ENERGY DISSIPATION AND STRUCTURAL INTEGRITY IN FRONTAL IMPACT

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ABSTRACT

Currently, vehicle structures for series production mainly consist of metals. Lightweight structures are becoming increasingly important to ensure vehicles utilizing alternative electric drives are competitive. This is one of the driving forces behind the use of CFRP (Carbon-Fiber-Reinforced Plastics) in vehicle structures at BMW. However, in crash impact events, the material behavior of CFRP in terms of energy dissipation may be different compared to that of ductile materials such as steel. Notwithstanding, the potentially high specific mechanical properties of lightweight materials like CFRP make these appealing for applications in vehicle structures. In order to take advantage of the specific material properties in frontal impact applications a new approach to energy dissipation whilst maintaining structural integrity is required.
The primary objective in passive safety is to ensure the protection of the car occupants, who are enclosed by the passenger compartment. In order to protect the occupants from potential injury in the case of a crash, the passenger compartment must meet highly demanding requirements. To this end, the front structure is divided into separate energy dissipation zones. Each zone has different requirements with regard to residual load capacity and integrity, both of which increase in proportion to the proximity to the occupant cell. This use of effective energy management ensures the structural integrity of the occupant cell is maintained.

STRUCTURAL INTEGRITY

Conventional vehicle structures consisting of metals have a long history of crash design. The requirements for structural integrity are well established and the criteria for fulfilling these are known. As a general rule one does not allow significant rupture in load paths, connections such as spot welds or in the structures of the passenger compartment. This standard ensures a certain degree of robustness in the crashworthiness of a vehicle. Vehicles made of lightweight materials such as CFRP are no new innovation. There is a long history of using CFRP for racing cars or in low volume super sports cars, see also [1]. In contrast to normal series production these vehicles have different requirements for passive safety and are not generally tested by consumer protection authorities. CFRP currently used in series productions is usually limited to individual parts of the vehicle such as the roof panels. The large scale use of CFRP in crash relevant vehicle structures (main load paths, passenger compartment) demands a new approach for structural integrity. The requirement of minimizing significant damage as used in metals is no longer suitable, since energy dissipation involves splintering in CFRP structures in contrast to plastic deformation of steel structures.
Our goal is a crash design which exploits the advantages of CFRP and other lightweight materials in order to maintain or even improve the crashworthiness compared to conventional vehicles. The goal is achieved by clear definition of the structural behavior dependant on the crash zone and material/geometry used.

BMW i3

The classification of the crash zones will be illustrated using the example of the i3, BMWs electric mega-city vehicle. The general vehicle concept is based on a horizontal-split variant of a Life/Drive-architecture:

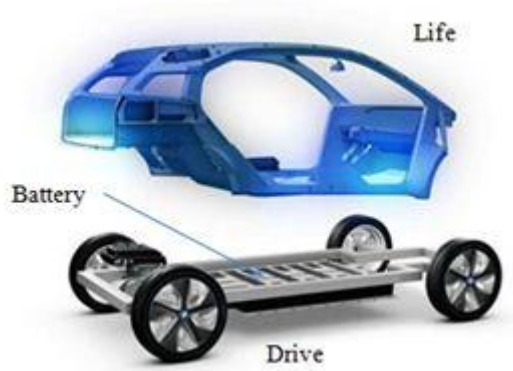

Figure 1: Life/Drive concept BMW i3

The battery is enclosed by the aluminum Drive structure with the advantages of a low center of mass, balanced weight distribution and ideal protection against external impact. This space-efficient storage in the under floor section has also the advantage of significantly more interior space than other vehicles with the same wheelbase due to omission of a centre tunnel. The front and rear structures are part of the 'Drive' module and as such made of aluminum. The 'Life' cell (passenger compartment) is a CFRP-shell construction which is mounted and affixed on top of the 'Drive' module. In case of frontal or rear impact the main part of the energy absorption is completed

by crash active aluminum structures. The principal function of the 'Life' cell is passenger protection. In case of side impact the cell (especially the CFRP-rocker panel and roof rail) plays a decisive role in energy absorption and provides an optimal protection against intrusion.

DEFINITIONS

The requirements for structural integrity depend on the actual material used, the respective energy dissipation zone and the geometry. In order to specify these, it is necessary to provide the following definitions:

1. **Structures**:
    - **a. Membranes** are parts, formed by bent surfaces, whose thickness is small compared to their other dimensions. Examples are the roof, floor panel, bulkhead, …
    - b. **Profiles** are parts with a significant length/width-ratio. Examples are the rocker panel, roof rail, A-, B-… pillars, engine support beams…
2. **Materials**:
    - **a. Ductile metals** are materials with high fracture toughness and show a ductile rupture pattern. Examples are cold worked steel panels, extruded aluminum profiles, …
    - **b. Castings** are materials with low fracture toughness and show a brittle damage pattern. Examples are aluminum die-castings, sand castings, magnesium-castings…
    - **c. CFRP** is carbon-fiber-reinforced plastic
    - **d. Composite design:** CFRP combined with metals.

