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FINAL REPORT

LIGHTWEIGHT COMPOSITE MATERIALS FOR HEAVY DUTY VEHICLES

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1. INTRODUCTION

1.1 Background

In the United States, commercial truck classification is determined based on the vehicle's gross vehicle weight rating (GVWR). Such classification is done under the US DOT Federal Highway Administration (FHWA) Vehicle Inventory and Use Survey (VIUS) standards, which groups Class 1, 2 and 3 as "Light Duty", 4, 5 and 6 as "Medium Duty", and 7-8 as "Heavy Duty". Vehicles in Class 7 have GVWR ranges from 26,001 to 33,000 pounds (11,794 to 14,969 kg). The Class 8 truck gross vehicle weight rating (GVWR) is anything above 33,000 pounds (14,969 kg). These include all tractor-trailer trucks, which are used in intercity freight hauling. According to the Transportation Energy Data Book (2012, 2013), there were 10,770,000 heavy trucks registered in the U.S. in 2010. These trucks account for about 22 percent of U.S. transportation petroleum use and nearly 15.2 percent of the U.S. petroleum use in 2010 and 2011 (19 million barrel per day). Figure 1.1 shows the historical petroleum consumption for heavy trucks in the U.S. The plot in Figure 1.1 clearly shows that trucking is energy-intensive and accounted for 69 percent of freight energy use.

The domestic petroleum production is just 7.51 million barrel per day in 2010. The remaining petroleum is obtained from foreign sources. Therefore, improving fuel efficiency for heavy-duty trucks, particularly for Class 8 trucks, is necessary to achieve energy sustainability and support future economic development. Therefore, new technologies are needed in order to increase energy security in the transportation sector at a critical time for global petroleum supply, demand, and pricing. However, the oil dependence continues to increase unabated to the present and the oil price run up of July 2008 ($147 per barrel of crude) illustrated the rapidity with which these discontinuities can occur (*Vehicle Technology Program, 2010*).

Additionally, there is an environmental responsibility concomitant with oil dependence to reduce greenhouse gas emissions, primarily carbon emissions from ground transport vehicles. Transportation sources emitted approximately 40 percent of all GHG emissions in the United States. Medium- and heavy-duty vehicles (above 8,500 lb gross vehicle weight rating) represented about 22 percent of the transportation emissions, up from 15 percent in 1990 (*EPA 20013*). In 2008, trucks accounted for 69 percent of freight energy use, consuming 2.35 million barrels of oil per day in 2008 and generating 363 million metric tons of carbon dioxide (*EIA, 2009*). Consequently, trucks are an important place to look for energy savings and climate change mitigation in the transportation sector.

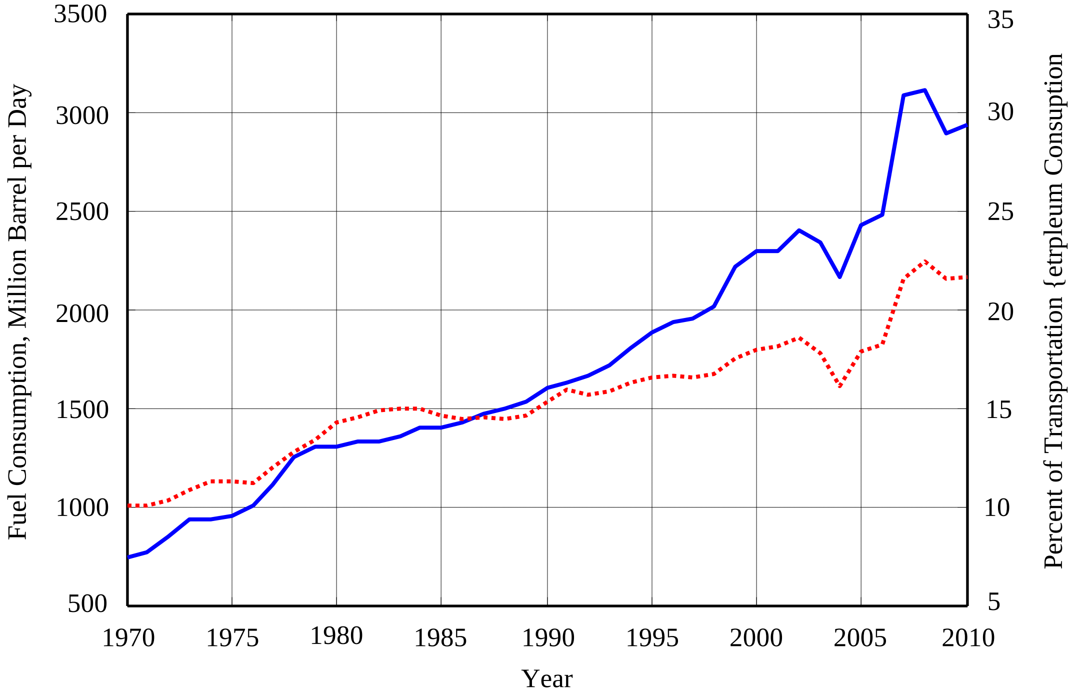


Figure 1.1 Petroleum Consuption of Heavy Trucks in the United States.

Neither petroleum reduction goals nor carbon emissions reduction goals can be achieved without new and more efficient vehicle technologies. While achieving petroleum and GHG reduction goals will be extremely challenging, such challenges represent a unique opportunity for the U.S. to establish a sustainable energy infrastructure.

The increasing price of oil across much of the world has brought the issue of fuel efficiency to the front of many car buyers' minds. The automotive industry has responded with a variety of new approaches to minimize the weight and improve performance of their vehicles. Lightweighting of vehicles is one of the most realistic ways in meeting these requirements due to the inherent relationship between mass and fuel consumption. In addition, lightweighting may benefit other advanced fuel-saving but load constrained technologies, such as battery-powered vehicles (*Center for Automotive Research 2011*). Studies suggest that a 10-percent decrease in vehicle weight results in a 6.6% increase in fuel efficiency. In fact, according to an ATG report, there is no single cost-effective technology that can accomplish the targeted fuel efficiency without significant weight reduction.

One of the easiest ways to reduce mass is to look at alternatives to traditional steel. Materials such as Composites, Aluminum, Magnesium, Zinc and High Strength Steels each offer unique value propositions for OEMs to consider when considering various options for vehicle mass reduction. However, the ability to introduce new lightweight materials into vehicles is not a trivial matter. Many see a new concept, or limited production, vehicle introduced to the market with lightweight materials and feel that adoption by mass produced vehicles is a simple matter of "remove and replace." However, this is not the case, factors such as existing infrastructure, material cost, and high volume capacity become of great importance for mass production vehicles. In addition, many of the low production vehicles incorporate these lightweight materials as a method for gaining experience on their performance. Without significant data to support durability, the risk-averse automotive culture will not adopt new materials. Therefore it often takes many years to implement lightweight technology in mainstream production vehicles.

Bandivadekar et al. (*2008*) showed that reduction in vehicle weight and size could significantly reduce fuel consumption and greenhouse gas emissions. They estimated that direct weight reductions through the substitution of lighter materials as well as basic vehicle design changes which, for example, maximize the interior volume for a given vehicle length and width enable secondary weight reductions as other vehicle components are appropriately downsized. A shift in vehicle size distribution away from larger vehicles also reduces average weight and initially can be accomplished by changes in production volumes. They estimated a maximum potential vehicle weight reduction of 35% at plausible cost, which allow for the additional weight of future safety requirements and convenience features. Vehicle weight reductions of this magnitude could alone result in some 12–20% reduction in vehicle fuel consumption.

Reduction in vehicle body mass was considered to offer the greatest opportunity for achieving near-term, cost-effective reductions in fuel consumption. This led the US Department of Energy and U.S. Council for Automotive Research (USCAR) to continue their research and development efforts for ways to reduce body mass by substituting new materials such as high-strength steel, advanced high-strength steel, aluminum, magnesium, and composites for current materials. The materials industries also conducted research to advance new materials (for example, through the Auto-Steel Partnership, the Aluminum Association, and the American Chemistry Council). Increased costs for lighter and stronger materials result from higher material costs and higher costs of component fabrication and joining. It is estimated that every 10 percent reduction in vehicle weight will result an approximate 7 percent saving in fuel (*Reinforced Plastics, 2005; Schewel, 2008*). Estimates of the body-mass reduction that can be achieved in the near term vary from 10% (with mostly conventional and high-strength steels) to 50% (with a mostly aluminum structure). Adopting materials such as carbon fibers and polymer matrix composites could produce weight reductions of 25-70%, while improved manufacturing and use of high strength steel can reduce vehicle weight by 15-25% (*Reinforced Plastics, 2005, Cheah et al., 2007; FKA, 2007*). Even greater reductions are feasible, but they require expensive composite structures that involve such materials as carbon fiber. A midsize-car body with closure panels (no trim or glass) can weigh roughly 800 lb (about 25% of the vehicle curb weight). Vehicle testing has confirmed the reductions in fuel consumption associated with reductions in vehicle mass. (*Pagerit et al., 2006; U.S. EPA, 2007*).

1.2 Research Scope

A comprehensive research and development effort was initiated by the U.S. Department of Energy (DOE) in 2002 at West Virginia University (WVU) in order to investigate the technical feasibility of reducing the structural weight of heavy vehicle systems. In 2005, the potential of achieving 40-60% weight savings in heavy trailers was demonstrated by tailoring the design and assembly characteristics of their floor/chassis system to the specific properties of lightweight composite and aluminum materials. A reduction of about 50% in the structural weight of a 48 ft long heavy trailer would reduce by about 6% the fuel consumption of the vehicle. As the operators of long-haul highway transportation systems are expected to load always their vehicles up to the maximum allowable gross weight (for example 80,000 pounds), so that any reduction in the structural weight of vehicle is likely to result in the transportation of heavier cargo loads for the same amount of fuel consumption. Assuming that a typical long-haul vehicle travels, on average, 100,000 miles per year, a reduction of 3,250 pounds for example, in the empty weight of the vehicle would translate into an annual saving of 350,000 gallons of fuel for every1000 tons of freight cargo transported by that vehicle during the year.

Since most freight loads are usually transported within cargo containers that can be moved easily from one type of vehicle to another and can be loaded or unloaded expediently, energy savings similar to those described above can be achieved by reducing the structural weight of such containers. Therefore, the benefits of using lightweight composite materials for the manufacturing of cargo containers are equivalent to those associated with corresponding weight reductions in any structural component of the vehicle itself.

