

CF/PA6 sandwich structures for crash energy absorption

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Abstract:

The Interurban Vehicle is one of three vehicle concepts that are developed within the DLR Next Generation Car project. Its packaging involves special requirements for the Body-in-White structure. A crash concept relying on an innovative side sill structure is developed. Crash energy is absorbed by sandwich panels out of carbon fibre organo-sheets. Two variants are investigated, one with a balsa wooden core and one with a corrugated organo-sheet core. The current results from simulation and experimental tests are presented – from coupon joining testing sandwich panel tests up to a successful component crash test.

Keywords: CF/PA6, Vehicle Structure Development, Crash concept, Lightweight Structures, Fibercrushing

Introduction

The Interurban Vehicle (IUV) is a vehicle concept developed within the DLR “Next Generation Car” project, see Figure 1. The focus for the development of the IUV are comfort, safety and sustainability. Passenger comfort is addressed by specifications such as an automation degree of SAE level 4, a flexible interior, an ergonomic sliding door concept and a total driving range of up to 1000 km. The challenge of enabling such long ranges for a five-seater vehicle is addressed by using hydrogen as main energy storage combined with the development of lightweight structures for weight reduction. In terms of safety, the development focuses on crashworthy Body-in-White (BiW) structures addressing NCAP and IIHS crash test programs. Designating a theoretical release era from 2035, the implementation of potentially sustainable materials like thermoplastic matrix or balsa wood as well as future series production possibilities as fast thermoforming are considered. A zero-emission powertrain is achieved with an electrified driving system extended by a hydrogen powered fuel-cell system.

The ergonomic sliding door entrance involves a non-permanent b-pillar and together with the hydrogen tanks packaged inside the floor, a new crash concept for a safe, intrusion resistant floor is required and presented in this work.

IUV Body-in-White

The overall vehicle concept development defines gravimetric, volumetric and geometric concept which defines the requirements for the vehicle structure [1]. Lightweight materials as well as lightweight design methods considering hybrid design and function integration or lightweight manufacturing methods have been utilized in the development of the BiW. An organo-sheet intense design with non-woven, endless, unidirectional carbon fibre layer stacking was pursued. Based on a simplified static finite element model with relevant static loads like e.g. torsional stiffness and equivalent static loads for crash scenarios, topology optimization and free-size optimizations reveal relevant load paths and structural areas where sandwich design is advantageous. Size- and shuffle-optimization determine composite layup orientation and number of layers for each defined section of every part. The result is a BiW with sandwich design in the roof and main floor assembly. The implementation of load carrying metal foil layers for integrated data and power transmission revealed further potential for weight savings. After static optimization, a BiW mass of less than 250 kg was achieved, bringing the total curb weight of the IUV down to 1600 kg.

Crash concept

The main differences for the IUV BiW structure to conventional BiW structures are its intensive fibre reinforced design, the non-permanent b-pillar and a “thicker” floor providing enough packaging space for the storage of the hydrogen tanks. Looking at crash testing programs, two tests are identified as most critical for the new vehicle concept structure. The side barrier test where the energy is mainly absorbed by the doors and the side pole test where the intrusion energy is concentrated on the small contact surface of the pole. This paper focuses the development of a crash concept of the vehicle floor, requiring resistance to the intrusion of the pole for the protection of the hydrogen tanks and the passengers.

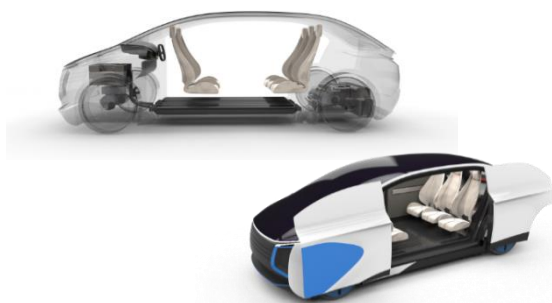


Figure 1: The Interurban Vehicle Concept

Therefore, a nontypically high value of 50 % of the impact energy should be absorbed by the side sill structure. Considering the given lightweight objectives, a high specific energy absorption (SEA) is required which can be achieved with the principle of crushing of fibre reinforced plastics [2]. Crash load absorbing principle components with varying fibre orientations and matrix systems (Epoxy, PU, PA6) under high speed crushing and bending load were benchmarked and used for further simulation calibration in [3]. With SEA values of 60-70 kJ/kg, the SGL material Sigrafil C T50-4.0/240-T140 with PA6 matrix and their subsequent inhouse manufacturing processes were found suitable for further structural developments. Using carbon fibre reinforced plastics, precautions against catastrophic bending rupture need to be taken. Aluminium extruded profiles enclosing the hydrogen tanks provide the necessary support.



