EXPERIMENTAL STUDY AIMING TO IDENTIFY OPTIMAL MATERIAL FOR AN AUTOMOTIVE CRASHBOX

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Abstract
This paper presents a design and experimental works aiming to develop a composite crashbox suitable for a 1000 parts/day production at low cost and adapted to current mass market vehicle design. Various matrixes (Epoxy, fast-curing epoxy, polypropylene and low viscosity polyamide), various preform type in including interlock textile (Glass or carbon fiber, braided or weaved) and various manufacturing process has been evaluated by axial and 15° of-axis crash test. Solutions for short term development are proposed, with 66% weight reduction compared to current steel parts, and an estimated price of less than 5€ per saved kilogram.

1. Towards composite crashbox in mass market vehicle

CETIM aims to help the mechanical industry to find innovative solution to their challenge. Current research aims to help the automotive industry to use composite material for reaching lightweight objective induced by environmental regulation.

To use composite materials in primary structures of vehicles and mobile devices, it is necessary to control their crash behavior. Solutions exist in sports cars to reach an energy absorption level of typically 50 to 80 kJ per kg of crushed composite material [1]. These solutions are based on carbon / epoxy materials with complex preforming and manufacturing, and are therefore not economically applicable for common vehicles.

1.1. Requirements for crashbox in mass market vehicle

Main requirements in automotive industry are low cost and high manufacturing ratesof the parts. Current designs use metallic crashbox and body in white to absorb the required amount of energy to protect the passengers thanks to yielding created by local buckling. Such design costs approximately 3€/kg of parts to be produced, and may be made thousands times per day thanks to process like stamping and welding. Up to nowadays, decreasing the costs was more important than reducing the weight. Comparedto a penalty of 95€ per grams of CO_2 emission above the regulatory target that will be applied by the European commission after year 2020, a cost of 9.5€ per kg of light weighting may be acceptable (if there is no lower cost solution!), as a 10kg cut in the vehicle weight allows decreasing of CO_2 emission of approximately 1 grams/km. Concerning the process time, a production of 1000 parts/day is needed to address the mass market.

Additional requirement are given by adaptation constraint of the vehicle to its environment:

- A front end module is fixed on the crashbox, and must be kept linked with the body in white even after the crash
- Crashbox must be easily mountable and dismountable for final assembly in factory and reparability in after-sale workshop.
- Dimensions are limited by the targeted vehicle compactness

Finally, performance may be consistent on a broad range of test parameter, as crash scenario change from one case to another. In particular, performance in off-axis crushing must be checked.