The purpose of the current research effort presented this study is to address the call of the U.S. Council for Automotive Research and the U.S. Department of Energy for new "Vehicle Technologies for Improving Fuel Economy" that help to reduce vehicle body mass by substituting new materials such as high-strength steel, advanced high-strength steel, aluminum, magnesium, and composites for current materials. It is anticipated that the body-mass reductions that can be achieved in the near term vary from 10% (with mostly conventional and high-strength steels) to 50% (with a mostly aluminum structure). Even greater reductions are feasible, but they require expensive composite structures that involve such materials as carbon fiber. Significant advances towards this goal can be presently pursued by leveraging the experience and findings accumulated so far at WVU in the areas of lightweight, durable, design and joining concepts for heavy vehicle systems.

1.3 Project Objectives

The main objective of this project is to develop, analyze and validate data, methodologies and tools that support widespread applications of automotive lightweighting technologies. Two underlying principles are guiding the research efforts towards this objective:

- Seamless integration between the lightweight materials selected for certain vehicle systems, cost-effective methods for their design and manufacturing, and practical means to enhance their durability while reducing their Life-Cycle-Costs (LCC).

- Smooth migration of the experience and findings accumulated so far at WVU in the areas of designing with lightweight materials, innovative joining concepts and durability predictions, from applications to the area of weight savings for heavy vehicle systems and hydrogen storage tanks, to lightweighting applications of selected systems or assemblies in light–duty vehicles.

2. RESEARCH EFFORTS ON VEHICLE WEIGHT REDUCTION

2.1 Introduction

This chapter presents a review of the current and emerging technologies that could be adopted and integrated in order to reduce the structural vehicular weight, hence improve their fuel efficiency. The review also would help identify specific components or systems, as well as specific engineering materials, such as carbon fiber composites, aluminum, high-strength steel or magnesium, which are most likely to demonstrate, by applying the design, analysis and manufacturing methods developed through the project, the feasibility of achieving drastic reductions of structural weight at affordable manufacturing costs and without compromising safety and durability. The literature indicates four main directions sought by researchers and automotive manufacturers in order to reduce the structural weight of vehicle components as described in the following sections.

2.2 High Strength Steel

Steel has been the base choice of material for automobile bodies due to its strength, ductility and low cost. This has led to the development of a vast knowledge of the material and processing properties as well as methods for efficient design of steel structures (*Du Bois et al.*, 2004). As the demands for increased fuel efficiency and safety have increased together with competition from other materials the steel suppliers have responded by developing more grades and types of high strength steels. Recently, the Society of Automotive Engineers (SAE) has reclassified formable and high strength sheet steels for automotive use. This new classification is based on formability and strength levels as used in the automotive industry. The SAE recommended practice furnishes a categorization procedure to aid in the selection of low carbon sheet steels for identified parts and fabrication processes. There are two new SAE specifications covering automotive sheet steels:

- SAE J2329 Categorization and Properties of Low Carbon Automotive Sheet Steels.

- SAE J2340 Categorization and Properties of Dent Resistant, High Strength, and Ultra High Strength Automotive Sheet Steel.

Realizing that most cars and trucks have been getting progressively heavier over the last three decades, Mazda made concerted effort to turn that around by focusing on weight as a way to improve fuel consumption and carbon dioxide emissions while maintaining the agile handling and safety levels. Mazda's R & D managed to reduce the weight by over 200 pounds compared to the previous generation car by utilizing high-strength steels to optimize the design of the whole body to reduce the weight while improve the rigidity and crash resistance. Sixty percent of this weight savings came in engineering solutions, including the body shell, which has an optimized structure and uses high and ultra-high tensile steels for less weight, greater rigidity and better crash resistance. Another 20 percent were saved by features adjustments and 20 percent saved by decreasing the length of the vehicle by 40 mm and height by 55 mm. These weight-saving measures make the new Mazda a trendsetter for fuel efficiency and low carbon dioxide emissions (*Abuelsamid, 2007*).

The Materials, Manufacturing and Concepts Center at Daimler carried out fundamental research on various manufacturing processes that showed that the old technique of roll forming showed a lot of untapped potential for automotive construction. The researchers discovered that high-strength steel is well suited to this process; hence it could be used for weight saving. With the flexible roll forming, it was possible to produce deep-drawn parts that can achieve the tolerances required in automotive design quickly and with high precision. The very high degree of dimensional consistency needed is achieved by a quick readjustment of the rolls. The use of super high-strength steels enabled reducing the wall thicknesses and therefore achieving lightweight constructions. This in turn makes it possible to cut the weight by up to 1.5 kilograms per part (*Daimler HighTech Report, 2008*).

2.3 Aluminum

The use of aluminum has been viewed as a desirable weight saving approach; however its use was restricted due to the complex shapes of aerodynamic hoods, bumpers, and fairings; the limited room-temperature formability of aluminum; and the high cost of forming tools (*Lavender et al., 2006*). However, recent studies by The Aluminum Association, Inc. indicated that automakers increasingly use aluminum to boost fuel economy, cut emissions and improve safety (*IBIS Associates, 2008*). A new study by Ducker Worldwide (*Schultz, 2008*) confirms that the aluminum content reached an all-time high at 8.6 percent of average vehicle curb weight in 2009. The presented data demonstrate that the use of automotive aluminum in North America has been increased steadily in the past four decades from 2 percent in 1970 and 5.1 percent in 1990. Additionally, the integration of aluminum in cars and light trucks is projected to be nearly 11 percent of curb weight by 2020. A scenario comparison presented by IBIS Associates (2008) indicates that replacing steel components with aluminum in a midsize car would result in a 17 percent mass reduction at 1 percent less cost. Such a weight saving translates into more than a 15 percent increase in average mileage per gallon (*IBIS Associates, 2008*).

A recent study conducted by the Institut fur Kraftfahrzeuge (2010) analyzed 26 automotive components to assess the further potential or limits of weight reduction for both steel and aluminum. The study found that using aluminum could result in significant weights savings for the analyzed components, ranging from 14 to 49 percent, compared to only 11 percent for high-strength steel. This study combined with other data on the benefits of aluminum suggest a total of about 525 pounds of additional weight savings, which could result in 2.7 more miles per gallon or a nearly 10 percent further improvement in fuel economy over a typical automobile, while maintaining the vehicle safety. Being more crash absorbent than steel, aluminum can safely reduce vehicle weight without reducing vehicle size. This offers great potential, since lighter vehicles can produce fewer emissions and need less fuel to operate.

Weight reduction potential using high strength steel was limited to about 11 percent. The reason the potential weight reduction using high strength steel is so small, is that nearly 40 percent of the parts analyzed simply cannot be made thinner regardless of the grade of steel used. If high strength steel were to be used to lightweight these parts, their stiffness would actually be reduced and the car's performance would suffer, whereas, aluminum could be used without reducing stiffness or causing the car's performance to suffer.

Superplastic forming of fine-grained 5083 aluminum is an elevated-temperature gas pressure forming process that has been widely used in aerospace applications and was more recently introduced by General Motors (in a modified form) for selected aluminum automotive components (*Verma et al., 1995*). Advantages of superplastic forming include low-cost tooling, the ability to form complex shapes, simplified die design compared with traditional stamping, low noise and environmental impacts and the opportunity for significant part count consolidation (*Nyberg, 2007*). Although SPF is traditionally viewed as a slow-forming process, recent advances in aluminum alloys and forming process procedures have reduced typical forming times to the point where SPF appears well suited for automotive production volumes. However, a number of technical barriers remain, including the ability to form Class A surfaces, the availability of suitable SPF sheet materials for large components, and the field performance of SPF components and structures in automotive applications.

Tolani and Eberhardt (*2006*) investigated the applications of superplastically formed aluminum for commercial truck cabs, which are currently made of steel, to provide a lightweight and low tooling-cost alternative to steel and sheet molding compound. A large exterior truck body panel having a complex shape and moderate production volumes was selected to be redesigned using finite element analysis. Forming simulations were conducted to verify manufacturability. Prototyping trials made it apparent that the part could not be made consistently without splitting in some area because of the variations in the manually controlled forming process parameters. There was a very significant scrap rate.

Lavender et al. (*2006*) explored the possibility of replacing the low-strength glass-fiber reinforced plastics with superplastically formed aluminum in heavy vehicle hoods and other cab components that can reduce the weight of Class 6-8 truck components. The research focus was to demonstrate the technology, using mutually agreed-on truck components, with the goal of developing the superplastic forming design and material property knowledge base to the point where the individual automobile companies have the ability to implement it for their new vehicle designs.

2.4 Magnesium

Magnesium is one of the lightest structural metals. Its use in the automotive industry has grown by 10-15 percent per annum over the past 15 years to an average of 10-12 lbs. (range 1-35 lbs.) for an average U.S. 3,360- pound vehicle. This is compared to 260 lbs. of plastics, 280 lbs. of aluminum, and 2,150 lbs. of steel/cast iron. The primary advantage of magnesium is its ability to reduce vehicle weight and enhance its performance. Magnesium parts can be tuned to those critical frequencies where noise, vibration and harshness are reduced (*U.S. Automotive Materials Partnership, 2006*).

Currently, magnesium alloy castings are being used on a limited number of production vehicles. These castings provide a significant mass saving and are currently being used to achieve shapes that are not feasible using stamping techniques and to integrate numerous small parts that would otherwise require fixturing and welding (*Lotus Engineering Inc., 2010*). For example, a single large casting could be used to produce an instrument panel cross-car beam, which reduces the manufacturing error and misfit, reduce the manufacturing cost and craftsmanship, and reduce the susceptibility for rubbing and vibration between the elements (*U.S. Automotive Materials Partnership, 2006*). Additional reported applications of magnesium castings include the roof frame for the Chevrolet Corvette ZO6, the dash panel for the Dodge Viper, the liftgate inner for the Lincoln MKT and the front end module for the Land Rover LR3. It is estimated that a magnesium casting similar to that used on the Lincoln liftgate combined with an aluminum outer panel is approximately 40% lighter than the same Venza components made from equivalent steel stampings (*U.S. Automotive Materials Partnership, 2006*). Although such applications demonstrate the magnesium ability to enhance the vehicle design and performance, in addition to reducing mass, the challenges and technical barriers to increasing magnesium in automotive applications are significant. A key component to increasing magnesium use in the automotive sector is developing an enabling infrastructure. There currently is no North American industrial supporter for magnesium, as there was historically for aluminum and steel. Automotive manufactures also raised concerns about the limited engineering experience with magnesium and low-confidence in material characterization, which would require using higher safety factor in component design.

