direction (left) with the corresponding HS-video frames (right) at the indicated time steps.

#1: 8 layers CFRP [-45°/0°/45°/0°], Reinforced with 0.75 mm DP-Steel

#2: 12 layers CFRP [-45°/0°/45°/0°/45°/0°], Reinforced with 0.75 mm DP-Steel

#3: Pure 2.0 mm DP-Steel

#4: 12 layers GFRP [-45°/0°/45°/0°/45°/0°], Reinforced with 1.5 mm DP-Steel

$t_3 = 7.45$ ms  
$t_5 = 14.75$ ms  
$t_6 = 20.75$ ms  
$t_7 = 57.90$ ms
At \( t_0 \) the impactor hits the specimen. The corresponding force signal shows an incline until the sill begins to buckle at \( t_1 \) until \( t_3 \). Between \( t_1 \) and \( t_4 \) the sill collapses (coinciding with a drop of the force signal). At \( t_4 \) the sill is fully compressed and the impactor reaches the intact CFRP-metal crossbeam \#2 underneath the sill. Between \( t_3 \) and \( t_7 \) the CFRP part of the central crossbeam is crushed and the metal reinforcements are wrinkled. At \( t_4 \) the impactor rebounds.

2.2 Qualitative Damage assessment – characteristics and categorization

The damage mechanisms in hybrid material systems cover a broad spectrum defined through the individual constituents’ and the respective interface damage mechanisms. Depending on the overall quality and quantity of the damage found in a structure, it is possible to derive more complex measures such as the structural integrity or residual load bearing capacity.

Table 1 depicts the scope of the damage mechanisms found in FRP-metal hybrid material systems under dynamic loading sorted by the respective discrete phases in the hybrid system. Steel is known to yield and buckle when surpassing specific tensile or compressive loads. These two mechanisms can lead to a periodic folding in dynamically crushed structures (see Alexander [19] for a detailed analysis of this mechanism) where yielding and local buckling at the hinges compels the material to fold forming periodic lobes. When the strain to failure is exceeded, ripping with sharp edges occurs.

| Hybrid Phase | Principal Damage Mechanism | Macro-level Damage |
|--------------|-----------------------------|--------------------|
| Steel        | • Yielding / Necking        | • Periodic Folding |
|              | • Local Buckling            |                    |
|              | • Fracturing / Ripping      |                    |
| Composite    | • Interlaminar              | • Progressive Crushing |
|              |   • Delamination            | • Splaying          |
|              |   • Intralaminar            |                    |
|              |     • Matrix fracture       |                    |
|              |     • Fiber fracture        |                    |
| Adhesive     | • Adhesive failure          | • Phase Separation |
|              | • Cohesive failure          |                    |

In the brittle composite phase, the main damage mechanisms are divided into interlaminar delamination and intralaminar matrix and fiber fracture [20]. When subjected to dynamic axial compression, CFRP structures may exhibit a highly energy dissipative damage mechanism called “progressive crushing”, which is caused by a complex interaction of the different microscopic damage mechanisms and frictional effects (see also Hull [21]). The adhesive bonding between the composite and the steel phase can fail adhesively at either of the two interfaces or cohesively within the adhesive layer itself. Both types result in a phase separation on a macro-level. Figure 3 depicts hybrid CFRP-steel components after testing under crash loading with an indication of the various damage mechanisms discussed above.

In order to derive integrative damage assessment measures on a structural level, all relevant mechanisms need to be assessed in terms of their quality and quantity. One of the most important structural measures is the structural integrity (SI). However, SI in automotive crash lacks a clear and concise definition. With respect to the field of application, different aspects, such as residual load bearing capacity, the absence of rupture or the integrity of critical components (e.g. fuel tank), are evaluated. According to Sahr, the material strength (no total failure) and overall capability of a component to remain in its original shape mainly define its SI [22]. Since brittle fracture is inevitable with composite structures, this definition does not apply to those material systems tested. Ferenczi et al. presented an approach to the SI assessment of CFRP automotive structures by proving that such
structures – in contrast to metallic ones - still exhibit a significant load bearing capacity after major fracture occurs [23].

![Damage mechanisms in FRP-Metal hybrid systems after dynamic testing.](image)

Figure 3. Damage mechanisms in FRP-Metal hybrid systems after dynamic testing.

