Light-Weighting Methodology in Rail Vehicle Design through Introduction of Load Carrying Sandwich Panels

Licentiate Thesis

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Abstract

Lightweight design in rail vehicles has been important for quite some time. Structures have been optimised to fulfill their purpose and cut unnecessary weight to reach allowable axle loads. Classically this is done by using steel, thin-walled structures, throughout the car body, or, alternatively, power-pressed aluminum profiles.

The use of composites and sandwich structures has, however, been somewhat limited in the railway industry, especially when considering High-Speed trains. The anticipated weight savings, and reduced complexity of this type of structure are believed to have great potential in the future.

This thesis covers the development of methods for structural stiffness design of lightweight, load carrying, sandwich panels for high-speed rail vehicles. Focus is on reducing the weight of the vehicles while simplifying the construction to reduce manufacturing costs and assembly times. Significant work is put into understanding the dynamic influence this type of structure has on the car body.

Figure 1: Module sandwich car body.
Acknowledgment

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Finally, to my family and friends, for your reliance, confidence and support, thank you.

Stockholm, April 2011

David Wennberg
Outline of Thesis

This thesis contains an introductory part describing rail vehicle car body design, a general introduction to sandwich theory, the Economical and Ecological (ECO²) aspects of light-weighting in the railway industry, as well as the following appended papers:

Paper A
David Wennberg, Per Wennhage, and Sebastian Stichel: *Orthotropic models of corrugated sheets in Finite Element analysis*. Manuscript accepted for publication in ISRN Mechanical Engineering, 21 March 2011.

Paper B

Paper C
David Wennberg, Per Wennhage, and Sebastian Stichel: *Selection of Sandwich Panels for the Load Carrying Structures of High-Speed Rail Vehicles*. Accepted for oral presentation at the International Conference on Composite Structures (ICCS) 16, 2011.
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Chapter 1
Introduction

1.1 Background

Rail cars are relatively heavy in comparison to other transportation modes. As an example, the weight per seat is around three times higher for rail vehicles than for buses (X 2000, a Swedish high speed train, vs Neoplan Spaceliner [1]). In addition to this, the price of rail cars per kilogram is high. Reasons are partly short series and individual design for each customer. Conservative load assumptions in railway standards are another contributor.

Today there is quite a lot of knowledge existing about properties and manufacturing possibilities of sandwich structures. Therefore a sandwich car body or a combination of a steel/aluminium car body with sandwich design is considered to be a realistic alternative to conventional steel or aluminum designs. Some applications in rail vehicles as well as busses already exist [2]. A factor that has prohibited wider use of such innovative concepts is, however, the cost aspect.

1.2 Car body function and design

Definition: The car body of a rail vehicle refers to the load carrying structure, doors, windows, interior with seats etc, inner lining and so-called comfort systems for lighting, heat, ventilation and sanitation.

The technical equipment for propulsion, braking etc is by definition not included in the car body, even though this equipment usually is attached/hinged on this (commonly under the car body). Sometimes the concept car body is limited to only the load carrying structure of the vehicle.

The car body must meet a number of requirements, including: safety requirements set up for crash scenarios, derailment, fire, projectiles impacts, pressure waves in tunnels, etc. The car body must also be within the specific construction profile of the operated line. It must be strong enough as not to fail during typical maximum loads or during cyclic loading. A large amount of these requirements are, for example, covered by the norm prEN 12663-1 [3].

The design should, furthermore, be reasonably easy to manufacture and maintain, it should be possible to repair damages to the car body, while keeping
Life Cycle Costs (LCC) within reasonable limits. For high speed trains it is important to have a good aerodynamic design with, for example a stretched front, smooth outer surface, enclosed undercarriage, etc. The car body is also the operators face outward, placing high requirements on exterior and interior design, a modern rail vehicle should look modern.

Beside these requirements, the car body must fulfill comfort requirements. For passenger vehicles the car body must provide the correct environment, e.g. a good ride comfort, the right lighting, space, temperature, fresh air and a low sound level.

1.2.1 Load carrying structure

In this section two concepts for the design of the load carrying structure of car bodies are presented, one stainless steel alternative in Figures 1.1 and 1.2, and one aluminum car body in Figure 1.3.

These two alternatives can be seen, on a conceptual level, as how the load carrying structure of modern high-speed rail vehicles is built.

Figure 1.1: Swedish X2 foundation in stainless steel.
Figure 1.2: Swedish X2 wall structure in stainless steel.

