DESIGN DRIVERS FOR ENHANCED CRASH PERFORMANCE OF AUTOMOTIVE CFRP STRUCTURES

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ABSTRACT

Crashworthiness using innovative materials, such as carbon-fibre reinforced composites (CFRP) requires a new understanding of the material response to crash events. Composite fracture differs from existing plastic deformation in metallic structures. Vehicle design using composites requires a detailed understanding of the microstructural material features with respect to a given fracture behaviour, as well as updated vehicle concepts and architectures to account for this inherent difference of CFRP to metallic structures.
To design composites for energy absorption all factors need to be known and understood. This study was focused on providing an overview of the most relevant material parameters. Current challenges with respect to CFRP vehicle design are discussed and particular attention is devoted to energy absorbing composite structures
The work presented here is a preliminary approach to managing the complexity of composite development including both geometrical and microstructural design. Composite materials offer benefits in energy absorbing structures and are one way of further reducing the weight of a body-in-white while also maintaining safety levels. However, such weight savings can only be achieved with a purposeful composite design. The work presented herein will highlight innovative aspects of crashworthiness with respect to composite materials.

INTRODUCTION

The use of advanced composites reinforced by long or continuous glass (GFRP) and carbon fibre reinforced plastics (CFRP) is not recent and can be traced back to their extensive use in Formula 1 vehicles from the 1980’s [1]. One motivation for the use of advanced composites in Formula 1 and sports cars was to reduce weight while also maintaining or increasing safety levels.
Since then, advanced composites have migrated into the super-sports car segment and sports car segment. All existing automotive applications have certain features in common, which can be summarized as follows:

1. Advanced Composite Manufacturing technologies are similar to aerospace and Formula 1 procedures, yielding a relatively low production volume in an automotive context.
2. Composites are used to form a monocoque around the passenger compartment, while energy absorbing crash structures are mostly made using aluminium parts, with a few exceptions mainly in the super sports car segment.

Consequently, the use of composites in mass-market applications has been limited to few parts such as roofs and bumpers [4], which do not necessarily serve as main load path in a high speed crash event for legal safety testing, such as FMVSS (USA) [2] or ECE (Europe) [3]. Future high volume plastic intensive vehicles (PCIVs) will have to achieve robustness in a crash for multiple different load cases currently not relevant to CFRP automotive structures. To achieve this the designer needs to choose not only the geometry of the structural component but also design the microstructure, such as the orientation of the fibres in the component. This work will thus be concerned with the drivers for robust vehicle design in energy absorption high-speed crash events. Existing concepts for frontal impact are used to illustrate the differences in material behaviour and this is then extended to innovative concepts for energy absorbing crash structures.

DESCRIPTION OF PROJECT i CRASH CONCEPTS

Project i is BMW’s product family for innovative electric and hybrid vehicles. Until today two vehicles have been announced in the product family, the i3 (often referred to as Megacity Vehicle MCV) and the i8, see Figure 1 and Figure 2. Both vehicles share the principle vehicle architecture of a “Life”-Module, or monocoque, made from CFRP and a “Drive”-Module made from aluminium. The drive module incorporates the main load path for frontal and rear impact, which is consequently made from aluminium.

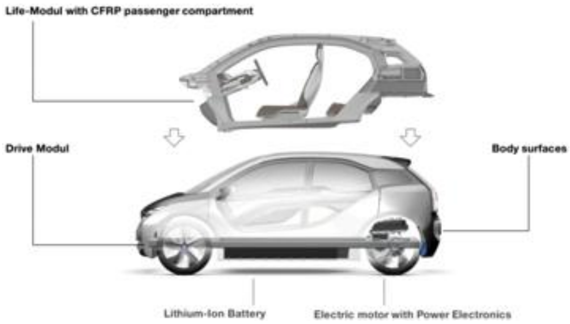

Figure 1: i3 vehicle architecture.

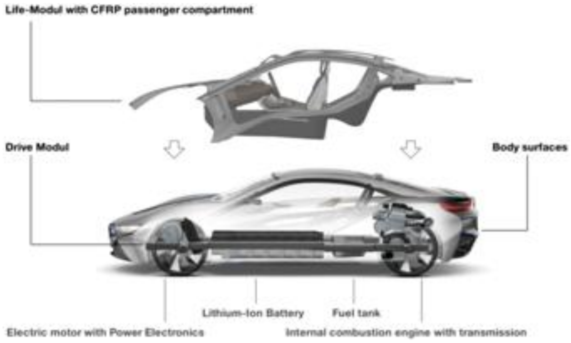

Figure 2: i8 vehicle architecture.

