HYBRID BODY OF UNDERGROUND RAILWAY CAR: PATH TOWARDS REDUCED WEIGHT OF RAIL VEHICLES

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The purpose of the development of a hybrid body for underground railway cars was to achieve weight reduction and a favourable impact on operating costs, primarily due to energy savings. The present paper describes the construction sequence of a prototype body shell.

KEYWORDS
underground railway, hybrid body, rail vehicles, weight savings, composite materials

1. INTRODUCTION

The weight of a rail vehicle is one of its important parameters. In order to meet the requirements for improved ride and passenger comfort, rail vehicles are provided with various installations which, in turn, increase their weight (e.g. air-conditioning systems, low-noise design, insulation and others). At the same time, vehicle operators require that axle load specifications are met. Common knowledge and evidence provided by physics are in favour of weight reduction. Specific running resistance of vehicle:

$$W = c_1 \cdot m \cdot g \pm s \cdot g \cdot m \pm a \cdot m + C_1 \cdot A \cdot \frac{\rho}{2} \cdot v^2 [N] \qquad (1)$$

Where:
W..specific running resistance of vehicle
c_1...coefficient of rolling resistance
C_1..aerodynamic drag coefficient
s ....rising gradient
A ...frontal area
ρ....air density
m ...vehicle mass
a....acceleration

The specific running resistance equation comprises terms for the rolling resistance, the resistance on rising gradient and the drag due to the environment. Except for the drag, all terms related to resistance depend on the vehicle mass. The body of a rail vehicle, or the body shell, which is a load-bearing structure that transmits the forces and loads in all directions, accounts for 12 to 18 % of the total weight of the vehicle. It is therefore desirable to seek weight savings in its construction.

2. BODIES OF PASSENGER RAIL VEHICLES

2.1 Input shaping basics

The following description is devoted to body shells of rail vehicles for passenger transport. These comprise bodies of passenger coaches, electrical and diesel multiple-unit trains, underground railway and tramway cars [Heller 2009].

Over the many years of rail vehicle evolution, the car body shells were developing as well (Fig. 1). Their construction was dictated by the manufacturing capabilities and materials available at the time. The following figure shows the timeline of the body shell evolution from the initial wooden construction to the present-day hybrid construction.

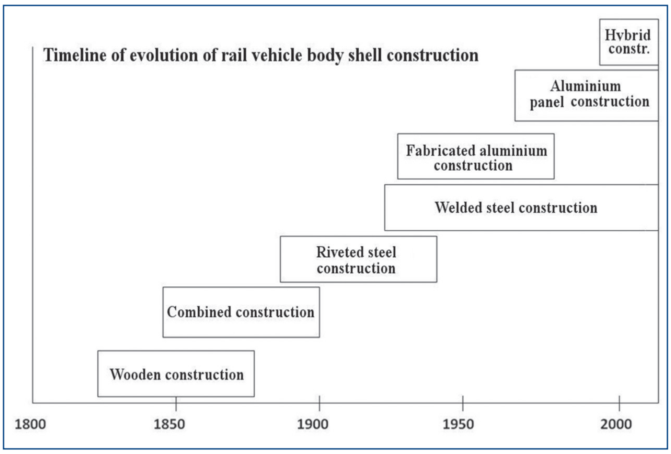
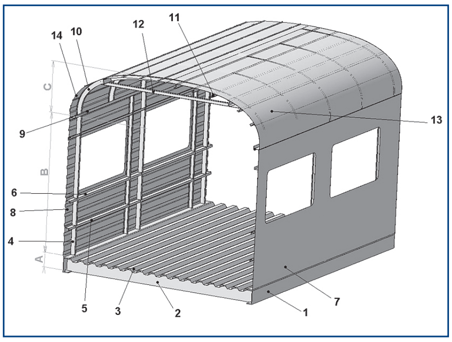


Figure 1: Timeline of evolution of rail vehicle body shell construction

3. CHARACTERISTIC FEATURES OF RAIL VEHICLE BODY SHELLS

3.1 Fabricated Body Shell Construction

It is characterized by structural parts which are manufactured by joining elements made of the same material. Typically, it is a welded steel construction. Fig. 2 shows the individual parts and elements of the fabricated body shell.