Figure 1.3: DB ICE body structure constructed in aluminium.
1.2.2 Car body dynamics

From a space and loading perspective, it is beneficial to have the car body as long and as wide as possible. However, as a consequence of the loading profile, which sets limits on the size of the car body cross-section, the structure can become rather long and slender with relatively low rigidity.

A too flexible car body can lead to significant structural motion during operation, resulting in poor ride comfort or even structural damage of the car body.

During operation the car body is continuously excited due to the dynamic interaction between track, wheels, boggie and car body. To avoid resonances, the principle of separating frequencies is employed (cf. Figure 1.4, this is also briefly mentioned in [3]).

A common design principle is to keep the first natural frequency of the car body as high as possible, typically above 10 Hz.

The first five natural frequencies and modes of a high-speed car body are presented in Figure 1.5. These are the typical natural modes of a high speed car body, however, the order and frequencies may differ from this specific example.

The natural frequencies of the car body give a good impression of how stiff the construction is. Especially the vertical bending mode gives a hint of how well the car body will manage the payload.

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To construct a car body that has sufficient stiffness with respect to vertical and lateral bending, has a stiff cross-section as well as being stiff in torsion is a challenge for the designer. There are several functional design aspects of the car body that severely reduce the stiffness of the structure. As an example, the first vertical bending frequency is especially sensitive to the door openings, which are sometimes as many as 2-3 per side.

The best place for door openings, with regard to high vertical bending frequencies, is at the ends of the car body or in the middle. Here, on a large scale, the vertical transverse forces are at a minimum. This results in the least shear of the door openings as illustrated in Figure 1.6.

Freiholtz showed in [4] that door placement, and size, may influence the first eigen frequency with up to around 1 Hz.

Looking from an operational point of view, however, optimal door placement may be to place the doors one third of the way in from each end to optimise passenger flows.

Other aspects that effect the rigidity of the car body are for example window size, car body length and cross-section geometry, boggie placement, etc.

Figure 1.6: Influence of door placement on the vertical bending behavior of the car body [4].
Chapter 2

Sandwich Design

2.1 Multi-functionality

In the previous chapter a number of criteria for the car body design were presented. This typically results in a complex structure, with a number of parts each by themselves fulfilling their own requirements.

What if it was possible to combine strength, stiffness, thermal and acoustic insulation and surface finish into one panel and manufacturing process? This would drastically reduce the number of parts, complexity and also assembly time of a car body.

These are some of the goals with the so-called multi-functional body panel design \[1][5][6], cf. Figure 2.1.

One of the most promising outcomes of such a structure is perhaps weight reduction, especially when using composite materials. R G Boeman et al. point out in \[7\] that weight savings of up to 30% can be achieved with glass-reinforced polymers as compared to traditional steel structures, and that mass savings of up to 60% for carbon fibre composites are possible.

The potential weight savings, however, depend on the function and constraints placed on the structure. For example, if designing for minimum weight of a general beam in Euler buckling, with hinged edges, cf. Figure 2.2, the critical load for such a structure is given by

\[
F_{cr} = \frac{\pi^2EI}{L^2} = \frac{\pi^2Ebh^3}{12L^2}
\]

where $E$ is the Young’s modulus of the material and $I$ is the second moment of area of the beam.
If we consider a steel or an aluminum beam, for the same critical load, and by only altering the height $h$ of the beam the aluminum beam can be made 52% lighter, all other geometry the same. However, if we instead set an extensional stiffness requirement the beams would have approximately the same weight. Further setting constraints on the height, $h$, the aluminum beam may not even be tangible. In this simple example the multi-functionality of the beam may be hard to define. However, in general, it comes down to fulfilling certain functions, or requirements, one of which could be a spatial requirement.

In a multi-functional design it is therefore important to take into account all aspects of the functions and constraints put on the structure, but at the same time keeping an open mind to perhaps allow for alterations to the original design if these give an advantage in other areas. In the aluminum vs steel beam example above, perhaps the large weight reduction potential can justify an increase in space usage.

![Euler buckling](image)

Figure 2.2: Euler buckling.
2.2 Sandwich structures

Sandwich structures consist of three main elements, two outer faces, or skins, and a centre core as shown in Figure 2.3.

![Figure 2.3: Typical sandwich panel, components and nomenclature.](image)

The face materials are commonly sheet metals or fibre reinforced plastics, i.e. high performance materials, while the core materials are usually of lower density such as balsa wood, honeycomb structures or polymer foams. There are, however, an almost endless amount of combinations and materials that can be used in sandwich construction and each have their own specific benefits and weaknesses.