However, relatively weak formulations such as “splintering should be minimized” and “a certain capacity is maintained” limit the transferability of their interesting work. Furthermore, they propose to apply NDT techniques in order to enhance the damage assessment and SI evaluation. Lukaszewicz extended the discussion on the SI of automotive CFRP structures and emphasized the need of the load paths’ functional integrity, as well as all parts of the passenger compartment to be maintained. Local debonding of joints however, is acceptable [24]. Consequently, SI assessment here is also performed by discussing and evaluating several aspects, although the authors are aiming to work on more robust and comprehensive SI assessment methods in the future.

3. **Optical Damage Assessment Techniques**

The following chapters introduce the assessment NDT-technologies used including a brief technological background.

3.1. **3D-Laser Topography Scanning**

Laser scanning is used to create digital three-dimensional (3D) models for applications related to reverse engineering and rapid prototyping by raster scanning of surfaces. A 3D-laser scanner consists of a laser sensor, which determines the distance between the laser source and the surface of the specimen using triangulation and a motion-tracking device, which tracks the orientation and position of the laser sensors itself or that of the object. The 3D-laser scanner used in the course of this work is the handheld device “HandySCAN 3D” (CREAFORM) which uses a stereo-photogrammetric system with optical reflectors for motion tracking. This system enables a dynamic registration of the scans. The software “VXelements 4” is used to control the scanning process and provides a real-time view of the generated 3D-data. Among the advantages of handheld laser scanners in terms of flexibility and scanning speed the performance of a 3D-Scanner is mainly influenced by its accuracy and resolution. In this context, accuracy means the extent of deviation of two physical points from their corresponding digital counterparts. The resolution of the 3D-model is defined by the scanning density, i.e. the number of detectable points in any given surface area. The used system scans with an accuracy of up to 0.030 mm and has a resolution of up to 0.050 mm [25].

3.2. **Ultrasonic Analyses**

Ultrasonic testing (UT) is based on the propagation and particular manipulation of short ultrasonic pulse-waves through the object or material to be tested. In the reflection or pulse-echo mode – as applied here
the reflection of the pulses at various internal features, such as voids, defects or imperfections, is received at the same transmitting device. These reflections are caused by jumps in the acoustic impedance of the medium and can be qualified based on the amplitude (intensity of the reflection) and the travel time (depth of the reflecting feature), as schematically depicted in Figure 4. The equipment used is a handheld DolphiCam 1.3 (see [26]), which is a real-time imaging ultrasonic camera with a dry elastomer coupling pad particularly designed to test CFRP-material of up to 16 mm thickness, see Figure 5. The imaging frequency is 2 Hz.

![Figure 4. Schematic depiction of the working principle of the UT reflection mode.](image)

![Figure 5. Handheld DolphiCam device used in this study [27].](image)

The transducer is composed of 124 x 124 piezo-electric elements which transmit particularly designed pulses in order to cover a broad spectrum of energies and frequencies and receive the reflected mechanical signals, which in turn are being turned into electrical signals before being processed (e.g. filtered) and visualized. The software is capable to visualize A-Scans, horizontal and vertical B-Scans, C-Scans in the amplitude and the time-of-flight mode as well as 3D-views of the specimen’s internal structure. By defining separate amplitude thresholds as “gates”, it is possible to inspect particular thickness regions of the material. All values above or below a defined amplitude threshold will be assigned the same color value.

### 3.3. X-Ray Scanning

X-Ray scanning is a non-destructive high-quality imaging method, which is used to detect irregularities in solid materials. Using a point-shaped radiation source (X-Ray or gamma-ray) differences of the density in a material can be visualized on a digital X-Ray film by means of a projected image. Differences in the material thickness or density are represented by local variations of the film exposure. The thicker or denser the material is, the lower is the amount of radiation that can penetrate through it in a given time and thus the brighter the X-Ray film will appear. The industrial radiography has to deal with different peculiarities e.g. object structures in the direction of transmittance are superimposed as a result of the projective geometric mapping as well as the stronger weakening of X-Ray radiation by metals in comparison to plastics. Generally, the image quality is influence by contrast, blur and noise [28]. The self-constructed X-Ray system used in this project contains an YXLON FXE-225.48 X-Ray tube [29] and an PerkinElmer XRD1621 xN3 ES detector [30]. The X-Ray images were taken at an X-Ray tube voltage of 160 kV, a tube current of 350 mA and an exposure time of 1000 ms.
4. Results and discussion
The following sections introduce the results achieved with the respective damage assessment techniques and discuss the potentials and limitations regarding their application to the hybrid material systems tested.