Where:
A..... CAR FLOOR STRUCTURE
B...... SIDE WALL
C...... ROOF
1...... side sill
2...... cross member
3...... corrugated floor sheet
4...... side bearer
5...... longitudinal stiffener
6...... section under the window
7...... sheet covering
8...... corrugated sheet covering
9...... purlin
10..... curved roof beam
11..... longitudinal stiffener
12..... ceiling panel brackets
13..... metal sheet roof covering

Figure 2: Axonometric view of a section of fabricated rail vehicle body shell

Variously modified and adapted versions of this construction are typical of passenger coaches and tramway vehicles.

3.2 Panel Construction of Body Shell

This type of construction is characterized by each structural part consisting of a single structural element made of one material. However, each structural part combines several functions. The structure is built of large-area extruded aluminium sections which are welded together (Fig. 3). This type of structure is used in City Elefant and Regio Panter electrical multiple-unit trains, in M1 underground railway cars and in numerous other vehicles outside the Czech Republic. The following figure shows a simple schematic representation of this construction. Its advantages include low labour intensity in production and integrated functions of the large-area extruded aluminium sections. The sections allow the devices on the underside of the body to be easily attached and interior parts to be installed. Among their disadvantages, there is the dependence on a single supplier of the aluminium sections, complicated repairs of the damage sustained in accidents and, naturally, the high price of the parts (sections).

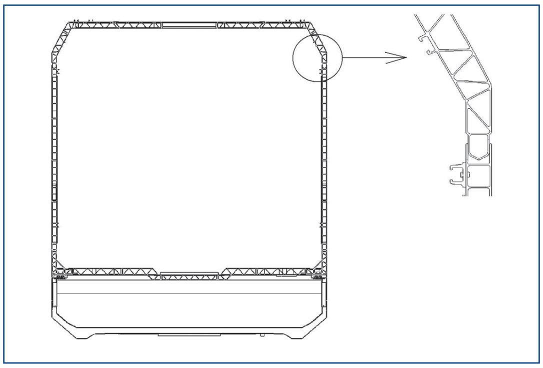


Figure 3: Cross-section through a panel-construction body shell of a rail vehicle

3.3 Hybrid Body Shell

The hybrid body shell should be understood as a vehicle body shell of combined construction. Various parts of the body shell are made of various materials with specific properties suitable for the part. An example of a hybrid body shell construction is shown in the following Fig. 4. The purpose of this construction is to achieve weight savings, the importance of which was discussed above.

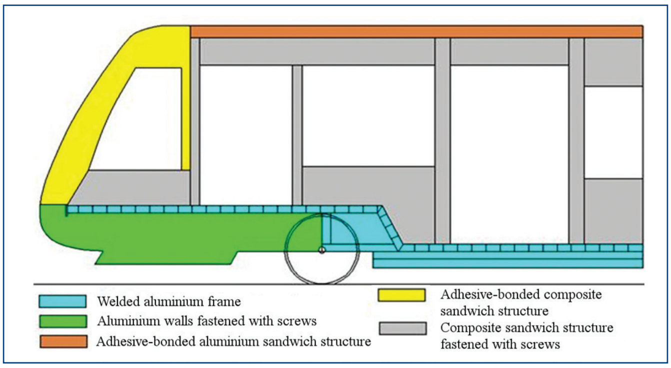
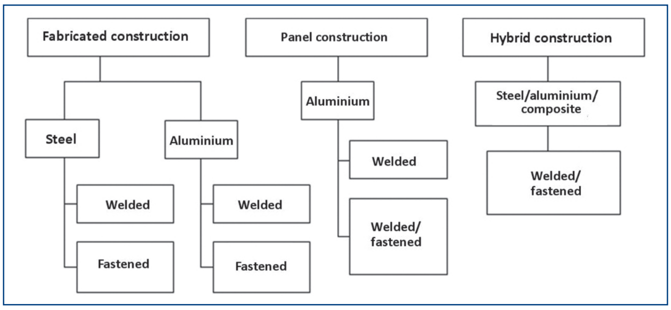