Considerable research efforts have been funded by the U.S. Department of Energy in order to overcome the aforementioned barriers within the scope of FreedomCAR and Vehicle Technologies Program. The magnesium research and technology project was initiated at Pacific Northwest National Laboratory (*Nyberg, 2007*) to support the magnesium frond end research and development project in collaboration with China and Canada and to compile and evaluate the state-of-the art in magnesium research around the world.

Osborne (*2007*) conducted a research project focused on resolving critical issues that limited the large-scale application of Mg castings in automotive components. The project combined the science and manufacturing technology necessary to implement front and rear structural cradles that offer all of the difficult manufacturing issues, including casting process (high-pressure die, semi-solid, low-pressure, squeeze, etc) and joining, along with harsh service environment challenges, such as corrosion, fatigue, and stress relaxation associated with fasteners. The project proved the successful casting and production of magnesium engine cradle that passed all validation requirements with no issues and was tested in volume production on the 2006 Z06 Corvette. More efforts have been made later to investigate the effect of alloy composition on mechanical properties in the T4 and T7heat treated conditions and to establish cost models for automotive suspension components produced by different processes and different materials (*Osborne, 2010*).

Maj (*2007*) assessed the manufacturing feasibility, economics and mass reduction potential of thin-wall structural castings of aluminum and magnesium that could be used in place of conventional stamped and welded steel automotive body structures to reduce vehicle weight. Two emerging casting processes could be identified through this project, namely Sub-Liquidus Casting and Thixomolding with Multiple Hot Runners, which have the potential to produce low-cost large castings with mechanical properties much better than those achievable with high-pressure die casting (the industry's preferred process).

More research and development efforts have been conducted to develop and validate and low-pressure-cast magnesium automotive suspension components (*Cox, 2007*), and to develop casting process technologies needed to manufacture squeeze-cast and to demonstrate and enhance the feasibility and benefits of using magnesium alloys to replace aluminum in structural powertrain components (*Powell, 2007*). The later project demonstrated that there are no technical stoppers to prevent production implementation of magnesium powertrain components, which can leads to significant vehicle mass reduction (*FreedomCAR and Fuel Partnership, 2010; Powell, 2010*).

Luo (*2007*) conducted a research project to develop and validate lightweight magnesium front end designs for unibody and body-on-frame architectures (*Luo, 2007*) to accomplish 50% weight reduction compared to steel baseline with equivalent performance and acceptable costs. The initial design iterations indicated a mass reduction of 45 to 47 percent (*FreedomCAR and Fuel Partnership, 2009*). Design refinements were going to achieve 50 percent mass reduction and improve simulations in crashworthiness and durability.

2.5 Lightweight Composite Materials

The commercial application of composites has an extensive history in the marine, aerospace and construction industries but has evolved relatively slowly in the automotive industry. The utilization of composites in automotive sector has historically been limited to secondary structures such as appearance panels and dash boards. The major obstacles to automotive industry implementation of polymer based composites come from a variety of factors including industry inexperience with these materials, undeveloped high production rate processes, the need for new joining techniques, lack of knowledge about material responses to automotive environments, lack of crash models, immature recycling technologies and a small supplier base (*Kaw, 2006*; *Mangino et al., 2007*). In addition to the aforementioned limiting factors, carbon fiber based composites are restricted in industry use due to the high current cost of carbon fiber in comparison to other potential vehicle structural materials. By weight, about 8% of today's automobile parts are made of composites including bumpers, body panels, and doors (*Kaw 2006*).

Composite Materials are classified by the geometry of the reinforcement as particulate, flake and fibers or by the type of matrix as polymer, metal and carbon. Polymer fiber composite is most common form that has been used in the automotive industry. The first application of such materials was the fiberglass body of the Chevrolet Corvette in 1953. Since then, several research and development efforts were pursued to further the application of lightweight composites in the automotive sector. The Corvette was fitted with glass/epoxy composite leaf springs whose fatigue life of more than five times that of steel. Composite leaf springs also give a smoother ride than steel leaf springs and give more rapid response to stresses caused by road shock. Moreover, composite leaf springs offer less chance of catastrophic failure, and excellent corrosion resistance (*Bursel, 1990*).

Knouff et al. (*2006*) led an effort to achieve the rapid implementation of lightweight composite materials in Class 7/Class 8 vehicles via the development of advanced composite support structures. Class 8 tractor lateral braces were selected for such study as they offer an opportunity for significant weight savings and represent a large hurdle in terms of composite applications and market acceptance. The mass reduction target is 50% and the minimum requirement is 30%. Finite element analysis (FEA) was utilized to model composite support structures and to investigate potential failure mechanisms through progressive failure analysis.

In 2003, DaimlerChrysler completed vehicle testing that provided grounds for using an SUV/Pickup platform equipped with a hybrid frame. Results of the accelerated testing have proven that the hybrid frame design had sufficient strength and durability to meet the vehicle performance requirements; the frame was probably somewhat overbuilt and heavier than required, even though it provided a substantial weight savings as compared to the current baseline steel frame. Lavender et al. (*2006*) utilized a computer-aided engineering (CAE) approach to design a new generation frame that weighs less than the previously tested new-generation frame and requires 35% fewer components. A prototype of the frame was fabricated and evaluated by flexural testing and road tests.

The completed frame was assembled into a Dodge Durango and evaluated by using a vehicle simulator at the DCX Auburn Hills Technical Center. The frame successfully completed a satisfactory lifetime.

In 2009, General Motors led off a prototype of the extended range electric Chevy Volt that was slated for production in the next year. The design of the Volt utilized 100 pounds of thermoplastics including composites in the hood and doors in addition to unreinforced polymeric materials in the rear deck lid, roof and fenders. GM estimated that the Volt will save 1,892 liter of gasoline annually compared to similar sized gasoline-powered vehicles assuming an average daily drive distance of 40 miles (*Stewart, 2009*).

2.6 Summary

The current state-of-the-art of the lightweighting technologies of automobiles reveals that several lightweight materials and technologies have been evolved such as ultra-high strength steel, aluminum, magnesium alloys and titanium in addition to a wide variety of composite materials. The published literature as well as discussions and interactions with automotive manufacturers indicated that the industry is inclined more toward the use of aluminum and magnesium. The high cost of titanium and the difficulty encountered in its processing hindered its widespread application by automobile manufacturers. There is also a trend in using ultra-high strength steel; however it seems that the reduction in the thicknesses may adversely affect the global stiffness of the part.

The Composites technology has been utilized today in low volume in some vehicles such as Chevrolet Corvette, Dodge Viper and Ford GT. However at this stage, such technology does not deliver the level of affordable lightweighting performance that continuous oriented carbon fiber or glass fiber composites are capable of achieving. A major drawback for using composites in automotive applications is the typically long cycle times associated with part manufacturing. Low-cost processing methods have matured significantly in the last decade, but typical costs are still higher than comparable metal parts. Costs along with the slow processing cycle of polymer composites are the two major deterrents against their wider usage in automotive markets.

3. DEFINITION OF PRACTICAL CASE STUDY

3.1 Introduction

The first task of the project involved the detailed definition of a case study selected in close coordination with the industrial partners for implementing and showcasing the lightweighting technology developed through the current and previous research efforts. The objective is to identify specific components or systems of a heavy- duty vehicle, such as the chassis, floor pan or suspension, as well as specific engineering materials, such as carbon fiber composites, aluminum, high-strength steel or magnesium, which are most likely to demonstrate, by applying the design, analysis and manufacturing methods developed through the project, the feasibility of achieving drastic reductions of structural weight at affordable manufacturing costs and without compromising safety and durability.

3.2 Case Study Definition

An extensive research and development effort was initiated by the U.S. Department of Energy (DOE) in 2003 at West Virginia University (WVU) in order to investigate practical ways of reducing the structural weight and increasing the durability of heavy vehicles through the judicious use of lightweight composite materials. The research efforts were focused on 14.63 m (48 ft) long Great Dane P-Series haul trailers. A detailed 3D finite element model for such trailers has been developed using LS-DYNA software (*Hallquist 2006*) as shown in Figure 3.1. The main feature of such model is that it included all the substructure assemblies of the box trailer structure. The 3D finite element model was also used to estimate the weights of different components of the trailer in order to identify the heavy components that would require a redesign in the process of reducing the weight of the current design configuration. The model results indicated that in such trailaers, the chassis components constitute 73% of its load-free weight, which is about 6,850 kg (Prucz and Shoukry 2004, Prucz *et al.* 2006). The oak floor panels and supporting steel cross I-beams contribute

47% of the structural weight of such trailer hauls. Therefore, research efforts on weight reduction of trailers were focused on the structural configuration and materials of floor design (Prucz *et al.* 2006, 2009).

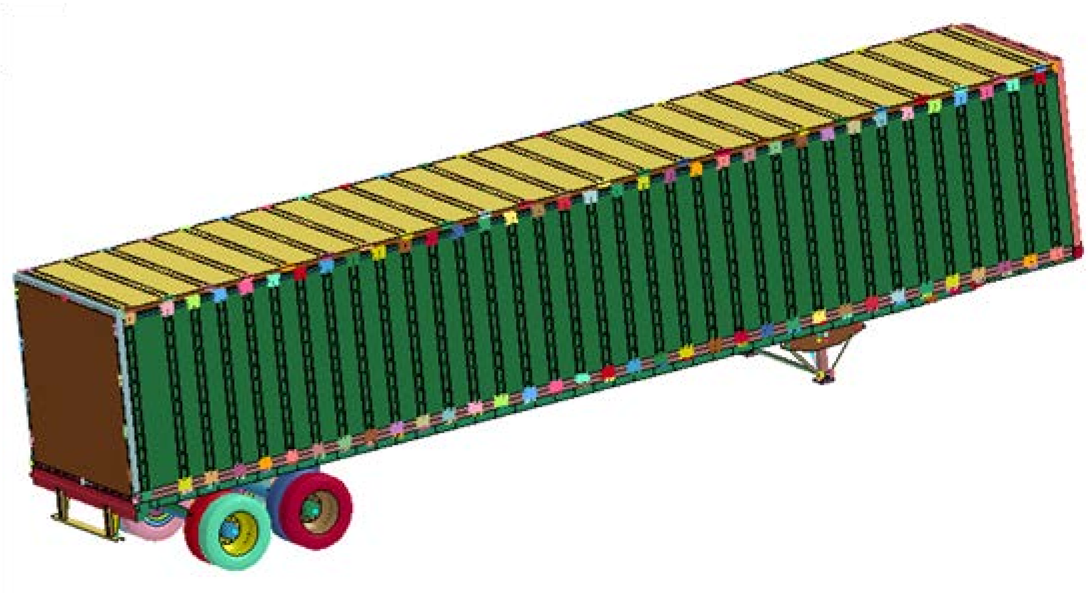


Figure 3.1 Finite Element Model for 48-ft Long Van Trailer**.**

The current floor design configuration of van trailers system comprises 35-mm thick oak floor panels resting on cross I-beams evenly distributed at 0.305 m (1 ft) spacing along the central section of the van, whereas the other set consists of I-beams with overhanging cantilevers over the suspension rail as illustrated in Figure 3.2. This indicates that the floor assembly has a great potential for weight saving through integrated material-structural analysis.