ENERGY DISSIPATION ZONES

The description of the energy dissipation zones is illustrated for the front part of the vehicle including the A-pillar. An equivalent classification of energy dissipation zones is also defined for the rear and side parts of the vehicle.

Zone 1: Front-End – Bumper and Crash Boxes.

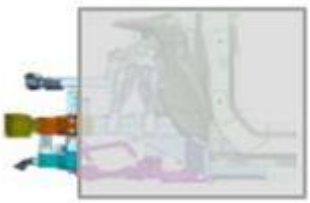

Figure 2: Crash Zone 1

In zone 1 plastic deformation is allowed. Separation or damage of the bumper cross beam or the crash boxes is acceptable as long as function and continuous energy absorption is maintained by the following structures.

Zone 2: Longitudinal Beams to Suspension Turret Inclusive Subframe Front Area.

Figure 3: Crash Zone 2

In zone 2 plastic deformation and damage within deformed components acceptable. Separation or damage of the load paths is to be minimized. The first front subframe connection to the longitudinal beams and the front branch of the suspension turret may separate to enable more deformation in the main load path and therefore increase energy absorption.

Zone 3: Longitudinal Beams between Bulkhead and Suspension Turret Inclusive Subframe Rear Area

Figure 4: Crash Zone 3

In zone 3 plastic deformation and damage within deformed components acceptable. Separation or damage of the load paths is to be minimized. Separation of the different load paths (front subframe to longitudinal beams, suspension turret to longitudinal beam) is to be minimized. This enables protection of the 'Life' cell.

Zone 4: 'Life' Cell – Bulkhead, Side frame

Figure 5: Crash Zone 4

In zone 4 deformations are allowed. Significant damage is to be minimized. The detailed description of acceptable crash-behavior in this zone is enclosed in the next section.

MATERIAL BEHAVIOR

As mentioned before the criteria for structural integrity depend on

- Energy dissipation zone (1-4)
- Material (metals, castings, CFRP)
- Geometry (membranes, profiles)

Since the front part of the BMW i3 mainly consists of aluminum structures and the requirements for structural integrity for metallic structures are well known, the following explanations focus on the passenger compartment which mainly consists of CFRP structures. The requirements for structural integrity in zone 4 (passenger compartment) are the same for frontal, side and rear impact.

Structural integrity after crash is given for…

….profiles made of CFRP located in a crash zone where damage is minimized (zone 4) and/or a certain load bearing capacity is maintained for example by ensuring that several fiber layers remain intact.

…membranes made of CFRP as part of the Life cell (bulkhead, floor panel, roof...) if damage is minimized and/or splintering can be controlled (e.g. fiber layers in different directions).

…connection of membranes and profiles made of CFRP (for example floor/rocker panel) if damage to the connection (adhesive, rivet…) is minimized or is bridged by another (intact) structure.

While splintering in CFRP structures is acceptable, significant rupture in metallic structures (profiles and membranes) located in zone 4 should be minimized. The reason for this difference is that, in contrast to structures made of CFRP (as shown in the next section "test results"), rupture in metallic structures is difficult to control and metallic structures have little load bearing capacity once significant rupture occurs.

In spite of the occurrence of damage for example in the bulkhead (in case of frontal impact) or the side frame (in case of side impact) the intrusion level of a passenger compartment made of CFRP is comparable to that of similar conventional vehicles (i.e. size and mass) made of steel. As figures 6 and 7 show, the intrusion after frontal impact as well as after side impact (oblique pole) are in similar ranges.

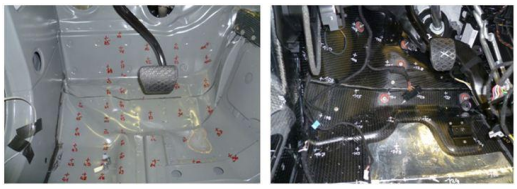

Figure 6: foot well after frontal impact steel vs. CFRP

Figure 7: passenger compartment after side impact steel vs. CFRP

The main difficulty when judging damage and splintering in CFRP structures is the determination of the degree of damage (i.e. are all fiber layers affected or are there still intact fiber layers). Usually one cannot determine this by a simple sight check. One possibility for checking such undetermined damage is CT-scanning. This was done for example for typical damage and splintering in the bulkhead (see figure 8) after frontal impact.