Figure 4: Schematic illustration of a rail vehicle hybrid body shell

Important to the body shell construction are the manufacturing processes used. The following figure provides their overview. The fabricated aluminium construction was developed by simply substituting steel with aluminium and by increasing the dimensions of the sections accordingly. Due to large weld distortions, this construction was later superseded by aluminium panel construction. As integrated sections cannot be employed in all cases, some parts of the panel-construction body shell are designed as fabricated assemblies.



4. RESEARCH AND DEVELOPMENT OF RAIL VEHICLE HYBRID BODY

The title of this section is the name of a research and development assignment carried out between 2011 and 2013 as the FR-TI3/449 project under the TIP programme sponsored by the Czech Ministry of Industry and Trade [Heller 2013]. The group of investigators comprised the University of West Bohemia in Pilsen, the Faculty of Mechanical Engineering and the Regional Technological Institute. Co-investigators included ŠKODA TRANSPORTATION a.s., LA Composite s.r.o. and Research and Testing Institute Plzen. The concept chosen for the project was the hybrid construction of an underground railway car body shell. Its dimensions were identical to the underground railway car for St. Petersburg (Fig. 5) manufactured by ŠKODA TRANSPORTATION at the time of production of this functional sample. Several aspects which contributed to this decision. They included the space available in the production halls of the ŠKODA TRANSPORTATION company and this company's substantial financial support.

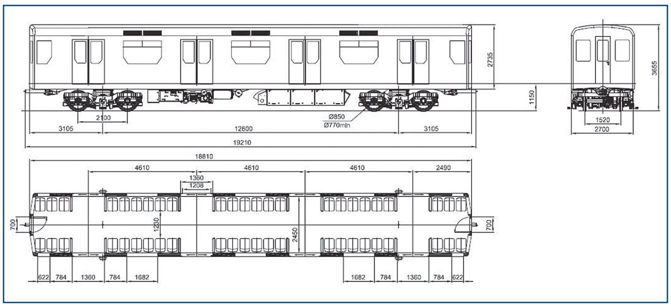


Figure 5: Layout drawing of underground railway car for Saint Petersburg

The base of the hybrid-construction body is the car's main frame. The initial design of the main frame was based on the underground railway car for Saint Petersburg. It was redrafted and steel with a high yield strength of 700 MPa was used. The entire main frame was built from this steel, except for the sheet metal floor of corrugated stainless sheet. High-yield-strength material was employed for the purlins between the composite side walls and composite roof parts. As the steel had high yield strength, the thickness of some assemblies on the main frame could be reduced. These modifications were explored by strength calculations. The sufficient dimensions of the main frame assemblies was thus verified. The reduction in the material's thickness was particularly effective in those components which were present in larger numbers on the main frame, such as the 11 intermediate cross members.

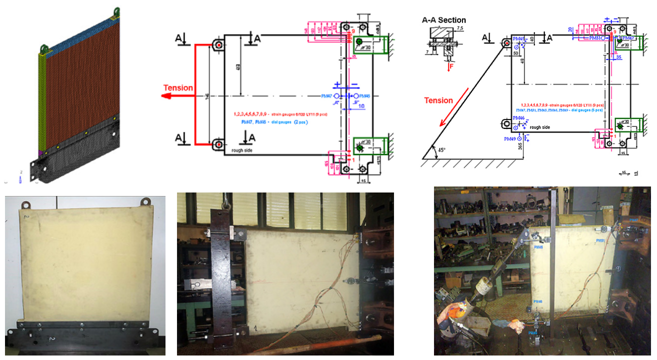
The composite sandwich sidewall panels are constructed of a steel frame, sandwich foam and composite skin of glass-reinforced flame-retardant epoxy resin. The skin was made of prepregs.