The baseline loading scenario assumed for integrated structural design of the floor components consists of structural dead loads and the live load applied by a moving loaded forklift, whose weight is assumed to be 11 kN (2,500 lb) per wheel, where the wheels are spaced at 1.0 m.

Prucz *et al.* (2009) suggested several alternative design concepts for the structural floor of a van trailer in order to reduce its weight below that of the current baseline configuration. Such lightweight designs relied on sandwich panels with various material and geometric characteristics of the core. The main design objective utilized in this comparative study was chosen to be an optimal tradeoff between the overall weight and stiffness of the floor. The following design criteria had to be met by all the suggested alternative configurations considered:

1. The factor of safety in flexure should not be lower than 2.0.

2. The maximum deflection of a cross beam in an alternative, lightweight floor should not exceed that calculated for a similar steel beam currently used in the baseline floor configuration.

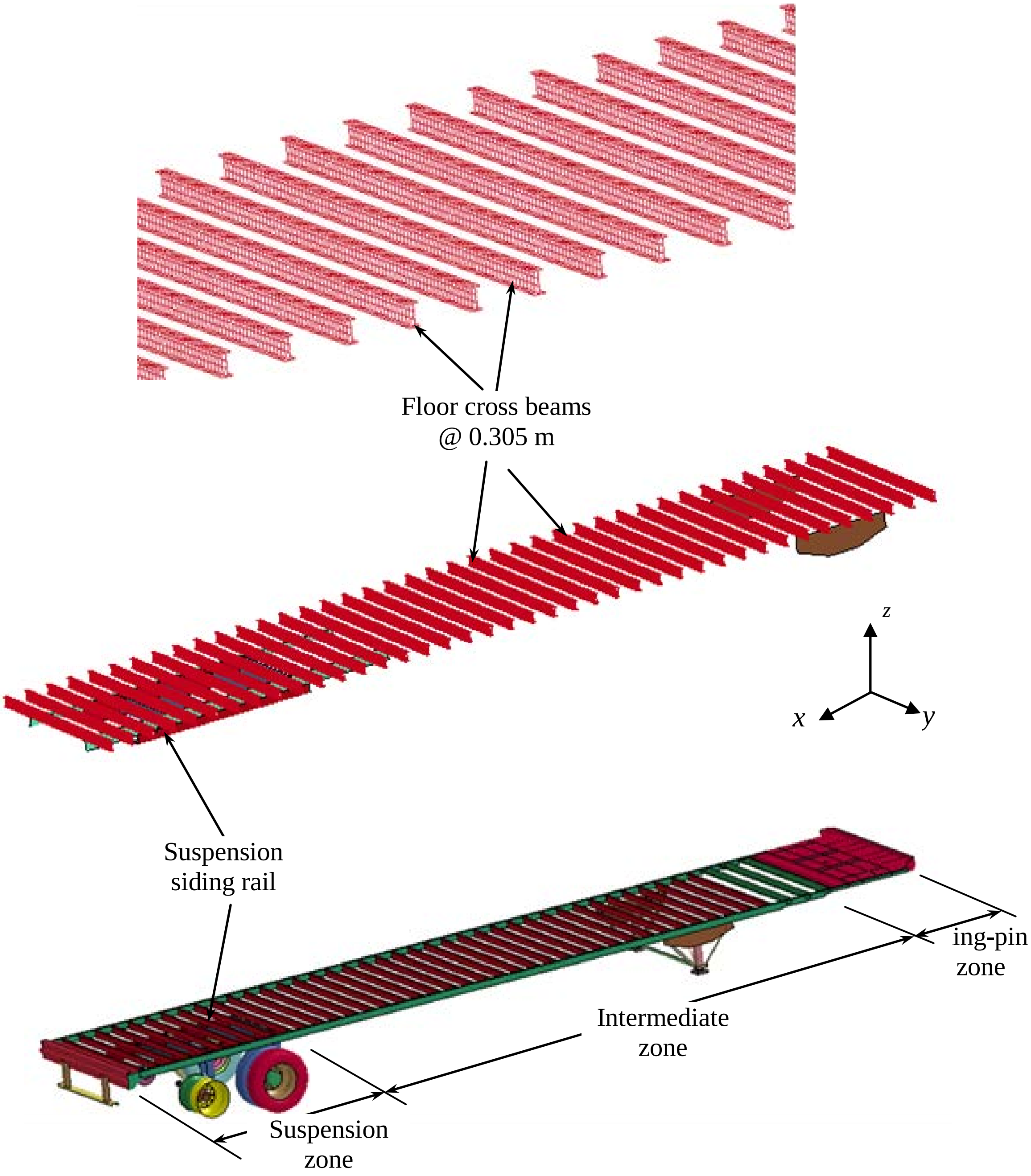


Figure 3.2 Floor Cross Beams.

In each design alternative, a simple mechanics of material approach was initially used to estimate the required size of the cross-beams, and then the analysis was further refined using 3D finite element analysis. The full span of the floor was modeled along with its major structural members such as cross-members and stiffeners as shown in Figure 3.2. All cross-beam members of the floor were represented by using 4-node quadrilateral shell elements. Other major parts of the floor, namely the stiffeners, bogie I-beams and sidewalls were all represented by using beam elements. The finite element model developed for the four different design configurations. In each design configuration, the cross-beams were assumed to be made of various materials. For each alternative material selection for the I-cross beams, Table 3.1 specifies the minimum standard dimensions required for the I-beam cross-section to satisfy the design criteria outlined above. In addition, Table 1 displays the factor of safety, the maximum deflection, and the weight of the unit floor area corresponding to every material option for the I-beams.

Table 3.1 Alternate Material Solution for I-Beam Floor.

MATERIAL CANDIDATE	SIZE				Section Properties			Ultimate Strength	Flexural Stress	Factor of Safety	Mid-span Deflection	Weight
	d	b_f	t_w	t_f	A	Ixx	S					
	mm	mm	mm	mm	cm^2	cm^4	cm^3	MPa	MPa		mm	kg/m^2
STEEL	102	64	4.1	6.6	12.3	217.6	42.8	550	208.43	2.64	14.40	31.61
Aluminum	204	58	3.4	4.8	12.39	770.0	75.7	240	117.83	2.04	12.04	31.73
EXTREN 525	204	102	9.5	9.5	36.97	2306	227	206	39.31	5.24	14.79	22.50
Carbon-Carbon	152	76	6.0	6.0	18.6	662	87.2	1096	102.31	10.71	7.00	9.65
Nitronic 19D Stainless Steel	102	64	4.1	6.6	12.3	217.6	42.8	714	208.43	3.43	14.61	31.15
Nitronic 60 Stainless Steel	102	64	4.1	6.6	12.3	217.6	42.8	1110	208.43	5.33	15.36	31.73
NItronic 30 Stainless Steel	102	64	4.1	6.6	12.3	217.6	42.8	811	208.43	3.89	15.51	30.75
Magnesium	152	76	6.0	6.0	18.6	662	87.2	185	102.31	1.81	22.10	10.62

The mesh sizes were adjusted in such a way that most of the nodes were common to two or more surfaces, thus reducing the need for contact elements. The maximum size of the quad element was normally maintained at 15 cm. This approach resulted in models consisting of about 5,000 elements, on average. The top covering layer of the floor is made of oak wood (Modulus of Elasticity, E = 11 GPa and Poisson's ratio, ν= 0.3) and is represented using shell elements whose thickness is assumed to be equal to be 35 mm.

The boundary conditions of the models were formulated by assuming that the trailer was in stationary condition. The floor was constrained in the vertical, Z, direction at points where it rests on the landing gear and the bogie. Nodes corresponding to these locations were identified first, followed by applying the constraints directly on these nodes. Four concentrated loads representing the four wheels of the forklift were calculated by assuming that each wheel carries a load of 11 kN. The position of the concentrated loads is assumed to be at the center of the floor span, where the deflection is expected to be the highest. The structural behavior of each floor design configuration was determined and evaluated as summarized in Table 3.2.

Table 3.2 Weight and Deflection Comparison of Structural-Material Integrated Design Concepts.

Material	I-Cross Beams Connected by Bars through Web Centers		Fiberglass Faceplates C-Channels Core		Ribbed Fiberglass Faceplates with Core of Hollow Cross Tubes		Sandwich Panels with Light Core	
	Deflection (mm)	Weight (kg/m^2)	Deflection (mm)	Weight (kg/m^2)	Deflection (mm)	Weight (kg/m^2)	Deflection (mm)	Weight (kg/m^2)
STEEL	14.40	31.61	10.05	32.71	10.11	61.99	10.05	32.71
Aluminum	12.04	31.73	10.41	19.67	10.56	28.46	10.41	19.67
EXTREN 525	14.79	22.50	8.86	26.85	32.81	34.12	8.86	26.85
Carbon-Carbon	7.00	9.65	7.65	10.80	7.65	29.30	7.65	10.80
Nitronic 19D Stainless Steel	14.61	31.15	10.20	32.19	10.25	60.95	10.20	32.19
Nitronic 60 Stainless Steel	15.36	31.73	10.72	32.78	11.86	62.07	10.72	32.78
Nitronic 30 Stainless Steel	15.51	30.75	10.83	31.77	11.00	60.16	10.83	31.77
Magnesium	22.10	10.62	16.80	12.62	17.03	18.34	16.80	12.62

ALTERNATIVE 1

The core of the floor consists of I-cross beams that are 0.305 m (1 ft) apart as illustrated in Figure 3.3 and made of various materials. For each alternative material selection for the I-cross beams, Table 1 specifies the minimum standard dimensions required for the I-beam cross-section to satisfy the design criteria outlined above. In addition, Table 3.1 displays the factor of safety, the maximum deflection, and the weight of the unit floor area corresponding to every material option for the I-beams.