2.2.1 Sandwich function

The sandwich structure functions in a similar manner as an I-beam in bending, the outer faces are there to withstand the compressive and tensile stresses much like the flanges of an I-beam and the centre core carries most of the shear stresses. To better explain this a simple example will be used, see Figure 2.4, which illustrates a solid beam of length $L$ bent to a radius of curvature $\rho$.

![Figure 2.4: Bending of a solid beam.](image)

The relation between bending moment, $M_x$, strain, $\epsilon_x$, and stress, $\sigma_x$, can for a beam bent as in Figure 2.4 with a constant Young’s modulus, $E$, be expressed as

$$\sigma_x = \epsilon_x E = \frac{M_x z E}{D}$$

(2.2)

where $D$ is the flexural rigidity of the beam, calculated as

$$D = EI = E \int z^2 dA$$

(2.3)

If we instead take the sandwich beam in Figure 2.3, the Young’s modulus will vary across the thickness of the beam. When calculating the flexural rigidity
of such a beam, the Young’s modulus in Equation 2.3 needs to be moved inside
the integral giving

\[ D = \int E z^2 dA \]  \hspace{1cm} (2.4)

By using the nomenclature in Figure 2.3, and assuming that \( E_{f1} = E_{f2} = E_f \), \( t_{f1} = t_{f2} = t_f \), we can write the flexural rigidity of the sandwich structure as [8]

\[ D = \int E z^2 dA = \frac{E_f t_f^3}{6} + \frac{E_f t_f d^2}{2} + \frac{E_c t_c^3}{12} = 2D_f + D_0 + D_c \]  \hspace{1cm} (2.5)

where \( E_c \) is the core elasticity modulus and in accordance with Figure 2.3, \( d = t_c + t_f \).

For this 2-dimensional case the flexural rigidity is per unit of width. The first term on the right-hand side of Equation 2.5 represents the flexural rigidity of the two faces bending about their own neutral axis. The second term represents the rigidity of the faces bending about the neutral axis of the entire sandwich beam while the last term represents the flexural rigidity of the core.

In this type of structure the faces and core fulfill different functions. During bending of the structure the face sheets will carry most of the bending moment as direct stress while the core mainly carries shear stress, preventing the face sheets from sliding relative to each other. The approximate stress distribution in a general sandwich panel in bending is illustrated in Figure 2.5.

Compared to an Euler type beam, it is important to be aware of that a sandwich beam usually exhibits a fairly high amount of shear deformation due to the low performance core.

![Figure 2.5: Approximate stress distribution in a sandwich beam in bending (red areas). The top face sheet experiences compressive, negative, direct stresses, while the lower face sheet experiences extensional, positive direct stress. The core carries the largest part of the shear stress, which is approximately constant over the core cross-section.](image)

Typically for sandwich structures the term \( D_0 \) of Equation 2.5 is dominant, being magnitudes larger than both \( D_f \) and \( D_c \) (if \( t_f << t_c \) and \( E_f >> E_c \), which is usually the case). This results in that the flexural rigidity of the sandwich panel is highly dependent on the thickness \( d \), cf. Equation 2.5. This characteristic is shown in Figure 2.6, and is known as the Sandwich Effect [8].

Sandwich structures are not only found in man-made constructions but also in nature where the combination of high strength and low weight is of utter importance. For example the bones in human and animal skeletons are comprised of sandwich structures with foam-like cores as well as the branches of some trees and plants.
2.2.2 Composites

A composite is generally defined as a material made from two or more constituent materials, which remain separated and distinct from one another. An example of a natural composite is wood (cellulose fibres and lignin keeping them together), while engineered composites typically are Fibre Reinforced Plastics (FRP).

Figure 2.7 illustrates a unidirectional composite lamina. This lamina is made up of a number of fibres, i.e. the reinforcement (e.g. carbon fibres or glass fibre), and a matrix material, commonly a polymer. The matrix surrounds the fibres and keeps them in place. This results in high strength and rigidity in the fibre direction, while in the transverse direction, it is the strength and stiffness of the matrix that dominates the mechanical properties of the laminate. This lamina is therefore a highly orthotropic component.