The drive module represents a good compromise between various requirements, such as fatigue, stiffness and crash energy absorption. However, the specific energy absorption (SEA) and stiffness for composites may be higher than for comparable aluminium structures. Consequently, composites may be one way of reducing the weight of the body-in-white (BIW) further while also maintaining crash performance.

COMPOSITE CRASH ENERGY ABSORPTION

Existing steel and aluminium vehicle structures absorb energy in a crash due to plastic deformation, work hardening and heat losses. By contrast, composites absorb energy by undergoing fragmentation, which can occur in various different modes. Figure 3 illustrates the difference between the respective progressive deformation in an aluminium (left) and a composite tube (right).

Figure 3: Comparison between plastic folding in metals (left) and fragmentation in composites (right) [5].

Overall there are four principle deformation modes for energy absorbing crash structures [6]:

1. Global buckling
2. Progressive folding
3. Progressive crushing
    a. Progressive splaying and
    b. Progressive fragmentation

The first and second deformation modes are general modes and may occur in any structure undergoing compressive loading including aluminium and steel, where progressive folding is the principle mode of energy absorption. It should be noted that composite structures may also deform in progressive folding.

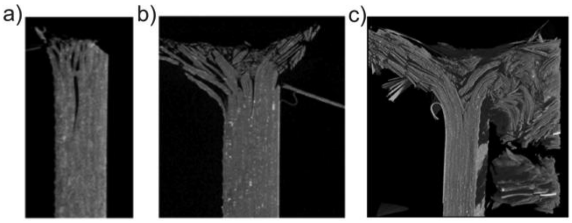

Figure 4a –c): Crushing fragmentation in a composite structure [7].

In addition composite may deform in progressive crushing or fragmentation modes, which tend to exhibit higher specific energy absorption than progressive folding. Figure 4a to 4c show the principle fracture in a composite structure during progressive crushing. In most composite structures the progressive splaying and fragmentation occur simultaneously. Initially, delaminations propagate longitudinally through the structure. The outer plies splay to the inside and outside respectively, while the plies in the middle are fragmented. These deformation modes then propagate through the structure. Energy is mostly dissipated through fragmentation and friction, both between the plies as well as the impactor. Depending on the exact sequence of deformation the amount of energy dissipated through the fracture or friction may change significantly.

To design composite structures for energy absorption the designer needs to be able to control the deformation behaviour of the component by designing the microstructure of the composite component. This is illustrated in Figure 5, where the typical design decisions affecting SEA are shown. Structural design of a metallic structure mostly requires a choice of suitable alloy.

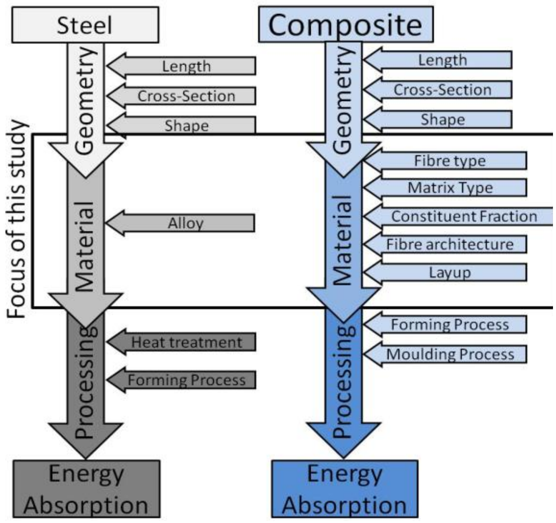

Figure 5: Comparison between typical design decisions affecting the specific energy absorption of a component.

When designing composite structures for energy absorption the designer needs to make informed decisions about the exact material configuration, such as fibre architecture and layup to achieve the desired crash properties. The focus of this work is thus a detailed understanding of the effect of the microstructure on SEA. The following sections will thus aim to illustrate the range of properties that can be achieved with geometrically identical composite specimens having different microstructures.