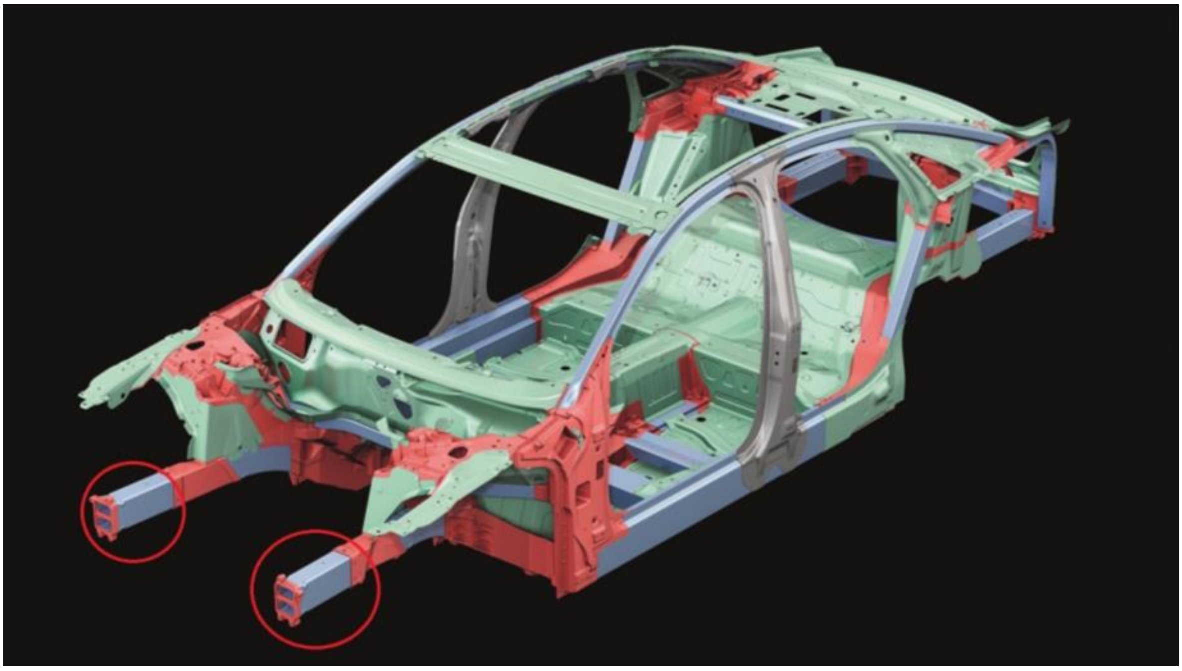

Figure 1. Position (red circles) of an automotive crashbox in the body in white (source : Audi.com)

1.2. Proposed design and process solutions

Due to the high cost of the material, especially carbon fiber, design-to-cost analysis shows that only very simple shapes may be used for designing the crashbox:

- Material waste must be reduced to a minimum. Therefore preform must be produced by an in-line process
- One step process should be chosen, including the triggering mechanisms

Therefore, the assembly solution for linking the crashbox to the car is a key aspect of the innovation. Tested solution will not be detailed here due to patent pending mater. The following principles are used:

- Mechanical clamping with simple interface parts, on easily produced shape, with tolerance to manufacturing scatter
- Clamp length adapted to fulfill off-axis bending strength requirement
- Regular shape to avoid localized effect that may change the crash behavior

Several process adapted to this design has been evaluated to checked the achievable performance. Due to the variety of tested parameters and to the manufacturing constraint, a complete experimental plan has not been set up.

A first type of crashbox has been made with a conical geometry of 150mm length, approximately 5mm thickness, 100mm larger outside diameter, and 2° of apex angle. The conical geometry has several benefits:

- Crash behavior is progressive and robust in case of off-axis crush
- Proposer assembly concept is more efficient
- Shape can be demolded, leading to easy manufacturing of such parts in RTM process

Triaxial braided preform has been used and the following parameter has been tested:

- Carbon tow : 24K (Toray T700S) or 50K (SGL Sigrafil)
- Bias Fiber orientation: Preforms are made with 50% of axial fiber and 50% of bias fiber with ±25° or 30° or 45° orientation
- Matrix : Mono component Epoxy (Cytec Prism EP2400) or Bi-component Epoxy (Momentive Epikote 05475/Epikure 05443) or Mono component PA66 (Solvay Evolite). Tests with bi-component PA6 or bi-component Acrylic are planned.

All configurations have been produced in the same RTM Mold. Epoxy RTM are alerady on the market process,while thermoplastic RTM still neede process development. 50K carbon tows are low-cost product.

A second type of crashbox has been produced with a cylindrical geometry of 120mm diameter. Cylindrical geometry offers opportunity to develop a continuous consolidation process (like pultrusion) and an extensive range of available textile technologies.
The following types of crashbox have been manufactured:

Triaxial interlock braided tube, manufactured by commingled consolidation, with 50% of Axial fiber + 50% of Bias fiber orientation	**Material**	Glass/PP twintex Tex 1870	Carbon/PA6 Comfil 50C-PA6-1600		
	Bias fiber orientation	20-30°	45°	60°	75°
Balanced Weaved tube, manufactured by epoxy infusion,	**Fiber**	E-Glass	Toho-Tenax Carbon 24K	Toho-Tenax Carbon 48K	
	Preform	Interlock	Wrapped		

Table 1. Tested parameters for the cylindrical crashbox.