A number of these lamina can be stacked on top of each other, creating a composite laminate. The laminate can be created to further increase the strength and stiffness in a certain direction, or the stacking sequence, the lamina lay-up, can be varied as shown in Figure 2.8. In this figure four lamina, of various thickness are stacked together to create a laminate with the lay-up $0^\circ / -45^\circ / 45^\circ / 90^\circ$. The lay-up angles are defined from some predetermined $0^\circ$-direction. This laminate has enhanced shear stiffness and transverse stiffness as compared to the unidirectional lamina, however, the stiffness in the $0^\circ$-dir is reduced (in unit per area).

Adding composite face sheets to the sandwich structure gives added complexity to the problem but also added design space. The composite face sheets can be engineered to optimise the directional properties of the component.

For a structure like the load carrying structure of a high-speed train’s car body, which has to carry many different loads in various directions it is important to have a somewhat balanced ply lay-up. Several design guidelines for such a structure are mentioned in [9].
2.3 Sandwich structures in rail vehicles

Sandwich structures are especially popular in aerospace and marine applications, e.g., passenger planes, space shuttles, satellites, pleasure boats and navy applications. Almost half of the wetted surface area of the Boeing 757/767 is honeycomb sandwich [10], and the first non-government funded space ship had, among other things, wings constructed in sandwich with carbon fibre reinforced polymer epoxy skins and honeycomb core.

In ground transportation sandwich structures can be found in cars, busses and trains. Since the 80s front cabs of locomotives have been built with sandwich technology because of its high strength and good impact and energy absorption properties. Some examples of this are the XPT locomotives in Australia, the ETR 500 locomotives in Italy, the French TGV and the Swiss locomotive 2000 [10].

There are also some examples of sandwich paneled rail vehicles; e.g., Schindler’s wagons Revvivo, Munico and Neitec [11], the Korean Tilting Train eXpress (see Figure 2.9) [12] and Bombardier’s C20 FICAS (see Figure 2.11) [13].

2.3.1 The Korean Tilting Train eXpress (TTX)

The TTX was designed to run at 200km/h and is composed of four motorised cars and two trailers.

To reduce the wear on the tracks the TTX upper body was constructed of a lightweight sandwich structure with a supporting steel inner frame, cf. Figure 2.10. The floor frame is manufactured from conventional stainless steel giving a low centre of gravity thereby increasing stability during curve negotiation. The steel floor frame also provides increased stiffness against global bending [12].

A preliminary design of the car body was without the supporting inner frame. However, during structural verification, the deformation of the body shell during vertical loading was deemed excessive.

The sandwich structure elements consist of carbon fabric/epoxy pre-pregs for the faces and an aluminium honeycomb core. The entire car body is manufactured as one single structure. This was accomplished by means of large scale auto-clave. A large mould was built in which the outer face was firstly laid out. The outer face was then cured in the auto-clave. Secondly the inner frame and honeycomb core was placed on top of the outer skin. The core and skin was
bonded by use of an adhesive film. After this step followed lay-up of the inner face. Lastly the entire structure was cured in the auto-clave after appropriate vacuum bagging. By constructing the entire car body as one structure weak links between panels are eliminated. The only remaining weak link is between the upper body and floor frame [14].

The sandwich structure reduced the upper car body weight by 39% compared to a stainless steel car body. The total weight reduction, including under frame, was 28% [12].

Figure 2.9: South Korean Tilting Train eXpress (TTX).

Figure 2.10: Cross-sectional view of the TTX train constructed with composite sandwich panels and stainless steel frame [15].
2.3.2 C20 FICAS

The C20 FICA has been in operation in the Stockholm metro system since July 16 2003. FICA is a Flat package concept, i.e. the car body is made up of several modules that are bolted together. Compared to the conventional C20 the FICA system has introduced large scale lightweight sandwich panels into the load carrying structure. This has increased the aisle space with 30% and reduced the tare weight per passenger by about 8%. The C20 FICA is a 3-car unit with a total length of 46.5 m and an operating speed of 80-90 km/h.

![Bombardier’s C20 FICAS metro train.](image)

The C20 FICA body structure consists of sandwich panels in the sides, roof and floor. End beams were inserted into the sides as supports, see Figure 2.12. The sandwich panels consist of stainless steel face sheets and a Polymethacrylimide foam core.

<table>
<thead>
<tr>
<th>#</th>
<th>Component</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Core</td>
<td>PMI foam</td>
</tr>
<tr>
<td>2</td>
<td>Face sheets</td>
<td>Stainless steel</td>
</tr>
<tr>
<td>3</td>
<td>Inner frame</td>
<td>Stainless steel</td>
</tr>
</tbody>
</table>

![Cross-section view of typical sandwich section for the C20 FICAS.](image)
Chapter 3

Light-weighting

3.1 ECO\textsuperscript{2} aspects

ECO\textsuperscript{2} stands for economy and ecology. Sustainability can only be achieved by including both of these aspects into the development of new technology. Below the ECO\textsuperscript{2} aspects of lightweight sandwich design in high-speed rail vehicles are presented.