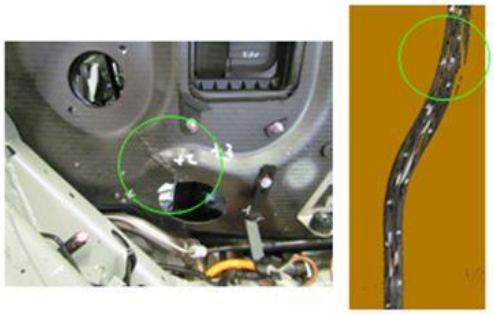

Figure 8: CT-scan of splintering in bulkhead after frontal impact

The results of the CT-scanning show that permitted splintering in this area is not significant, i.e. many fiber layers are still intact. The resulting documentation for characteristic damage modes in different laminate layups can be used as an assessment catalogue for further visual inspections.

TEST RESULTS

Splintering can be accepted in CFRP structures due to the fact that CFRP structures maintain load bearing capacity even after damage occurs, the fiber layer structure of membrane elements provides a natural crack arrestor. Several test results confirm these assumptions, as shown in this section:

Regarding frontal impact, see also [2], the same test was executed with an increased load on the bulkhead. Although permitted splintering occurred in case of the lower impact, the damage was only lightly increased in case of the higher impact (see figure 9). The requirements for dynamic and static intrusion where fulfilled in both cases.

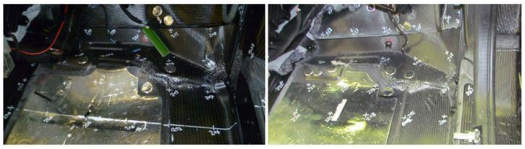

Figure 9: foot well after frontal impact in CFRP Life-Cell with lower (left) vs. higher (right) load impact

For side impact component tests showed similar results:

The experimental setup is a dynamic 5 point bending test with CFRP crash structures (roof rail and rocker panel) which approximates the impact of a FMVSS214 oblique pole test, see also [3].

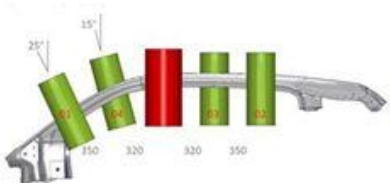

Figure 10: Component test setup roof rail

The test was repeated with the same, now partially damaged, structure. The set up, thus the load impact (mass and velocity of impactor) was equal to the first test. Although the characteristic of the damage in the CFRP structures corresponded to the damage after a FMVSS214 oblique pole test, the structures were able to absorb the same energy a second time (as shown in figures 11 and 12). Even the load level was nearly the same. In case of metal structures one would expect a considerable drop off of the force level if a significant rupture occurs.

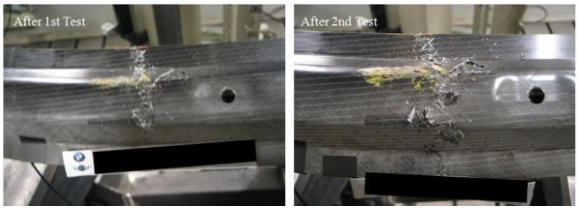

Figure 11: roof panel after 1st (left) and 2nd (right) impact

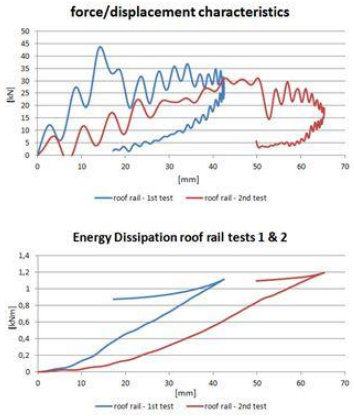

Figure 12: Force/Displacement characteristics of both roof rail tests

CONCLUSIONS

CFRP structures require different evaluation criteria when compared to structures made of ductile metals. The reason is, that metal structures may collapse if the load continues after significant rupture occurs whereas CFRP structures have ongoing load bearing capacity even after significant splintering occurs. Furthermore, CFRP structures show different performance regarding crack propagation. The fiber layer structure provides a natural crack arrestor as shown with the help of CT-scans.

This paper provides a basis for the definition and interpretation of future vehicle architectures and the use of lightweight materials with non-ductile material behavior in crash structures.

CFRP is a suitable material for crash applications, due to the high specific mechanical properties. State of the Art crashworthiness requirements in terms of structural integrity can also be fulfilled.

REFERENCES

[1] Barnes G, Coles I, Roberts R, Adams DO, Garner DMJ. Crash Safety Assurance Strategies for Future Plastic and Composite Intensive Vehicles (PCIVs). Cambridge, Massachusetts, USA: Volpe National Transportation Systems Center, 2011.

[2] U.S. Department of Transportation National Highway Traffic Safety Administration, Laboratory Test Procedure for FMVSS 208, Occupant Crash Protection, TP208-14, April 2008.

[3] U.S. Department of Transportation National Highway Traffic Safety Administration, Laboratory Test Procedure for FMVSS No. 214, Dynamic Side Impact Protection – Rigid Pole Side Impact Test Requirenments- TP-214P-01, September 2012.