2. Experimental works

2.1. Crash test definition

Crushing tests were carried out by using a drop-weight tower. A 319 kg mass can fall from a height up to 3.4 m for a maximum energy of 10650 J. The tubes are fixed with rivets (for cylindrical crashbox) or on a fixture representative of the patented automotive solution (for conical crashbox) and instrumented with a force transducer. They are fixed in the drop-weight tower axis or with an inclination of 15°. The crash is filmed by a synchronized Photron SA1 high speed video camera. Images are stored at a frequency rate of 4000 pictures per second and give us the displacement of the falling mass. An accelerometer on the falling weight allows data check.

The specific energy absorbed (SEA) was calculated:

$$SEA = \frac{W}{\rho A \delta} = \frac{\int_{\delta 1}^{\delta 2} F d\delta}{\rho A(\delta 2 - \delta 1)} \; ou \; \frac{\int_{0}^{\delta} F d\delta}{\rho A \delta} \qquad (1)$$

Where W , ρ , δ_2 , δ_1 and A hold for the absorbed energy, composite material density, boundaries of the interval of stable crushing and cross-sectional area of the tube, respectively.

Figure 2. Drop-weight tower in test configuration

2.2. Crashworthiness database

114 crash tests have been performed in the framework of this study. The following table contains results sorted to highlight main parameters of interest.

	Mean of SEA (kJ/kg)	Standard deviation (kJ/kg)
Bias angle : 25°		
Crash inclination : 0°	50,5	2,3
Crash inclination : 15°	35,5	2,6
Bias angle : 30°		
Crash inclination : 0°	48,6	6,1
Crash inclination : 15°	33,2	Only one value
Bias angle : 45°		
Crash inclination : 0°	47,6	4,0
Crash inclination : 15°	44,2	1,3

Table 2. Conical geometry, Cytec matrix, 24K carbon fiber : influence of bias angle and crash inclination

The axial crash performance increases slightly as bias angle decreases. On the contrary, for 15° off-axis, better performances are achieved with 45° bias angle. This could be linked to the enhanced hoop stiffness, which stabilizes the crush mode in off-axis crash. Crash mode is mainly fragmentation for all these tests.

	Mean of SEA (kJ/kg)	Standard deviation (kJ/kg)
Carbon tow 24K		
crash inclination : 0°	48,3	4,3
crash inclination : 15°	37,8	5,1
Carbon tow 50K		
crash inclination : 0°	39,6	4,4
crash inclination : 15°	29,5	2,3

Table 3. Conical geometry, Cytec matrix, 30° bias angle: influence of carbon tow and crash inclination

Axial and off-axis crash performance decreases when low-cost heavy tow are used. Performance gap is around 25%, which is approximately the price gap between the fibers. Crash mode is mainly fragmentation for all these tests.

	Mean of SEA (kJ/kg)	Standard deviation (kJ/kg)
Matrix : Cytec Epoxy		
crash inclination : 0°	47,6	4,0
crash inclination : 15°	44,2	1,3
Matrix : Momentive Epoxy		
crash inclination : 0°	47,4	4,5
crash inclination : 15°	40,0	Only one value
Matrix : Enhanced Momentive Epoxy		
crash inclination : 0°	57,8	1,2
Matrix : Solvay PA6		
crash inclination : 0°	43,3	5,5
crash inclination : 15°	39,4	Only one value

Table 4. Conical geometry, 45° bias angle, 24K carbon fiber : influence of matrix and crash inclination

Fast curing epoxy offers same level of performance that aeronautic 180°C grade epoxy. That is a major fact concerning opportunity to use such crashbox in mass market vehicle. Higher performances have been obtained in using a toughened non-commercial fast curing epoxy grade. Fluid Nylon offers approximately same performance than epoxy. But crushing mode is different, as the thermoplastic fold and keeps linked the fragmented carbon fibers. Work is still under progress to evaluate other types of thermoplastics material with this crashbox.

Figure 3. Carbon/PA6 conical crashbox after test

	Mean of SEA (kJ/kg)	Standard deviation (kJ/kg)
Minimum twist fiber		
crash inclination : 0°	43,3	7,6
crash inclination : 15°	31,0	2,9
Highly twist fiber		
crash inclination : 0°	44,1	4,0
crash inclination : 15°	32,2	3,3

Table 5. Conical geometry, 30° bias angle, 24K and 50K carbon fiber: influence of fiber twist and crash inclination

For process optimization matters, it has been tested if fiber twist has an influence on crash performance of the composite. Fiber twisting may be useful to facilitate the textile process, but impact the material performances. Concerning crashworthiness, it has been found that twisting doesn't influence the test results. Test on cylindrical weaved tube have lead to the same conclusion.