The large mass discrepancy between buses and trains mentioned in Section 1.1 is partly explained by the fact that trains offer a lot more space per seat in comparison to buses. The remainder is within the construction.

A rail car’s main load carrying structure, i.e. walls, roof, floor and structural beams, contribute to about 35-40\% of the weight of the car body, the rest of the weight is stored in interior and equipment. Furthermore, wall, floor and roof panels only contribute to about 40\% of the structural weight, i.e. about 16\% of the total weight, while the rest is stored in the framework and other structural beams, see Figure 3.1.

A sandwich paneled car body will, as mentioned, not only reduce the weight

![Figure 3.1: Approximate weight distribution of a rail vehicle car body (bogies and drive system excluded).](image-url)
of the vehicle but also reduce manufacturing complexity, by reducing the number of parts needed and integrate several functionalities in to one single panel.

Another benefit of a sandwich paneled car body is reduced wall thickness. This was for example shown during the development of Bombardier’s metro car C20 FICAS [13]. Reducing wall thickness gives extra interior space. This may seem insignificant, but for the C20 FICAS the wall thickness was reduced by 120 mm. If the same was done on a high-speed train with 2+2 seating this could give an extra 6 cm between passengers, which is a significant amount of extra elbow room, increasing the comfort of train travel.

Reduced external sound, due to lower wheel-rail forces and reduced ground vibrations are also possible effects of weight reduction.

In Section 2.3, some examples of sandwich paneled rail cars are given. Even though these examples are very different from one another, they have at least one similarity: they all have steel support frames to increase the stiffness or strength of the rail vehicles.

An optimum solution, with respect to weight and simplicity, would be to remove the framework. By utilising composites’ excellent optimisation characteristics and looking at large scale rail car geometry, such a solution is likely possible.

Composites offer an almost endless amount of material alternatives, which depending on what type is chosen, will have varying impacts on the environment. Ermolaeva et al. presented several different aspects of this with respect to human health, ecosystem quality and resources [16]. However, as often concluded, the material of the lowest density will likely be the most environmental friendly [16] [17]. This is mainly due to the long product life time of rail vehicles.

### 3.2 Energy

Rail vehicles (here electrical) can impact the environment in many ways during their life time, e.g. resource depletion, indirect greenhouse gas emissions, barrier effects in nature and vibrations. The greatest environmental impact is during the use phase of the rail vehicles. This is due to long life time and high mileage: rail vehicles have a life time of about 25 years during which they will travel several million kilometers (for long distance high speed trains this can be as high as 15 million kilometers). Helms and Lambrecht presented that a weight saving of 100 kg would save around 100 GJ during the use phase of a high speed rail vehicle [18]. A possible weight reduction of 4 tons, a probable figure for achieving the goals set in this PhD project, assuming a linear relationship, would then result in an energy saving of 4000 GJ over the use phase.

The Swedish high-speed train X 2000 has an energy consumption of around 10 kWh/train-km [19]. Assuming a travel distance of 15 million kilometers over the use phase, this equals approximately 540 000 GJ of energy consumed over the entire use phase. Approximately 25% of this energy may be coupled to the mass of the vehicle and only about 20% of the mass is within the load carrying structure which leaves 27 000 GJ coupled to the load carrying structure of the vehicle. A weight reduction of 30% then gives a energy saving of 8000 GJ over the use phase (note: this is a rough calculation, to be compared with the previous results by Helms [18]. For local city trains the relation between energy consumption and mass reduction is around 1/2 [19], due to more frequent
This energy saving could then be greater than the total energy consumption during production and raw material extraction phases [17]. This is illustrated in Figure 3.2, as well as in several other papers [16] [18] [20].

Energy consumption of rail vehicles is correlated with the physical resistances the vehicle must overcome during travel. These can be split into the following:

1. Rolling resistance
2. Gravitational forces
3. Acceleration forces
4. Aerodynamic drag

Resistance 1-3 above are all dependent on the mass of the rail vehicle. The aerodynamic resistance is dependent on the shape and length of the rail vehicle and is almost proportional to the square of speed. Weight reduction of rail vehicles thus results in lowering of the first three resistances listed above. There is, furthermore, also a lot being done to reduce the aerodynamic drag of trains, especially for high speed trains. This, together with increasing efficiency and utilising more and more energy efficient breaking results in that new trains running at greater speeds generally have reduced energy consumption as compared to older, slower, trains [19].