ENERGY ABSORPTION IN AXIAL AND OBLIQUE IMPACT

Sample Description

Composite specimens were manufactured from openly available carbon fibre for the braiding yarns and BMW proprietary carbon fibre for the axial yarns using triaxial braiding. In triaxial braiding three principle material orientations can be realized for each layer, such as (45, 0, -45). Braiding was chosen here as the principle manufacturing method since is it a highly automated manufacturing process with very low scrap ratios making it suitable for large-scale production. In addition the interlocking of the fibres in braided or woven structures has previously been shown to offer higher SEA than comparable unidirectional (UD) ply configuration [8].
To understand the potential performance benefits of composites specimens the fibre architecture was varied. In a first test the axial fibre fraction was varied between 28% and 60% and the thickness was varied, while the braiding angle was held constant, see Table 1. All specimens had a fibre volume fraction of 50%.

Table 1: Specimen Configurations for axial and oblique impact testing.

Parameter		**low**	**high**
UD-Volume fraction	[%]	28	61
Braid layers	[-]	2	4
Aspect ratio	[-]	1:2	1:1.08

Samples were manufactured to a final length of 400mm. The cross-section of the specimens was 140x70mm or 140x130 with a 15mm corner radius measured on the outside, Figure 6. The specimen ends were machined to the final length and then prepared with a chamfer trigger, which was necessary to initiate crushing and reduce the peak load.

Testing

The specimens were tested using a vertical sled configuration, see Figure 7. The specimen was fixed and was impacted by a drop mass. The test speed was 8.2m/s and the mass was varied to achieve a defined test length while not entirely disintegrating the specimen.

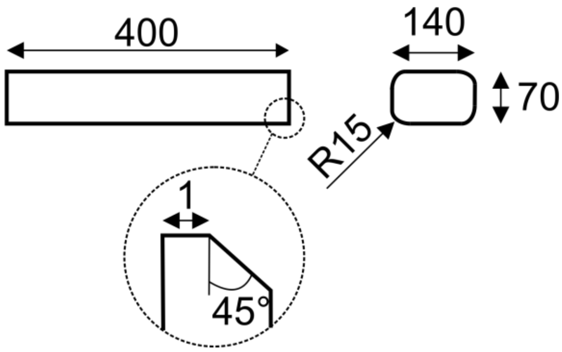

Figure 6: Specimen dimensions and Trigger configuration for an example specimen with a 1:2 Aspect ratio.

For the oblique tests the specimen was affixed identically to axial impact to the load cell and the impactor was canted. The reaction force was recorded using a piezoelectric load cell. An example of the deformation sequence is shown in Figure 8.

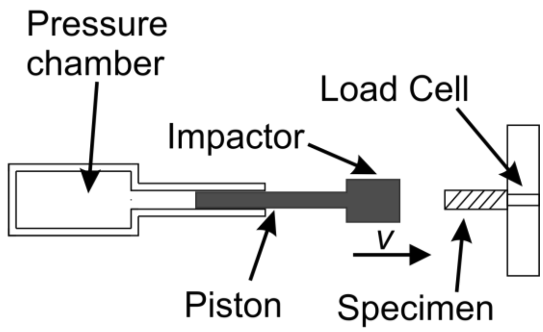

Figure 7: Impact test configurations.

Initially the trigger was destroyed, then the outside plies splayed out while the plies and in the centre and most of the axial fibres were destroyed through fragmentation. This principle sequence of deformation events was the same for all specimens; however some specimen exhibited a strong tendency to splay while others fragmented.

Results

Using the force displacement data the total energy absorbed by the specimens was calculated from Eq. 2

$$E = \int_{s=0}^{s} F(s)ds \qquad (2)$$

with E being the absorbed energy, F the instantaneous force and s the crushed specimen length. The specific energy absorption (SEA) was then calculated by dividing the crushed component mass by the absorbed energy