Sidewall manufacturing route: the steel frame was welded together from sections and its surface was finished prior to bonding. Foam cores of required shapes were made in order to fill the spaces in the frame and define the positions and shapes of windows. The structural parts were assembled in moulds in a clean room. First, the outer layers of the sidewall extending beyond the mould were placed onto the mould (the prepreg). Then, the surface-finished steel frame prepared for bonding was placed onto these layers. The foam cores were put into the steel frame. The structure was then completed by placing the inner layers (the prepreg semi-finished product) of the sidewall on top. Along the circumference of the frame and around windows, the inner and outer layers of the sandwich structure were stacked alternately in order to make a fully-bonded joint. After wrapping the part in process sheets, the mould with the part was placed in a furnace. The prepreg layers cured in the furnace at an elevated temperature 75 °C and became bonded to the steel frame and the foam core.

The ceiling panels are of sandwich construction comprising nomex cores and composite skin of glass-fibre-reinforced phenolic resin. The skin was made of prepreg semi-finished parts.

Ceiling panel manufacturing route: nomex honeycomb cores were prepared for the manufacture. Separate layers of the sandwich structure were stacked onto a flat plate and cured separately. The ceiling panel skin cured in an autoclave at elevated temperature and pressure (pressure of 600 kPa, temperature of 125 °C). The cured skin and the cores were placed into a shape mould for making the ceiling panels. Film adhesive was placed between the skin and the core. The mould with the part was then placed in a furnace where the skin was bonded to the core using the foil adhesive at an elevated temperature (125 °C). The edges of the parts which make the interface between the panels and the steel body of the car were then machined manually.

The joint between the composite side walls and the main frame is an important location. This joint was examined using calculations and tests of a small functional sample of the approximate size of 1 × 1 m, as shown in Figure 6.



Above: the meshed model. Below: the real-life specimen

Above: schematic representation of loading in pure tension. Below: the real-life specimen under load

Above: schematic representation of loading at an angle. Below: the real-life specimen under load

Figure 6: Investigation of the load-carrying capacity of a combined bonded and bolted joint between a composite sidewall and a steel side sill using a small specimen

The strain in the joint between the composite sidewall and the steel side sill was measured under gradually increasing axial force and a force applied at an angle.

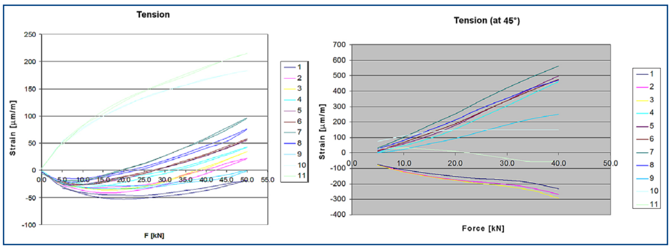


Figure 7: Measurement of the dependence of strain on the applied force. Left: pure tension, right: force applied at an angle

The combined bonded and bolted joint never failed during the tests [3]. Only at the very end of the testing programme, the force was increased to the point of destruction. The joint failed under a force which was many times higher than the nominal one.

The experience gained by testing the specimen was used for making the combined boned and bolted joint in the body shell. The shape of the vehicle's side sill cross-section was altered to provide adequate surface area for the joint. Cross-sections through these assemblies are shown in the following Figures 8 and 9.