By 2050 energy per passenger kilometer for long distance car travel and air travel could be lowered to 0.12 and 0.32 kWh respectively [21]. Long distance rail transport is already today below these figures and could by 2050 be as low as 0.05 kWh/passenger-km [21], probably even lower, as some trains today already have reached this level, cf. the "Green Train" research project [22]. Weight reduction is one step on the way to reaching these goals [19].

Figure 3.2: Primary energy over whole life cycle for a high speed train car body with four different material compositions [17].
3.3 Green house gas emissions

It is not always clear how to calculate the true environmental impact of weight reduction for rail vehicles. Compared to the majority of other transportation modes, electrical trains do not carry their energy supply with them during travel. This obscures the benefits of weight reduction with regard to emissions of greenhouse gases since this directly depends on the energy mix used in the region. Some argue that rail vehicles should be accountable for greenhouse gases equivalent to that from generating electricity from coal power plants, from the point of view that if the trains were not running it would be possible to reduce the electricity needed from these plants by the amount used by rail transportation. Others see this as an unfair comparison since trains run regardless of if coal power is imported/produced or not. Either way rail transportation can reduce their energy consumption with more effective and lighter vehicles and thus directly or indirectly reduce greenhouse gas emissions.

3.4 Effective rail transportation

Increased rail travel will not reduce the impact on the environment if it does not replace more energy intensive modes of transport.

Today the cost of a domestic flight in Sweden, between the largest cities, is in the same price range as train travel. For trains to compete with air travel they need to provide the right comfort, at the right cost, as well as providing acceptable travel times.

The Swedish high speed train X2000 is generally faster than airline travel for distances up to about 300 km, door to door. Compared to car travel, train travel is usually faster for distances above 150 km.

In the near future rail transportation will likely be charged in relation to how track ”friendly” the vehicles are, i.e. if they exert large track forces and large amounts of track wear or not. By lowering the weight of rail vehicles and thus lowering axle loads, train speeds may be increased, even on curved tracks, without increasing the wheel-rail forces. Already today trains are required not to exceed a certain maximum axle load in order to run at certain speeds. This is especially important when the number of axles are minimised, e.g. in articulated trains.

Higher speeds would likely make train travel more appealing and hopefully shift transportation from for example long distance car travel, domestic flight and perhaps even some international air travel to rail transportation. It should, however, be mentioned that light-weighting is currently not critical for the development towards higher speeds. Track deterioration on the other hand, which increases with higher speeds, is correlated to the weight of the vehicle.

Alternatively, weight reduction and widened inner space, achievable with thinner walls, could allow for increased payload at the same performance level. Thinner walls may be possible with the multi-functionality of sandwich panels. This could enhance profits and eventually lower ticket prices making train travel more reasonable not only from an environmental view but also from an economical.

Both alternatives increase the effectiveness of the transportation mode by increasing number of seats/passengers per time and distance effectively lowering
costs per payload-kilometer. This makes better use of the crew, increasing working kilometers. The same goes for other costs such as maintenance, energy, cleaning, infrastructure, etc. The reduced energy consumption can, of course, alone reduce costs and thus also enhance profits and/or lower ticket prices.

A modern attractive train is also highly valued by the customer and from experience will increase occupancy [23]. Use of composites in the body structure of the railcar may allow a new, more pleasing, aesthetic design further improving rail vehicles stand in the public transportation market.

A shift to more rail transportation from road and air travel will give a national economic gain since heavy road traffic and flight are not always taxed, or feed in proportion to their environmental impacts. Shorter travel times, which would be achievable with higher speeds, are also seen as very positive from a public economic view, this is due to the fact that travelers highly value time, and a reduction of travel time is valued proportional to a significant fraction of ticket prices [23].

3.5 Downsizing

Weight reduction can also set off a weight saving spiral or downsizing of components and equipment which can give an additional environmental saving hard to realise from just studying weight saving. Helms et al. claim that fuel savings per 100 km and 100 kg where four times higher when a rear axle transmission was adjusted to match the new power to weight ratio of a road vehicle after weight reduction than compared with only the lowered weight [18]. A downsizing spiral would undoubtedly also have several other economical advantages, e.g. simpler brakes, dampers, traction equipment, etc., can be utilised to achieve the same performance level.