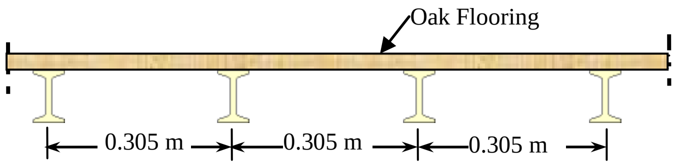


Figure 3.3 I-Cross Beam Floor.

The results presented in Table 3.1 reveal that the current weight of a baseline van floor can be reduced by as much as 69 or 66 percent when the steel I-cross beams are replaced, through an integrated design approach, by I cross-beams made of carbon-carbon composite or magnesium alloy, respectively.

These results demonstrate the drastic structural weight reduction in heavy vehicles that can be achieved through rational application of lightweight materials that integrate the layout and geometric design with the material selection process. This conclusion is further supported by similar studies on three other alternative design concepts for the trailer floor.

ALTERNATIVE 2

Sandwich panel consisting of top and bottom fiberglass faceplates and a core formed of transverse C-channel cross beams, as shown in Figure 3.4.

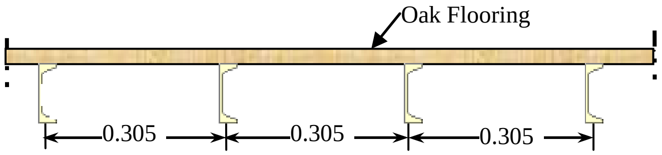


Figure 3.4 C-Channel Beam Floor.

ALTERNATIVE 3

Sandwich panel built of ribbed fiberglass faceplates with a core consisting of hollow cross tubes of either rectangular or circular cross-section, as shown in Figure 3.5.

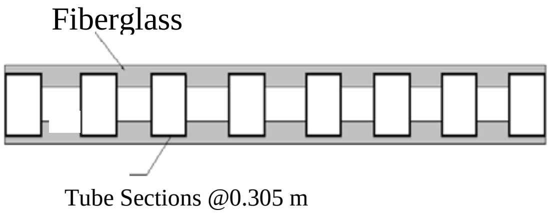


Figure 3.5 Tube Core Floor.

ALTERNATIVE 4

Floor constructed from sandwich panel with a homogeneous, lightweight core.

The results of minimum weight, integrated design studies for all the above four alternative sandwich panel configurations of the trailer floor are summarized in Table 3.2 for eight different material selections for the core of the panel. Both the maximum deflection and the minimum weight per unit area shown in Table 2 for every design option considered here, meet the design criteria defined earlier in terms of the factor of safety and deflection limit.

The results displayed in Table 3.2 indicate that, for any core material selection, the best design configuration for maximum weight savings is that of sandwich panels with light homogeneous core. On the other hand, the sandwich floor panel with core formed of cross C-channel beams may even increase the required weight of the floor for certain material choices for the core C-channels. However, this structural arrangement appears to provide higher stiffness than the other options compared here, for most of the material candidates listed in Table 3.2. Carbon-carbon composites allow the largest weight reductions and the minimum deflections for any design configuration. Obviously, the benefits of using carbon-carbon cores are strongly dependent on the structural configuration of the floor. Additionally, the recent technologies being developed for producing low-cost carbon fibers would allow broader use of such material at a fraction of the current cost.

Every structural arrangement evaluated above could be further optimized by altering, for example, the spacing between cross beams in Figures 3.1 and 3.2, or the characteristics of the face sheets. However, the main objective of this study was to assess the predicted tradeoffs between weight savings and stiffness for alternate core material selections, and not the optimization of any one particular structural arrangement or another. The predicted energy savings enabled by the lightweight floor design and joining configurations of a typical van trailer are shown in Table 3.3. Although these numbers appear to be small for transporting one ton of cargo, they become enormously significant considering the thousands and thousands of freight that any given trailer is likely to haul during its life in service.

Table 3.3 Energy Savings Through Floor Design Cocepts

Alternative lightweight designs	Minimum Weight (kg)	Weight Saving (%)	Gallons of Fuel Used to Transport One Ton of Cargo Over 1000 Miles
Current configuration	3,165	0%	5.82 (0.0%)
Fiberglass cross-beams	1,271	60%	5.41 (7.0%)
Fibergalss Face-Plates, Core of Magnesium Hollow Tubes	1,678	47%	5.49 (5.7%)

Fibergalss Face –Plates, Core of Magnesium C-Channels	1,475	53%	5.45 (6.4%)
MMC Duralcan Face-Plates with lightweight core, such as Balsa	1	57%	5.43 (6.7%)

Since the operators of long haul heavy trailers usually load them to reach the gross vehicle weight (GVW) in order to maximize the efficiency of every transport, structural weight reductions would not necessarily result in lower fuel consumption of the truck in terms of “miles per gallon”. Instead, the associated energy savings are best expressed in terms of fuel used by a heavy vehicle to transport one ton of freight over a certain distance, say 1,000 miles [gal/(kip*mile)]. The comparison illustrated in Table 3 indicates that the current weight of the floor in a typical van trailer can be reduced to half, or even less, if a sandwich panel design configuration and joining concept devised at WVU is utilized. The numbers presented in Table 3.3 are based on the floor and chassis assembly of 14.63 m long (48 ft) van-trailer and gross vehicle weight of 355 kN (80 kips).

4. DETERMINISTIC INTEGRATION DESIGN OF FLOOR-CHASSIS ASSEMBLY

4.1 Introduction

In this Chapter, the integrated material–structural design approach developed earlier at WVU for weight reductions in heavy–duty vehicles is adopted and applied in order to develop alternate manufacturing and assembly methods that demonstrate potential for significant weight savings by redesigning the floors of heavy duty vehicles as lightweight sandwich structures. For this purpose, three-dimensional finite element models were developed for the floor-chassis assembly of the Great Dane P-Series van trailer in order to serve as the primary tool for examining alternative configurations, by predicting potential failure modes of the new design under simulated loading scenarios. In such a design configuration, the 38 mm (1.375-inch) thick laminated hardwood floor is supported on wax-coated I-beam cross-members spaced at 305 mm (12-inch) distance from each other to provide a 16,000 lb forklift front axle rating. The main selection criteria for the best design configurations consist, at this stage, of their associated levels of potential weight reductions and durability enhancements.

4.2 Finite Element Model for Chassis Assembly

A detailed 3D finite element model for the floor assembly has been developed in LS-DYNA. This model is composed of an Oak floor on the surface, I-beams and hat shaped beams acting as the primary supports, and slider rails and landing gear angles to mark the locations where the floor connects to the suspension and the landing gear of the trailer. The model is comprised of 40 separate I-beams, four hat cross members, a slider support, two suspension rails, and two landing gear angles. All parts were modeled using shell elements as illustrated in Figures 4.1 and 4.2.

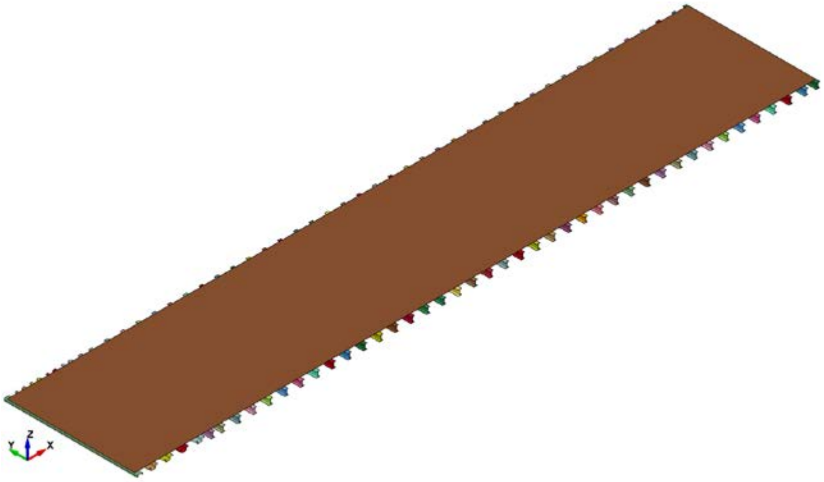


Figure 4.1 Finite Element Model for Oak Floor Supported by Cross Members.

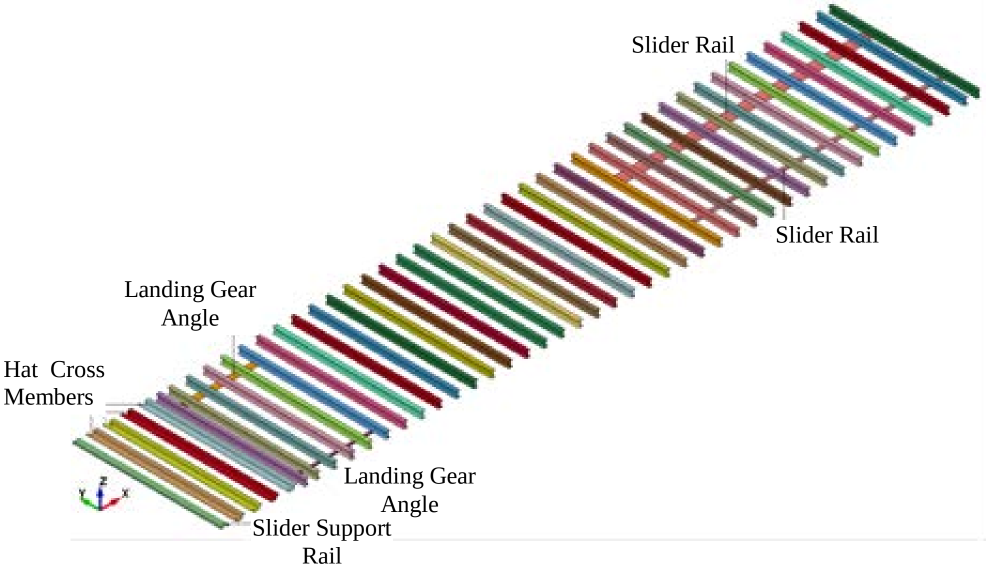


Figure 4.2 Finite Element Model for Floor Cross Members and Supporting Rails.