4.1. 3D-Laser Topography Scanning
Figure 6 shows a photography of the central cross beam of the hybrid specimen taken 1 month after testing (left) and a 3D-Scan of the same specimen recorded directly after testing (right).

![Figure 6. Central Cross beam #2 of the hybrid specimen. Photography of the specimen 1 month after testing (left); 3D-Scan directly after testing (right).]

Due to the different recording times, there are small deviations between the photography and the 3D-Scan especially in the angle of the two CFRP fronds. The 3D-Scan has not been digitally altered except for its resolution which was set to its maximum of 0.03 mm. The surface of the digital specimen is shown in blue, the non-scanned backside of this surface in black. Clearly visible are the positioning targets for the 3D-Scanning (white circles with a black rim). There are some dark areas e.g. edges or the black lines on the reflecting steel reinforcement, which have not been captured during scanning. This can be corrected by repeated scans, by adjusting the shutter speed of the scanner during scanning or manually by software-based post processing. Remarkably, the scan captures the exact shape of the steel folds, the fiber orientation patterns on the left CFRP frond (45°) and single ply delaminations.

Figure 7 provides an overview of the performance and handling of 3D-Scans as well as possible applications. 1) shows a photography of the tested hybrid specimen and 2) depicts the related 3D-Scan of the hybrid specimen. The main advantages of this digital model compared to the physical one are the easier handling and the possibility to analyze the surface from different angles and picture sections without much effort. Furthermore, it is possible to directly compare the tested 3D-model with the untested CAD model as shown in 3). This procedure gives a clear visualization of the extent and type of damages in comparison to the untested model. This comparison also allows for a quantitative assessment of the damage by measuring the geometric deviation between the CAD model and the 3D-Scan of the tested specimen in each direction. The method proved particularly suitable for objects with low wall thicknesses where a section cut can provide insightful visualizations of the damage (see 4).

Local damage mechanisms such as the delamination between the GFRP and the reinforced steel or the detached adhesive are shown in 3a). Moreover, in 3b) the classic folding pattern of the steel reinforcement at the central cross beam is detected, as well as severe delaminations of the CFRP phase.
Figure 7. Hybrid Subsystem 1) Photography; 2) 3D-Scan; 3) Comparison between 3D-Scan and the CAD Model; 3a) local enlargement of the 3D-Scan of the damaged sill and torn adhesive connection 3b) local enlargement of the middle crossbeam below the sill 4) Visualization of a section through the symmetry axis of the model (comparison between 3D-Scan and CAD).

4.2. Ultrasonic Analyses

In order to study the sensitivity of the considered ultrasonic device, a representative test specimen is used. The CFRP test specimen consists of 16 plies with a [0/90]-layup and an overall thickness of 5 mm. It contains representative damages realized by blind holes of five different depths and diameters in each case. The residual material thickness varies between 1 mm and 4.5 mm, the blind hole diameters are 1 mm, 3 mm, 6 mm, 9 mm and 12 mm. The material sound velocity is adjusted to 2700 m/s. A setup with three gates, with corresponding threshold values for the amplitude is used (see [26]). Exemplary results are given in Figure 8 for the 3 mm and the 6 mm blind holes with a residual material thickness of 1 mm, 1.5 mm, 2.5 mm, 3.5 mm and 4.5 mm.

Figure 8. C-Scan / B-Scan of the 3 mm and the 6 mm blind holes.

The analyses show, that the 1 mm blind holes are not reproducibly identifiable with the device. However, all the other damages are determinable and even the slight variation between 4.5 mm residual material thickness and the undamaged area is clearly detected. An analysis beyond the CFRP phase (e.g.
adhesive bond quality) is limited by the echoes from the back surface, which are not distinguishable from the impedance gap towards the adhesive or air (voids). The applicability in the context of the considered subsystems is analyzed in further measurements depicted in Figure 9.