	Mean of SEA (kJ/kg)	Standard deviation (kJ/kg)
wrapped		
crash inclination : 0°	41,5	5,9
crash inclination : 15°	31,7	0,6
interlock		
crash inclination : 0°	45,5	2,0
crash inclination : 15°	36,2	1,5

Table 6. Cylindrical geometry, 48K carbon fiber: influence of weaved preform type and crash inclination

As interlock composite is known to have better impact tolerances than 2D laminate [2], tests have been done to check crashworthiness performance of such material. Results show a small increase of performance for axial as for off-axis crash. Work is still under progress to find the optimal preform type for crash application.

	Mean of SEA (kJ/kg)	Standard deviation (kJ/kg)
Carbon/PA6		
Bias angle : 30°	63,0	11,1
Bias angle : 45°	47,7	10,7
Glass/PP		
Bias angle : 20°	18,4	5,5
Bias angle : 45°	34,4	0,2
Bias angle : 60°	40,8	1,3
Bias angle : 75°	35,9	2,5

Table 7. Cylindrical geometry, triaxial interlock braid, 0° crash inclination: influence of material and bias angle

The higher SEA of this crashworthiness database has been obtained with braided interlock tube using carbon/PA6 commingled fiber. High results have been obtained with low-cost Glass/PP material too. Optimal bias angle is different between Carbon/PA6 (the lower is better in axial crush, like for carbon/epoxy conical braid), and Glass/PP (maximum results is obtained with a 60° bias angle, which may be correspond to the best hoop to axial stiffness ratio). Crush mode of the Glass/PP tube were really specific in composite application, as the tube seems to fold under local buckling, like for metallic crashbox. First calculations have shown similarities between the buckling mode and load of the tube and the crash behavior. It opens an opportunity to develop for this type of composite, and possibly all thermoplastic composite material, simulation tool that can be more efficient than the one needed to represent fragmentation of thermoset composite material. Ph.D. thesis work of C. Priem focuses on this subject.

Figure 4. Glass/PP cylindrical crashbox with 75° bias fibers after test

3. Discussion

3.1. Short terms available solution

CETIM and its partner Momentive propose to the automotive manufacturers to develop a crashbox based on the conical design presented in this paper, with fast-curing epoxy.

Manufacturing study has been made: With only one braiding machine and one standard bi-component RTM press, with an injection tool allowing simultaneous injection of 9 crashbox, a 1000 parts per day production is feasible, and the cost of one part should be around or less than 10€. Proven process and material are used.

Easily adaptable in current car design, this crashbox may allow introducing composite at its right place to obtain optimal lightweighting of a car body-in-white: Obtained crash performances are tripled than those of current steel part. Composite crashboxes efficiency is well known on sports car.

3.2. Long terms possibilities

CETIM research strategy on composite material is focused in the development of a new process to allow easier use of thermoplastic material in the industry. First results obtained in this study shows comparable results between epoxy and polyamide with carbon fibers composite. Previous study [3] on composite with high performance thermoplastic matrix has shown much greater SEA for this type of composite. Many progresses are still to be done on thermoplastic composite process (enhanced fiber fraction, fiber/matrix adhesion, less porosity…), therefore CETIM will pursue the evaluation of various thermoplastic composite crashboxes to check if better performances may be obtained and to find a way to produce them always cheaper.

On the other hand, CETIM work with textile manufacturers to find the better way to produce preform at a lower cost and with higher performances. Interlock fabrics have not proven in this study significantly superior performances compared to 2D wrapped laminate. It seems surprising as through-the-thickness reinforcements are known [4] to have positive influence on the crush load of a composite material. Preforms definition include many parameters, so new attempts will be made to find a key parameter to enhanced composite crashworthiness.

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