The laminated oak floor was modeled by assuming elastic material behavior, and the remaining parts were modeled by using the piecewise linear plasticity model implemented in LS-DYNA, with a corresponding stress strain curve for each part. All cross members supporting the floor were modeled as high structural grade steel, as observed in the design details obtained from the Great Dane Company. The material models used in this study were all previously verified through a National Crash Analysis Center (NCAC) model of a different semi-trailer, which indicates that the material property values are reliable. Since most heavy van trailers share similar designs with minor deviations, any redesign of the floor and support assemblies, developed within the scope of this study, can be adapted to the desired truck model. Such design versatility is a valuable benefit as it can help facilitate mass production and consequently lower overall manufacturing costs.

Contact interfaces were used between different parts. For this purpose, the automatic_single_surface contact was first applied to all the parts. This option offers a bi-directional treatment of the contacts to ensure that no penetration occurs as a result of an unexpected displacement of any part during the simulation. Next, the tied_surface_surface_offset contact option was used to attach the cross members to the oak floor and the relevant I-beam nodes to the suspension rails and slider supports.

Both slider rails and both suspension rails were fixed in all degrees of freedom, as this is the location where the floor connects to the suspension and the landing gear. A uniformly distributed test load was applied to the surface of the floor acting downward to simulate trailer loading. After simulation, the structural response can then be examined in detail for each part. A sample of the total effective stresses (Von Misses stresses) and the resultant vertical, or Z-displacements can be seen in Figures 4.3 to 4.5.

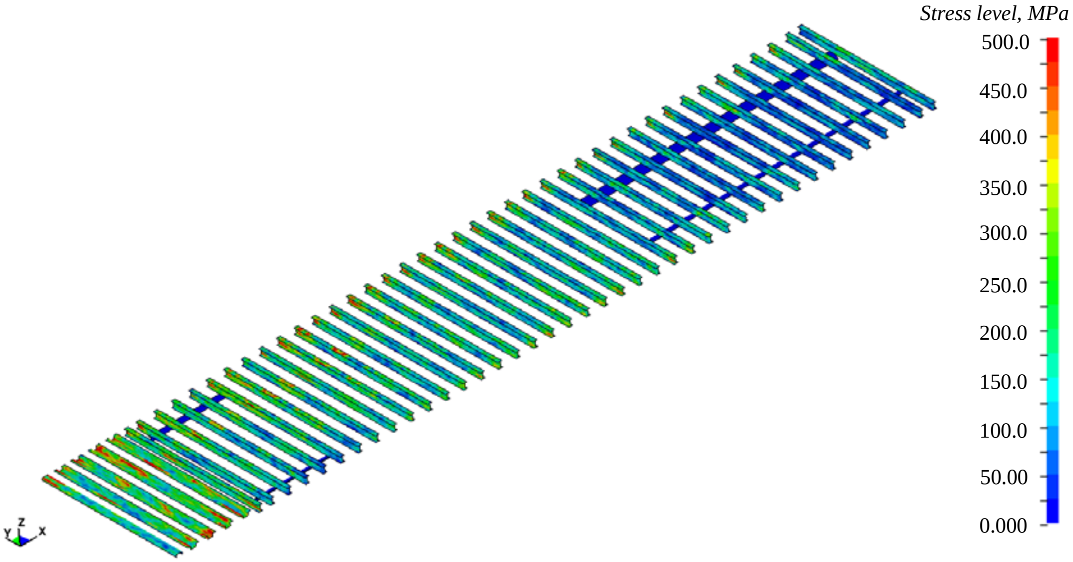


Figure 4.3 Von Misses Fringe Levels in Supporting Cross Members

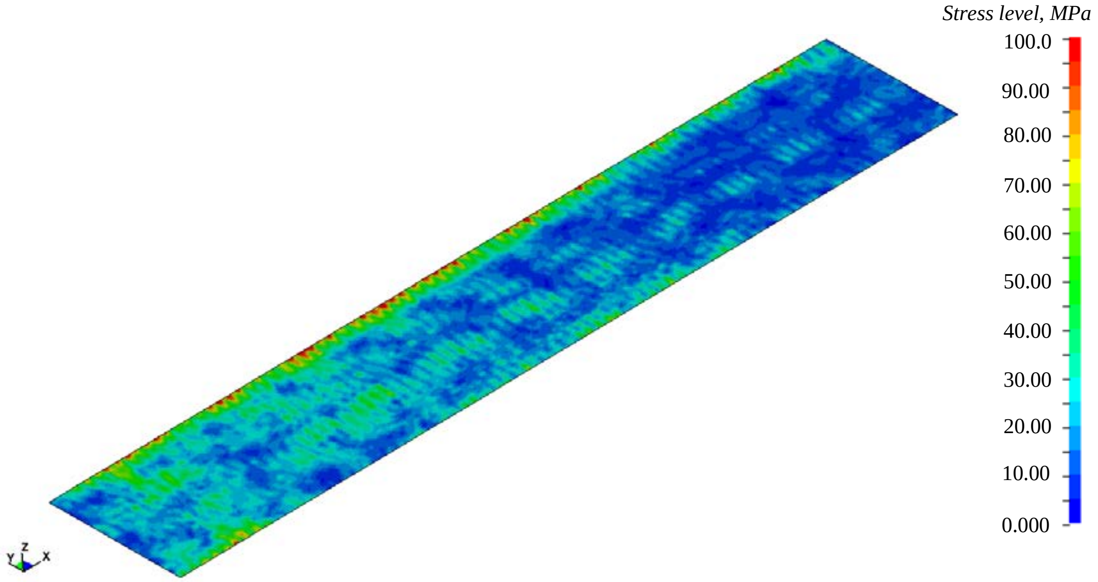


Figure 4.4 Von Misses Fringe Levels in Oak Floor.

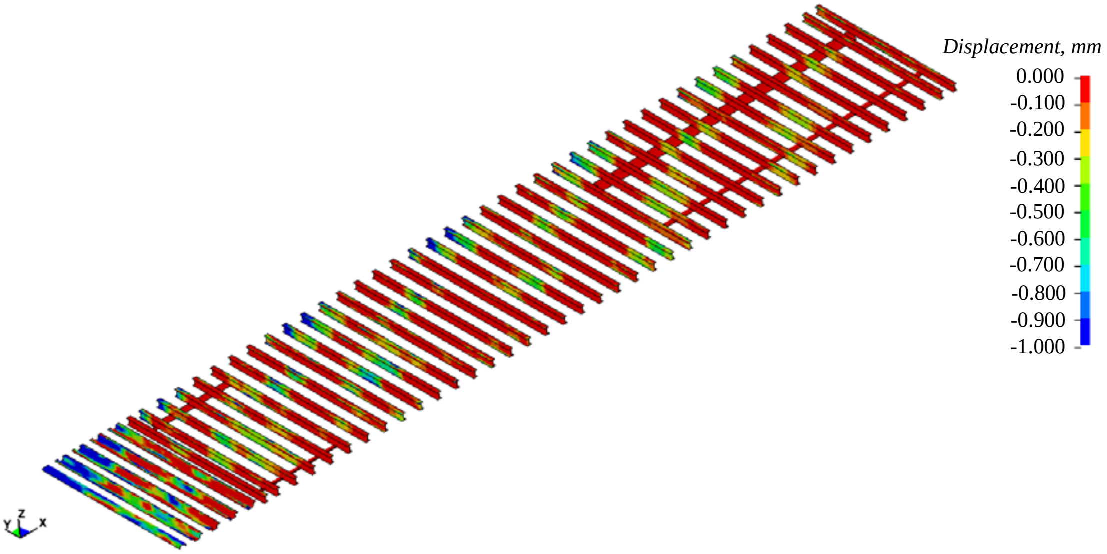


Figure 4.5 Z-displacement of Cross Members.

It is important to note that while the choice of laminated Oak provides a reasonably strong material that is considerably light, the use of high grade steel is necessary to provide sufficient support and stiffness to the trailer. The Oak floor's primary function is to provide a durable cover and flat surface for the cargo loaded in the trailer. Prucz et al.

(2010) *and* William *et al.* (2011) demonstrated that for 2007 Cheverolet Siverado both Aluminum and Magnesium can provide feasible alternatives in the chassis assembly, compared to the steel that is widely used at the present time. While on a much smaller scale, the widespread use of heavy steel in the Chevrolet Silverado is similar to its use in heavy van trailers, though on a much larger scale. Therefore, the next section will first explore the use of both aluminum and magnesium in select parts of the chassis assembly, while maintaining the current oak floor as a cover surface. Subsequently, a variety of design configurations will be examined using data from the aluminum and magnesium results to redesign the entire oak floor-steel cross member system. It is thought that this configuration will provide the greatest level of structural weight savings.

4.3 Alternative Design Configurations for Oak Floor

4.3.1 Lightweight Solid Panels

The loading scheme was also updated as a distributed load over the top surface of the oak floor to represent a fully loaded trailer. Weighing a total of 837.8 kg, the oak floor is a significant load of its own; reducing weight through a stronger, lighter structure can improve fuel economy and increase total cargo capacity. With this goal in mind, the first step was taken to achieve this by demonstrating that different materials, some of which are more durable and could extend the lifespan of the floor, are feasible alternatives when placed under the same load. Alternate configurations of Aluminium 6061-T6, Magnesium HM31A-F, and Fiberglass were considered as alternatives. According to the density of each material, the floor thickness was adjusted until the overall weight was in the same range as that of the original oak floor with the exception of fiberglass to account for additional protective coating. Figures 4.6 to 4.9 illustrate the fields of effective stresses developed in each design configuration under the effect of the distributed load. The maximum effective stresses were compared with the yield stress of each material to calculate the factor of safety to serve as a measure of comparison as illustrated in Table 4.1. Because the results for Aluminium 6061-T6 are similar to that of the original oak, higher grade aluminium, namely Aluminium 7075-T6, will likely allow for a reduced thickness without sacrificing stress, and consequently reducing weight. The higher safety factor in the magnesium configuration suggests that the floor thickness in this configuration can be further reduced while still maintaining the same strength as the original floor. Finally, the fiberglass floor also has a higher factor of safety despite the slightly reduced weight.