Figure 2: IUV floor with integrated hydrogen tanks (orange) encasing Al-profiles and CFRP side sill structure

Secondly precautions against buckling failure of the composite structure must be taken. Euler's analytical buckling formula reveals that an increase in young's modulus and second moment of area increase positively the critical buckling stress. Higher young's moduli come generally with higher cost. Higher second moment of area can be achieved by shifting the material off the neutral bending axis, like in a corrugated shape or, even more, in the shape of an I-beam. Replacing the I-beams web with a laminar low-density core material with mechanical properties able to sufficiently couple the two flanges results in sandwich structure. Two sandwich concepts were therefore pursued for the crash absorbing elements on the side sill structure. A concept where the CF/PA6 face-sheets absorb the main part of the crash energy and the core consists of a low-density balsa wood for preventing the laminate from buckling. A second concept deploying a corrugated organo-sheet replacing the balsa wood was investigated. While corrugated shapes tend for higher SEA [4], sandwich structures with homogenous core seem less dependent on loading directions and offer more possibility for function integration (thermal/noise isolation, electronics, aeration channels, etc.). The fact that floor and roof are made of sandwich structure might provide further safety for crash energies higher than the ones defined in crash test programs by

providing a continuous absorption instead of a catastrophic failure.

The required component crushing force was calculated from the crash energy of the vehicle. The total crash energy for the IUV side pole crash at 32 km/h is about 67 kJ. The requirement for the side sill is the absorption of 50 % or 33 kJ, which in turn are to be absorbed 72 % by two sandwich panels and 28 % by the aluminium profile. A sandwich structure should therefore be capable of absorbing 12 kJ with a crushing length of about 180 mm, which results in a targeted mean crushing force of 67 kN or above.

The next step in the requirement and specification process are virtual analyses. The explicit LS-DYNA finite element simulation, with MAT262 for organo-sheets, enables the optimization of the structure in terms of shape and thickness. The simulation shows a reduction in the amount of absorbed energy when the contact strength between face-sheets and core, the adhesive, is reduced. For low adhesive strength values around 6 MPa, an unstable failure behaviour of the laminate is observed. Similar failure behaviour is observed in the experimental compression test series of Baltek SB50 balsa wood. For preliminary experimental investigations, functional prototype sandwich panels were joined with PU adhesive and tested under guided, quasi static (80 mm/min) loading. The balsa core Baltek SB50 from 3A Composites was used due to its high specific shear stiffness. A core thickness of 25 mm was selected to avoid global buckling. The laminate orientation is $[90/0/0/90/0]_s$ with 0,16 mm ply thickness and 0° orientated in loading direction. All tested sandwich specimen in this work contained a milled trigger with either 45° or 70° trigger angle. The overall sandwich including the adhesive layer measures 30 mm. The compressive pole intrusion test results show forces around 80-90 kN and a stable crushing behaviour. However, a functional prototype component test of the side sill out of similar sandwich panels did not reproduce these results. The main differences in the test setup were testing speed at higher velocity (32 km/h) and lack of lateral guidance. The analysis of the test revealed an appearance of a longitudinal crack in loading direction in the laminate causing a peeling of the laminate along the pole. The expected crushing failure mode was not achieved. Subsequent tests were carried out for further findings on this phenomenon and its prevention. Benchmarking tests on different balsa densities/strengths and adhesive systems as well as a modification in the laminate layout for the component validation test were performed.