$$SEA = \frac{El}{ms} \qquad (3)$$

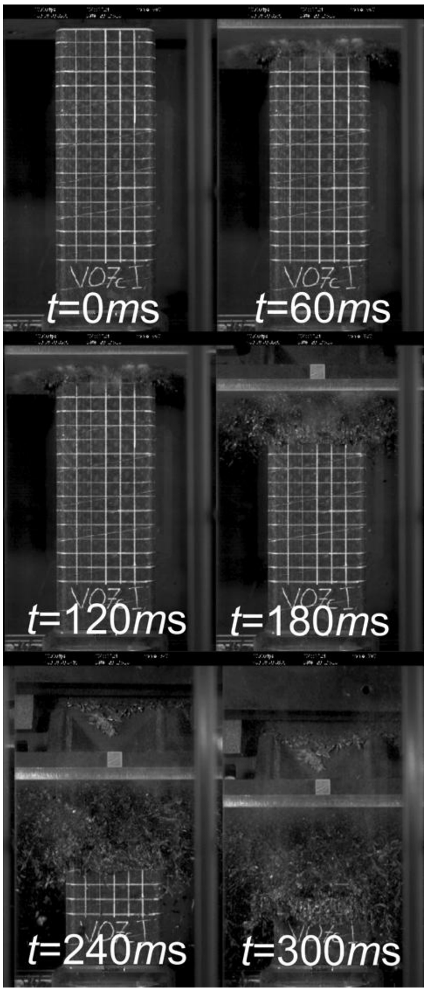

Figure 8: Deformation sequence for specimen V04 during high speed impact testing

with *l* being the initial component length, *m* the component mass and *s* the crushed specimen length. The SEA for the tested specimen configurations is given in Table 2.

Table 2: Calculated SEA data for the axial crush specimens.

Test #	**Corner Radius** *[mm]*	**UD-Fraction** *[%]*	**Braid Layers** *[-]*	**Aspect Ratio** *[-]*	**SEA** *[kJ/kg]*
V01	15	28	2	1:2	26.2
V02	15	61	2	1:2	29.6
V03	15	28	4	1:2	29.4
V04	15	61	4	1:2	35.8
V05	15	28	2	1:1.08	20.2
V06	15	61	2	1:1.08	24.7
V07	15	28	4	1:1.08	30.8
V08	15	61	4	1:1.08	38.9

When comparing the test results a few trends can be seen. First the energy absorption is always higher for specimens with a higher UD Fraction; the typical increase varies between 13% and 26%. When comparing specimens with identical aspect ratio and UD fraction it can be seen that specimens with a higher number of braid layers, i.e. thickness, have a higher specific energy absorption. Specimen V08 has a 57% higher SEA when compared to specimen V06. Lastly, the aspect ratio can have an impact on SEA, however the trend is less clear. Specimens with two braid layers have a higher SEA with a 1:2 aspect ratio, while specimens with four layers have a higher SEA for a 1:108 aspect ratio. From the variables investigated the specimen thickness has the highest impact on SEA and it is therefore the primary design variable when aiming to improve SEA in composite structures. However, by altering the microstructure of the composite structure, such as the ratio of axial to braid fibres the SEA can be increased by up 26%.
The results for the oblique tests are shown in Table 3, the specimen configurations were identical to Table 2. When comparing the test results to the axial impact data we can see that the SEA at an oblique angle of 10*deg* is actually higher in most cases, than for the same axial test specimens. This effect is more pronounced for the specimens with a 1:2 aspect ratio. At 20*deg* almost all specimens, with the exception of specimen V04 exhibited a lower SEA than for the axial impact case.

Table 3: SEA for oblique testing at 10 and 20 degree.

Test #	**10 deg** *[kJ/kg]*	**20 deg** *[kJ/kg]*
V01	28.9	24.2
V02	33.4	24.0
V03	28.6	32.3
V04	44.0	37.8
V05	25.8	21.5
V06	26.1	20.4
V07	29.8	29.8
V08	33.6	28.7

As discussed previously energy absorption in composites is amongst other things a function of the friction at the impactor surface and the energy that is dissipated by disintegrating the specimen. It is therefore likely that for small oblique angles, such as 10*deg*, the increase in contact length between the impactor and the specimen may yield higher SEA. For higher oblique angles the composite microstructure may disintegrates differently compensating the additional energy absorption due to friction and resulting in overall reduction of SEA.

HYBRIDISATION

As we have previously seen the energy absorption of composites may be controlled by changing the microstructure of the specimen, such as axial fibre fraction. This section will thus study the impact of hybrid braiding, i.e. braiding with different fibre types such as glass and carbon, as well as braiding angle on SEA.