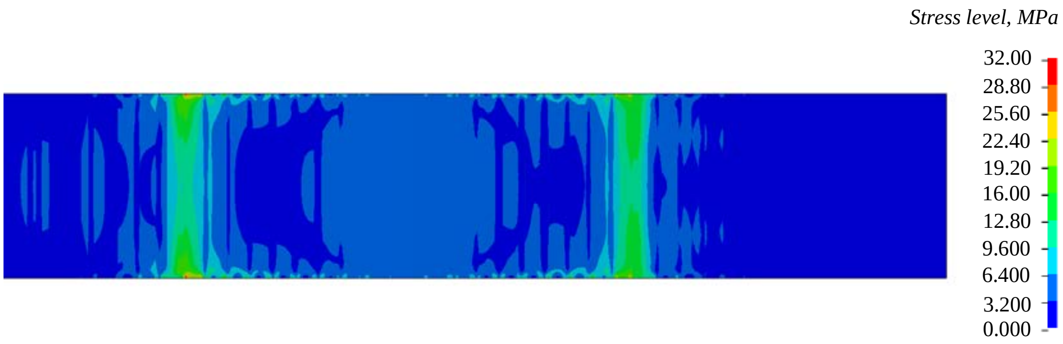


Figure 4.6 Maximum Effective Stresses in the Oak Floor Configuration.

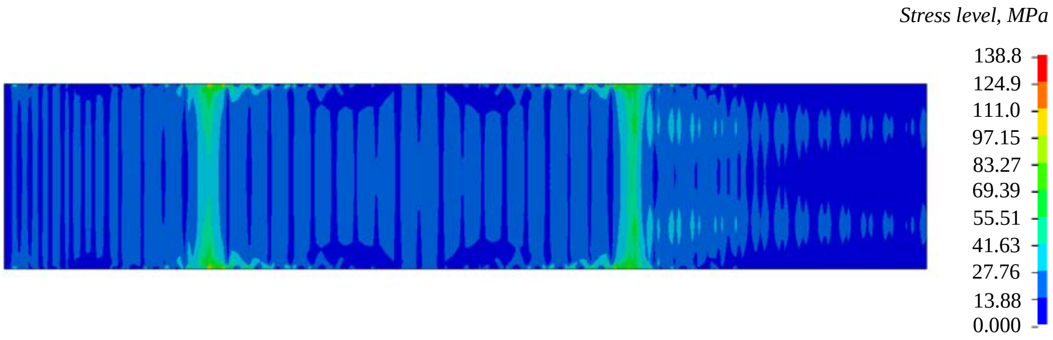


Figure 4.7 Maximum Effective Stresses in the Aluminum Floor Configuration.

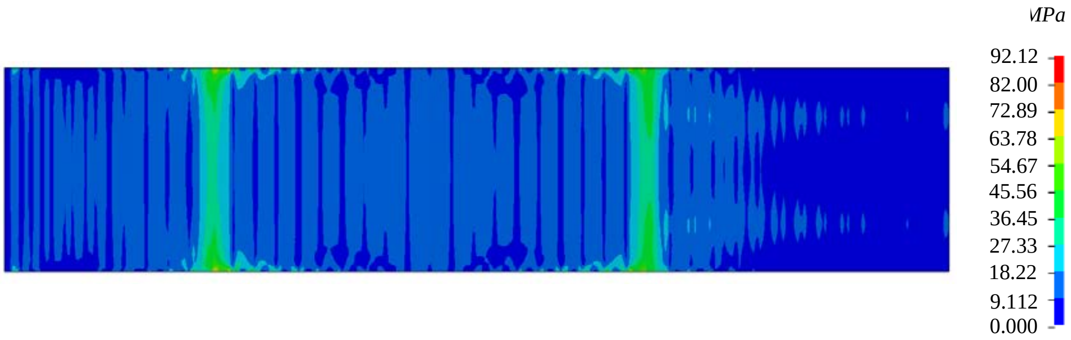


Figure 4.8 Maximum Effective Stresses in the Magnesium Floor Configuration.

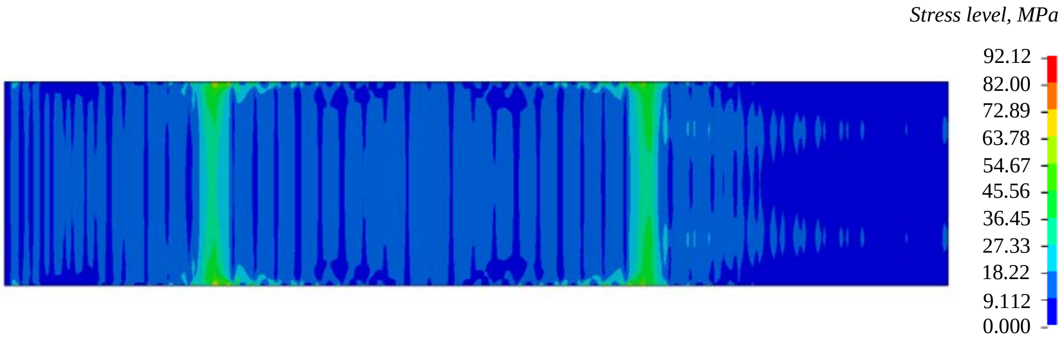


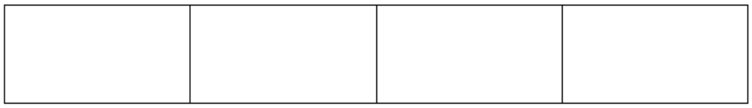
Figure 4.9 Maximum Effective Stresses in the Fiberglass Floor Configuration.

Table 4.1 Comparison of Various Floor Alternatives

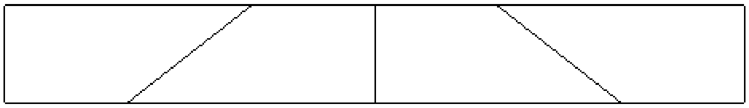
Material	Floor Thickness (mm)	Mass (kg)	Max Effective Stress (MPa)	Yield Stress (MPa)	**Safety Factor**
Laminated Oak (original)	34.925	837.8	31.98	40-60	**1.876**
Aluminium	9.5	835.1	138.78	276	**1.99**
Magnesium	14.25	835.1	91.12	230	**2.52**
Fiberglass	17	774.5	57.04	120	**2.1**

4.3.2 Lightweight Hollow Panels

Another approach to reduce the structural weight is replacing the 1.38-inch thick oak floor with thin-wall tubular aluminum panels. The main benefit of adopting such panels is that they could be easily produced in massive quantities at a reasonable cost. Two design alternatives were suggested for the panel configuration as ululated in Figure 4.10.



(a) Alternative 1



(b) Alternative 2

Figure 4.10 Suggested Tubular Aluminum Floor Panels.

The LS-DYNA finite element models detailing the suggested floor panels and underlying supporting beams were developed. A section of the wood floor was modeled, fixed, and evenly loaded on the top surface to determine both the maximum effective stresses and maximum deflection. The results of these models were then compared to alternative design configurations 1 and 2. These can be seen in Figures 4.11 to 4.16. It was found that either of the alternative configurations would provide a considerable weight savings, but the rectangular configuration 2 provided the highest factor of safety, least maximum deflection, and additionally provided the greatest weight reduction of 10.5% as summarize in Table 4.2.

To determine of the weight reduction could be further increased while maintaining a factor of safety equivalent to the original wood panel, an optimization study was performed by varying the wall thickness of the panel. Ultimately, only a reduction of 0.1 mm was able to maintain the same structural integrity as the original wood panel. However, this translates to a savings of 13.6% as could be seen from the results in Table 4.3.

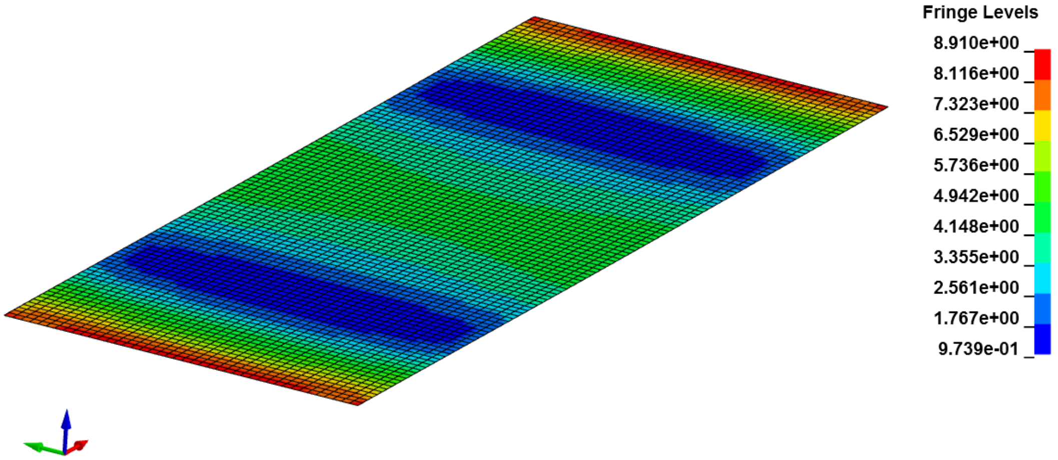


Figure 4.11 Maximum Effective Stress in The Original Wood Panel.

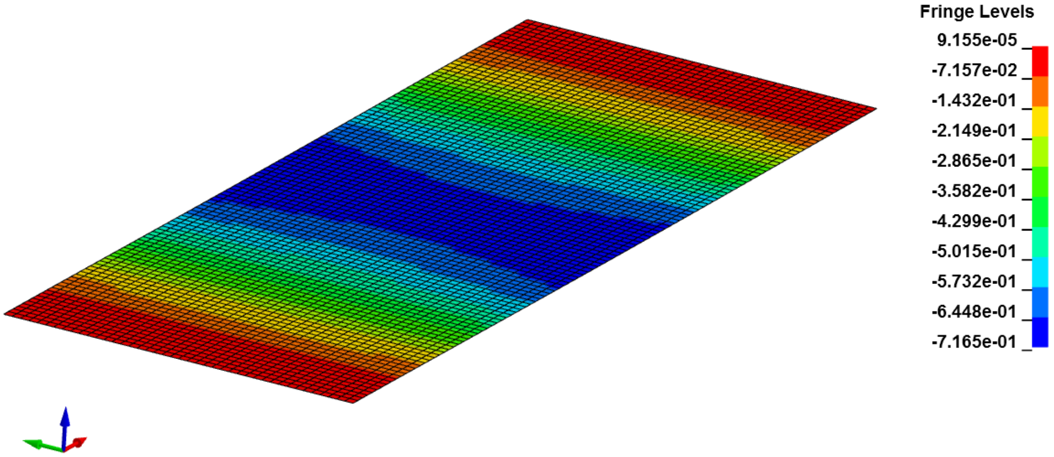


Figure 4.12 Vertical Displacement Contour in the Original Wood Panel.