![Image of a damaged beam and related C-Scan / B-Scan](image)

**Figure 9.** Damaged beam (left) and related C-Scan / B-Scan (right).

For this purpose, the damaged beam is examined in the highlighted delaminated area. The related C-Scan and B-Scan clearly indicate a damaged area (delamination) on the right hand side at a depth of approximately 3.5 mm. This proves, that the pulse-echo based device is generally applicable to the detection of such damage in the hybrid material systems studied here. However, remaining critical issues are the accessibility, the surface finish and shape as well as the resulting coupling. Coupling the signal into the steel phase results in a dominant echo before entering the adhesive phase, which effectively inhibits deeper analyses. This limits the technology to be applied to CFRP surfaces, which in turn need to be accessible to the device. Furthermore, in order to achieve good coupling, the CFRP surface needs to be smooth and without any major curvature.

### 4.3. X-Ray Scanning

For reasons of limited X-Ray detector size, Figure 10 is composed of several X-Ray images of the tested hybrid specimen separately recorded and post-processed (indicated by the dashed lines). For the optical 3D-scanning approximately 300 round reflecting targets have been glued on the tested specimen. Those targets are also visible in the X-Ray image 1). The highlighted areas 2), 3), and 9) show delaminations within the GFRP and inside the adhesive bond to the steel reinforcement. These delaminations might also be confused with successive folds or indentations which are superimposed along the path of the X-Ray beam. To ensure a sufficiently strong adhesive layer, rectangular metal spacers have been installed between the two components. The metal adhesive spacers are marked with 4). The [0°/±45°]-laminate of the CFRP can be recognized in the non-reinforced crossbeam depicted at 5). The highlighted areas 6) and 8) show severe delamination and splaying of the CFRP composite after crushing. In the marked area 7) the progressively folded metal is shown. In 10) single fibers and composite-fragments/debris inside the square tube are visible. Further analyses are conducted to check whether 11) depicts the adhesive bonding interface or a gap caused by delamination between the two bonded sheets. In terms of structural integrity it can be seen that based on the image in Figure 10, no major voids or gaps can be identified in the transition from beam #1 to #3 and #4. It can thus be assumed that a certain residual load carrying capacity is maintained. However, if the integrity of a loadpath through beam #2 is crucial, the overall SI is clearly violated.

Consequently, X-Ray imaging provides deep insights into the various damage mechanisms described in Table 1, some of which are more accessible than others. Needless to say, a computed tomography
scan resulting in a sliceable volume representation could clearly enhance the possibilities of damage assessment and simulation data validation.

![Figure 10. Composed X-Ray image with highlighted areas of hybrid damage mechanisms.](image)

### 5. Conclusions and future work

Generic automotive structural concepts composed of FRP-metal hybrid material systems have been tested under crash loading conditions and the major damage mechanisms usually found in such systems were discussed. Several NDT techniques have been applied in order to evaluate their potentials to enhance the damage assessment methods regarding such hybrid structures. The 3D-scanning proved to be an effective technique to generate a high-resolution topology representation of the structure covering various outer damaging modes such as FRP delamination, splaying and metal folding. A major advantage is the possibility to virtually validate simulations results interactively using the surface model. Obviously, the technique is limited to superficial damage mechanisms. Ultrasonic testing has shown to be quite difficult, since sufficient coupling of the signal into the structure is merely achieved at smooth and straight FRP surfaces. Damage (such as delamination or voids) within the FRP phase may be detected but the process generally requires good accessibility and a significant amount of expertise. X-Ray scanning as well implies user know-how at setting the filters and post-processing parameters. The resulting damage detection results however, provide significant insights into the structures external and internal damage mechanisms. Various FRP and steel damage types are detected and clearly visible and distinguishable in the composed X-Ray image. Particularly when combining the respective techniques, a good overview of the general state of damage within the structure may be achieved. Based on those results, a proper validation of numerical models (e.g. in terms of damage simulation) and a comprehensive understanding of the damage mechanisms might lead to improved designs of hybrid structural concepts for automotive crash applications.

Future work will focus on the potentials of computed tomography techniques which provide a virtual volume representation of the structure. Given the possibility to slice that volume and analyze internal as well as external damage mechanisms, this might be an approach synergistically combining the advantages of the NDT techniques studied here.

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