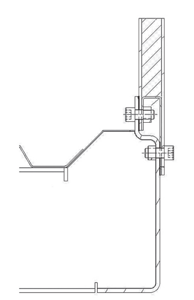


Figure 8: Cross-section through the side wall – side sill joint

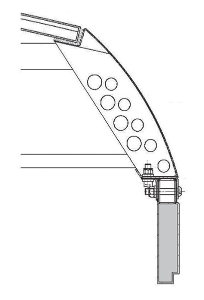


Figure 9: Cross-section through the side-wall – purlin – roof joint

These crucial assemblies consist of combined bonded and bolted joints. Adhesive bonding as the sole technique is only used for joining the curved roof beams to the purlins. During operations planning, this joint was evaluated using computational models of the body under load. It was found adequate, which was confirmed by trials on real specimens. The strength of this assembly was also found adequate in the tests of the entire body. The entire body comprises six side-wall panels between door openings and four end panels adjacent to the noses (Figs. 13–15). On the initiative of one of the co-investigators (the LA Composite company), one nose was made using the same process as the side walls (Fig. 11). Although subsequent testing revealed lower strength of this nose, one can assume that upon simple alteration to its design, the strength specification can be met. A conventional manufacturing process was used for the other nose (Fig. 10). Hence, the nose was a weldment from steel sections made by press brake bending.

Figure 10: Welded steel nose

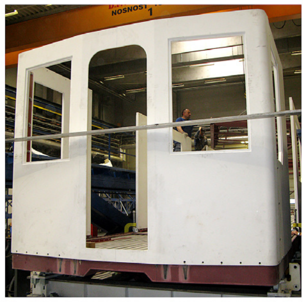


Figure 11: Composite nose

Due to their complex shape, curved roof sections were made as sandwich structures of paper honeycomb structure with glass-fibre reinforced plastic skin. No steel frame has been used here. The glass-fibre-reinforced plastic and foam and honeycomb cores have improved fire resistance, as indicated in their certificates. The body construction sequence is documented in the following figures.

Figure 12: Test-fitting of side walls onto the main frame

Figure 13: Finishing of the steel nose

Figure 14: Application of adhesive to the purlin joints on side walls

Figure 15: Interior of the completed body shell

The completed body shell was tested at the research department of ŠKODA TRANSPORTATION a.s. The static strength demonstration test (Figs. 16, 17) was carried out according to the ČSN EN 12663-1 standard. The body shell did not meet requirements for all loading states. For instance, the vertical load caused out-of-standard deflection of the body shell, particularly in door openings. However, the permitted stress levels in steel parts were not exceeded in any state.

Figure 16: Static strength demonstration tests of the body

Figure 17: Compression test of the nose panel below the bottom edge of window opening

Due to time and space constraints, it was impossible to upgrade the design of the structure, reinforce its parts around the door openings and repeat the testing. Despite that, the expected weight reduction in comparison with the aluminium panel structure is approx. 600 kg. The mass of a steel body with stainless steel skin of the same size is 6000 kg. The present hybrid structure would have a mass of 4900 kg after the purlin in the door openings was reinforced. Further weight savings can be achieved by altering the interior lining. The lining is not necessary on side walls, as the side-wall interior skin with an adequate surface finish can perform its function.

Figure 18: Final configuration of the hybrid body of underground railway car on transfer bogies

5. CONCLUSION

The research and development of a hybrid body opened new opportunities in the body shell construction for passenger rail vehicles. In simplified terms, the body may be thought of as a beam on two supports loaded in bending under uniform load. It is therefore desirable to make the floor structure and the purlins of high-yield-strength steel. The side wall and roof sections rely on the favourable properties of composite sandwich panels. Besides weight, this body construction also reduces the labour intensity in manufacturing. The costs of this design are a separate issue. In this project, only one functional testing specimen was manufactured. It is therefore difficult to estimate the potential costs and compare them to the costs of conventional body shell types.

The completed body shell was painted (Fig. 18) and exhibited at the Techmania Science Center in Pilsen, Czech Republic. It was on display for about six months as part of a thematic exhibition. Today, it is used for developing additional components, e.g. the ventilation system and sliding plug door, under the ALFA programme sponsored by the Technology Agency of the Czech Republic.

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