As an example we can look at the brakes of a rail vehicle. Future trains will likely more and more rely solely on electrical brakes. Today a mixture of electrical and mechanical brakes are used to achieve a sufficient deceleration. In future trains, both to reduce net energy consumption and brake maintenance, the mechanical brakes may be replaced (or at least reduced) by increasing the power of the electrical brakes. Since deceleration requirements are often stricter than acceleration requirements this means up-sizing the electrical motors. Reducing the weight of the rail vehicle directly lowers the amount of force needed for a certain deceleration, i.e. motor power does not have to be increased to the same extent.

3.6 Concerns

There are, however, a few aspects that may rather have a negative effect when reducing the weight of the car body and introducing composites into the load carrying structure.

A lighter rail vehicle is easier to push off the track than a heavier rail vehicle. Cross wind safety is therefore affected negatively when the car weight is reduced. This issue must be considered carefully to avoid the need for ballasting of the end cars.
Crash safety and energy absorption is another concern when using composites. Metals, and especially stainless steel, are well known in the industry and have good energy absorbing properties. Composite sandwich structures have a wide variety of failure modes, where only some may give sufficient energy absorption properties. The difficulty lies in finding which mode will fail first, and how to create a structure that will consistently fail in the same manner. Furthermore the analysis methods available for composite structure are not as evolved as those for metal structures.

Composites have exceptionally good strength to weight qualities, but this is only one advantage with composites. Generally, they also have good corrosion resistance compared with other materials, which is of course an advantage during the long life time of rail vehicles, perhaps resulting in less maintenance or less replacements of components. On the other hand this feature results in recyclability issues. There are, however, a lot of natural fiber composites that have been and still are in use, e.g. hemp fibers. These natural fibers have several advantages with respect to weight saving, recyclability, material price, etc. However, as the name suggests, these are natural materials, which results in poor consistency in quality compared to engineered materials. Furthermore the natural fibers cannot match other properties of the toughest engineered materials, for example: stiffness, strength, fire properties, water absorption and others.

Even though a lot of composites end up as land fill; some may be considered un-recyclable, and some are simply cheaper to new-produce, the increased interest in these materials will continue to put high pressure on solving recyclability issues.
3.7 ECO\textsuperscript{2} Overview

Table 3.1 gives a quick overview of some of the economical and ecological benefits that are possible by introducing sandwich panels into the load carrying structure of the car body.

Table 3.1: Example summary of benefits and concerns of a Sandwich car body. ECO\textsuperscript{2} benefits are both Economy benefits, interpreted as beneficial for the operator, and Ecology benefits, beneficial for the ecosystem in general. Results shown as -/+ are uncertain or may vary depending on choice of construction.

<table>
<thead>
<tr>
<th>Change</th>
<th>Outcome</th>
<th>ECO\textsuperscript{2}</th>
<th>Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lower weight</strong></td>
<td>{ Reduced energy consumption +</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduced external sound +</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Downsizing of components\textsuperscript{a} +</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduced track deterioration + +</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Indirectly reduced GHG emissions + +</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crosswind sensitivity -</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Thinner walls</strong></td>
<td>{ Increased payload capacity +</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increased comfort +</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fewer parts</strong></td>
<td>{ Easier manufacturing +</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Attractive design +</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>&quot;New&quot; materials</strong></td>
<td>{ Crash safety</td>
<td>-/+</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Recyclability issues -/+</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fire safety -/+</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{a} which may set off a downsizing-spiral effect.
Chapter 4

Summary

4.1 Discussion

The potential scope of this project is wide, which is in itself an obstacle: how to objectively define what areas of research are the most important given the time frame of a PhD thesis. Should focus be put on performance, multi-functionality, ecological or economical aspects? All parts fit into the same puzzle, however, focusing on one alters the shape of the others.

Material choice, for example, will in the end be a trade-off between mechanical, environmental and economical properties. Some of these are easy to quantify, for instance the mechanical properties: the rail car must achieve sufficient strength and stiffness in a large amount of different scenarios to be up to standard. Others are tougher to get an objective understanding about: what degree of non-recyclability can be compensated by a given weight reduction? Which effect is considered most significant/environmentally friendly? Furthermore, can a significant cost reduction compensate a more unfriendly material, and where is that line drawn?

For the environmental effects different indicator(s) [24], e.g., the Eco-99 indicator used in [25], or the corresponding lower level indicators, give an easy overview of the environmental impact of different material choices by illustrating it as single figure(s). However, this simplicity comes at the cost of uncertainty. Furthermore, several of the indicators and values seem to be highly suggestible, and different results may therefore be achieved when using different indicators.