Sandwich panel compression test series

Three test series of sandwich panels with varying balsa core densities of 109, 148 and 285 kg/m³ were tested under quasi static compression with a pole indenter of 254 mm diameter. The respective tensile strength perpendicular to the plane is 9, 12 and 18.3

MPa for Baltek SB50, SB100 and SB150. The sandwich panels of dimension 200 x 300 x 30 mm were joined with PU adhesive, clamped between two steel bars of 20 mm height and tested without further guidance. For the SB50 series a volatile behaviour of the force displacement curve was observed, fluctuating between 40-80 kN. The variances are caused by a crumbling behaviour of the laminate. Horizontal fractures appear and pieces of the laminate fold out without crushing. The damaged parts of the face-sheet still showed residues of balsawood which indicates no failure of the adhesive but failure of the core material. The SB100 test series showed reproducible constant force values above 80 kN followed by a sudden drop after 60 mm intrusion down to zero. The SB150 series shows a similar pattern. Force reaches average values above 110 kN and suddenly drops to zero after 50 mm intrusion. Wood residues on the laminate are hard to find confirming sufficient mechanical performance of the core material. Satisfactory results from the test series are obtained due to the high amount in force and the continuous crushing failure, until a sudden vertical crack splits the part in two and causes the drop of the force. The local intrusion of the round pole induces lateral loads into the laminate. With progressive intrusion, the amount of laminate withholding the vertical loads reduces. The high amount of 0° layers are positive on the force but not against the lateral loads. In this layup configuration only four 90° layers per face-sheet counteract the lateral loads.

Adhesive benchmark

Previous simulations hinted an increase in energy absorption with increasing adhesive strength accompanied by different failure behaviours. An experimental test series was therefore carried out to identify optimal bonding system performance. As thermoplastic materials are generally known to be difficult for adhesion because of their low surface energy, a suitable adhesive system for joining CF/PA6 organo-sheets were sought in an initial series of experimental tests. The identified adhesion system was then tested for joining CF/PA6 with balsawood in a second test series. For the first series shear lap tension tests between two 100 x 25 x 2 mm coupons were carried out. The 2K PU system Körapur 842/20 reached 11 MPa. Other Weiss 2K PU systems show slightly lower values. Epoxy systems generally failed at lower values here. But with a plasma pre-treatment from Novel-Tec for surface energy activation, an average shear strength of 11.5 MPa is seen for the 2K Weiss EP 200.101. It should be noted that a high variance in the results could be observed. Best results were obtained with Methylmethacrylat (MMA) based systems. The MMA system Acralock SA 10-15 failed at 15 MPa. For the application of Technicoll MMA systems, Primer (9603-1) functioned as pre-treatment. The TC9411 showed failure at 16 MPa and the best

results were obtained with TC9403 with an average value of 25 MPa shear strength. Nevertheless, the TC9411 has a can-time of 6 min while the TC9403's is 3 min making it difficult to use in manual component joining processes in a laboratory environment. In the second test series, the two Technicoll adhesives were tested under normal tensile strength with two 50 x 50 x 2 mm plates. Without core material, the TC9403 shows 22 MPa. Testing the adhesive in combination with 50 x 50 x 8 mm balsa wood, the results fall down to less than 7.6 MPa max, independent on the balsa density. Again, a high variance in the results can be observed. While not being able to establish a significant firmer joining between CF/PA6 and balsawood than the PU system, a simulative investigation for further insights was conducted, looking for the minimum bonding requirements based on simulation.

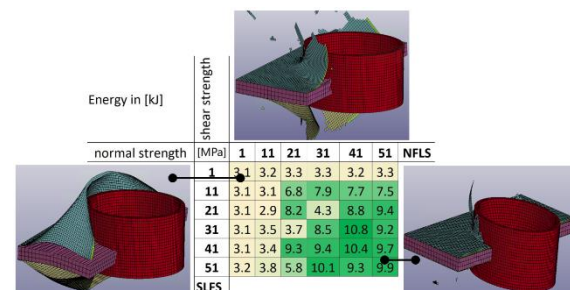


Figure 3: The effect of bonding strength variations on the amount of energy absorption

The simulation results show that shear strength is more important for backing the laminate than normal strength. Best results are obtained with normal and shear strengths of 31 MPa or greater. Some results for values at 21 MPa look also promising in the simulation. As experimentally these joining strength between CF/PA6 and balsa could not be reached with the tested adhesive systems (<7.6 MPa), focus is brought to the second, the robust concept with a corrugated CF/PA6 core.

Ultrasonic welding

Higher bonding strengths between CF/PA6 organo-sheets as measured with adhesives (TC9403 SLFS 25 MPa, NFLS 22 MPa) are expected for ultrasonic welding bonds. At the DLR-Institute of Structures and Design in Augsburg two CF/PA6 organo-sheets were welded together and waterjet cut into shear lap test coupons of 25 mm width. Repeating the welding process at different speeds, five test series were conducted. Average shear strengths of 27, 32, 33, 37 and 37 MPa are measured, surpassing the expectations.