Sample Description and Testing

Specimens were again manufactured using triaxial braiding. Specimens were manufactured using both glass and carbon fibre for the axial and braid fibres. In addition the fraction of axial fibres was varied between 0.6 and 0.8 and the angle of the braiding fibres was varied between 45 and 75 degree, see Table 4. For all variations specimens were manufactured using glass fibre for both the axial and braid fibres, using carbon for the axial and braid fibres or using glass for the braid fibres and carbon for the axial fibres.

Table 4: Specimen Configurations for hybridisation testing

Parameter		low	0	high
Axial Fibre Fraction	[%]	60	-	80
Braid Angle	[deg]	45	-	75
Fibre architecture	[-]	Glass	Carbon	Glass/ Carbon

Overall specimen dimensions were identical to previous tests with a 140x70 cross-section, see Figure 6. The test configuration was identical to previous tests as shown in Figure 7. A total of 12 different specimen configurations were tested.

Results

The results for the energy absorption were calculated as previously described and are summarised in Table 5. Glass specimens yielded low SEA values around 20*kJ/kg*, while both carbon and glass/carbon specimens yielded similar SEA values from 49 to 60*kJ/kg*. An interesting aspect is the impact of braiding angle on SEA. When comparing specimen V09 and V10 with 45deg and 75deg braiding angle respectively, the specimen with a higher braiding angle yields higher SEA and a comparable effect can be observed for glass/carbon specimens.
Similar to previous results the SEA mostly increases with increasing axial fibre fraction for carbon axial fibres. However, while the increase was previously up to 26% for an increase between 0.28 and 0.61, increasing the axial fibre fraction from 0.6 to 0.8 yields increases between 8% and 14%. In addition, for the glass fibre specimens, the SEA actually decreased when increasing the amount of axial fibres. While carbon and glass/carbon specimens exhibit similar SEA and important aspect is component cost. Although the composite specimens have a higher SEA, glass may be a more cost effective material due to the fact the cost for the fine 3k carbon braiding yarns is significantly higher.

Table 5: Specific Energy Absorption for glass, carbon and glass/carbon hybrid braiding.

Test	Braid Fibres	Axial Fibres	Braid Angle	Axial Fibre Fraction	SEA
-	-	-	*deg*	*%*	*kj/kg*
V09	Glass	Glass	45	60	23.0
V10	Glass	Glass	75	60	32.6
V11	Glass	Glass	45	80	17.7
V12	Glass	Glass	75	80	22.2
V13	Carbon	Carbon	45	60	50.2
V14	Carbon	Carbon	75	60	54.7
V15	Carbon	Carbon	45	80	57.0
V16	Carbon	Carbon	75	80	53.6
V17	Glass	Carbon	45	60	48.9
V18	Glass	Carbon	75	60	55.3
V19	Glass	Carbon	45	80	55.7
V20	Glass	Carbon	75	80	59.9

Consequently, by replacing carbon braiding-yarns with relatively cheap glass fibre glass/carbon hybrid specimens may exhibit higher cost specific performance. They may thus be a viable option to replace steel and aluminium energy absorbing crash structures due to potential weight savings.

CONCLUSION

To design effective energy absorbing composite structures, both geometric and microstructural features need to be understood. To this end, two sets of studies were introduced here, where the geometry, such as aspect ratio was varied. In addition microstructural features, such as braiding angle, fibre type and UD fraction were varied to study their impact on specific energy absorption. From these tests SEA values from 20 to 60*kJ/kg* could be obtained, illustrating the importance of informed decisions regarding the geometry as well as microstructure of composite energy absorbers. The design drivers for SEA in descending order are:

1. Laminate thickness
2. Fibre type(s)
3. Axial Fibre Fraction
4. Braiding Angle
5. Aspect ratio

However, to harness such potential weight savings requires changes in the vehicle architecture, which in turn may act as multipliers yielding more dramatic weight savings, in return. With new drivetrain architectures, such as hybrids and electric vehicles, innovative vehicle architectures are required and this may both be an opportunity for composite vehicle structures as well novel crash structural concepts utilizing composites. In conclusion, the results indicate that composites may be one way of reducing the weight of vehicle structures while maintaining or enhancing the current level of passenger safety.

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