The process of finding an optimum solution to the above questions will likely be a minimisation problem with weight as the objective function (seeing as reduced weight will likely give the largest environmental and economical gain), as well as an iterative process if large scale geometric modification of the rail car will be acceptable.

At the same time production costs should be taken under consideration for different alternatives to ensure that a realistic solution is ultimately found.

4.2 Present work

The work performed so far has concentrated on minimising the mass of the vehicle while achieving sufficient stiffness. An early goal was a 30% weight re-
duction of the load carrying structure of the car body by replacing this structure with load carrying sandwich panels, cf. Figure 4.1.

![Diagram of structure replacement](image)

Figure 4.1: Concept of structure replacement.

Both metallic and composite face sheets have been studied, with various core materials.

From the literature study performed in the beginning of this project [2], one of the main issues with load carrying sandwich panels was insufficient global stiffness of the car body. The following papers therefore have a large focus on achieving sufficient stiffness.

A Finite Element model of a Regina type car body was used as a starting point (courtesy of Bombardier Transportation).

The Regina car body is what is called a lightweight steel construction, with an extensive, ring-like, steel framework stiffening the cross-section of the car body.

Outer metal sheets carry normal and shear loads during bending of the car body and during coupler loading. These sheets are stabilised by the framework as well as additional stringers.

Large sole bars are used to enhance the vertical bending stiffness as well as carry the normal stress during loading over the couplers.

The original model was very highly detailed, and contained over 1.2 million elements. As a result, modal analysis took over 48 h on a standard calculation machine.

Initial work was focused on simplifying the model into a more manageable size of about 14 000 elements, to enable fast parameter studies of the car body. This required an increase in element size. One restriction on element size was the corrugated sheets in the roof and floor structure, which have a geometry such that requires rather small elements. This is the background to Paper A, where orthotropic modeling techniques for corrugated sheets are studied in Finite Element Analysis.

From the results of Paper A, sandwich panels have been derived from requirements based on the mechanical properties of the corrugated sheets. The sandwich panels are designed to replace the corrugated sheets while obtaining the same or increased performance. This is the background to Paper B, where a 600-700 kg weight reduction of these specific panels was achieved.

The global eigen frequencies of the car body have been used as the overall performance measure with respect to car body stiffness and dynamic characteristics.

In Paper C a semi automated method of deriving completely self supporting sandwich panels for the car body cross-section is presented, based on the knowledge gained from earlier work. A total weight reduction of over 30% was
achieved for the load carrying structure of the rail car. Commercial optimisation software was used to minimise the weight of the structure, giving a general and applicable method for reducing the weight of load carrying structures.

4.3 Future work

Currently only mechanical properties, especially stiffness, have been in focus. The toughest load cases of the prEN 12663 norm [3] have been tested, with satisfactory results. Stress levels were well below the strength of the derived panels. However, to truly evaluate the strength a detailed, 3D model, of the entire sandwich car body should be constructed.

The derived car body should also be evaluated from a comfort perspective by performing a full comfort evaluation in SIMPACK and comparing this with the original car body.

In the current design, the idea is to lead the coupler forces through the floor structure, instead of through the sole bars as in the original structure. One issue here is how to introduce these large forces into the sandwich floor, what type of connections are possible?

Furthermore, in the next phase of the project, acoustic and thermal requirements for the car body structure should be evaluated, and compared to the current sandwich structure. Based on the results from such a comparison, the next step would be to optimise the current solution to fulfill these requirements. This may increase the mass of the current sandwich panels, however, since they then can replace other components, beside the load carrying structure, the total mass will more likely be reduced further. One example is the "floating" floor structure in the vehicle, which fulfills an acoustic function and has a rather substantial mass. Can this be integrated into the floor sandwich panel?

Another interesting, multi-functionality, of the sandwich panels would be to study if the inner face could be designed to fulfill the inner lining requirements.

Eventually a car body design should be chosen, this could include a number of alterations, and optimisation to the current structure, e.g.:

- Window pillar placement, thickness and shape optimisation
- Modular study of door section
- Optimisation of floor-wall connection

Furthermore a general cost estimation (cost per kilogram car body), may be possible as well as a wheel wear and energy savings evaluation based on the mass reduction of the vehicle.

A simple LCC evaluation, perhaps based on commercial software, should also be performed.
Bibliography


Chapter 5

Appended papers A-C