Corrugated sandwich

With a milled aluminium pressing tool, 2 mm thick corrugated organo-sheets ([90/0/0/90/0]s) were manufactured. Under quasi static compression load

with a pole as impactor, an overall stable crushing behaviour is observed and forces between 25 kN and 40 kN were measured for a standalone corrugated core. To test the corrugated core as a sandwich assembly, two 1 mm face-sheets were joined with TC9411 to the corrugated organo-sheet. Quasi static testing shows constant forces of 60-70 kN. Repeating the test with an inclination of 3° - as it will position in the side sill of the vehicle – increases the constant crushing force to 80 kN. Dynamically, at 9 m/s, average loads up to 65 kN are obtained before the face-sheets start to peel off after 80 mm intrusion. This early peel off behaviour appears due to small panel sizes of 200 x 300 x 30 mm compared to the diameter of the impactor (254 mm). Few bonded surfaces are left on the sides to restrain the face-sheets from peeling. In wider panels – as it is the case for the side sill concept or component prototype – this effect should reduce. Sudden vertical ruptures as seen in quasi static tests with a balsa wooden core did not occur.



Figure 4: Left: Corrugated core; Right: Balsa wood core

Experimental validation on side sill component

The objective of this work is the validation of the crash concept on a functional prototype side sill component. The optimized simulation model is therefore adapted to the manufacturing possibilities available for this functional prototype. Two variants are tested. One with a single corrugated core and one with a double corrugated core. The extruded aluminium profile from the concept is replaced by 750 mm wide steel sheets welded together to a multi chamber profile. The corrugated sandwich crash elements have dimensions of 500 x 200 x 20/40 mm and are joined with TC9411 adhesive. The 500 mm closing structure is 3D printed with the DLR robot arm based screw extrusion process (SEAM) at Arena2036. The extrusion material is a PA6 matrix filled with short carbon fibres. Its brittle behaviour is supposed to fail locally where the pole intrudes but stay intact otherwise. A support for the sandwich panels should therefore be assured throughout the entire test. All elements are joined with TC9411. To avoid sudden vertical fracture, laminates with multiple 90° layers are utilized for the face-sheets. The force measurements show a rather constant crushing force shortly after impact. The crushing force drops before the metallic profile starts absorbing energy again in the last quarter. The results of the tests show peeling of the face-sheets and forces slightly lower than expected. The effect can be attributed to the increased amount of 90° layers

([90/0/90]_s). For the single corrugated core sandwiches, energy absorptions of about 8 kJ (at ca. 50 kN) per sandwich panel are achieved. The double corrugated component showed twice the performance up to the intrusion of 100 mm where one sandwich panel starts to tilt due to imperfections of the manual joining process. Nevertheless, more than 40 kJ (>33 kJ) of kinetic energy was absorbed in this test validating the concept suitability.

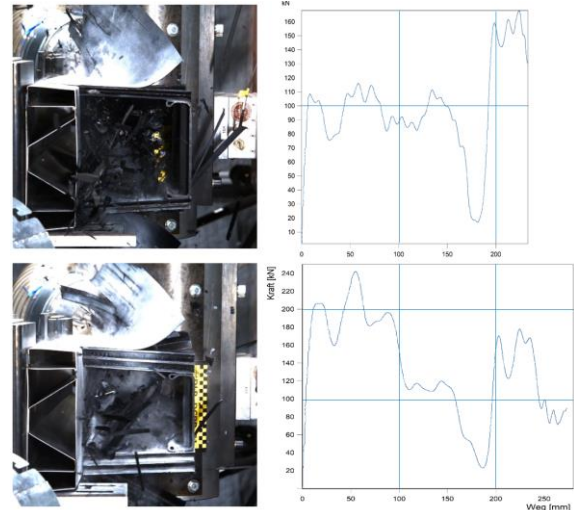


Figure 5: Crash concept validation test. Crash energy absorbing sandwich elements contain one (top) or two (bottom) corrugated core(s). Force-displacement measurements (right).

Conclusion

A crash concept was developed for the IUUV vehicle concept. The validation tests show that a lightweight crash concept based on crushing of CF/PA6 sandwich panels is possible. Significant influences by laminate layups, balsa core densities and especially bonding performances on failure behaviour and energy absorption were found during the development, suggesting room for improvement in future works.

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