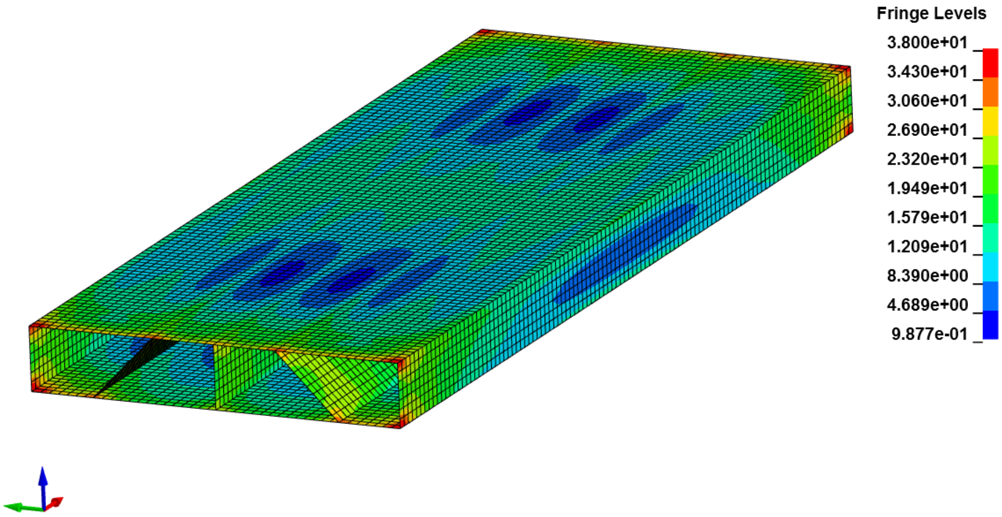


Figure 4.13 Maximum Fffective Stress in Alternative Configuration 1.

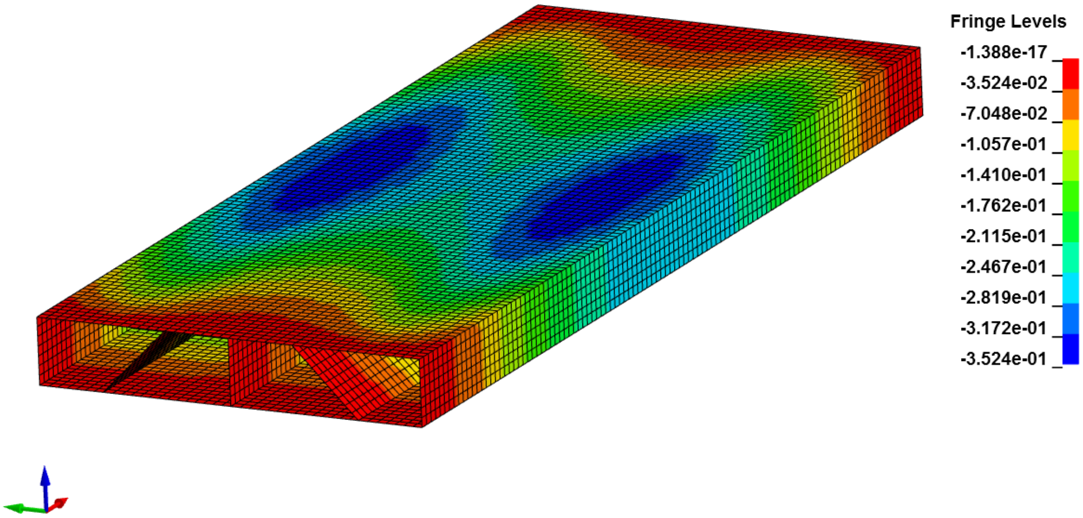


Figure 4.14 Vertical Displacement Contours in Alternative Configuration 1

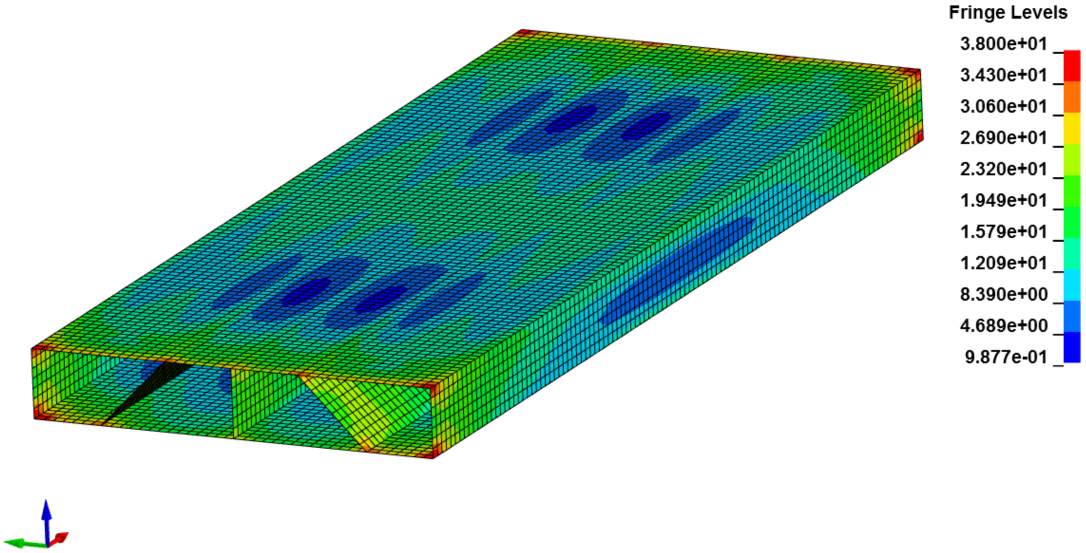


Figure 4.15 Maximum Fffective Stress in Alternative Configuration 2

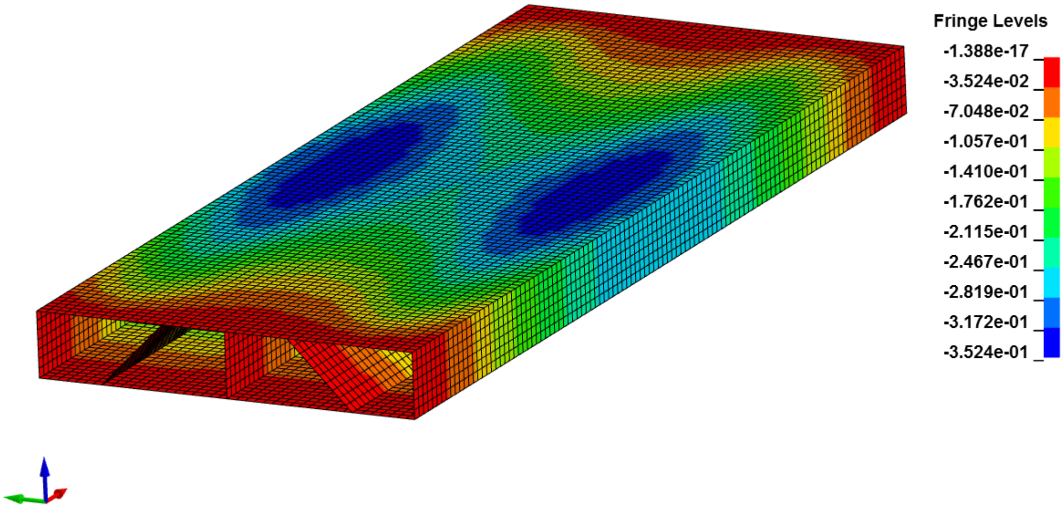


Figure 4.16 Vertical Displacement Contours in Alternative Configuration 2

Table 4.2 Comparison of Potential Designs to the Original Wood Panel.

Configuration and Material Type	Maximum Effective Stress (MPa)	Maximum Deflection (mm)	Mass (kg)	Factor of Saftey
Wood	9.7	7.33	2.94	5.88
Configuration 1 (Aluminum)	49.75	0.38	2.75	5.54
Configuration 2 (Aluminum)	45.5	0.33	2.63	6.07

Table 4.3 Optimization of Wall Thickness for Configuration 2

Wall Thickness (mm)	Maximum Effective Stress (Mpa)	Maximum Deflection (mm)	Factor of Saftey	Mass
2.5	53.52	0.41	5.15	2.19
2.6	51.68	0.39	5.34	2.28
2.7	49.90	0.38	5.62	2.36
2.8	48.28	0.36	5.72	2.45
2.9	**46.8**	**0.35**	**5.89**	**2.54**

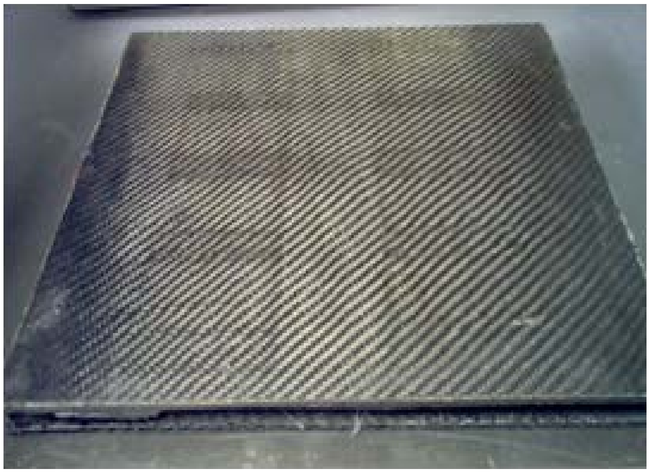
4.4 Alternative Design Configurations for Floor Assemby

Composite sandwich designs are effective for resisting bending loads with the potential for weight saving capabilities. The concept of incorporating extruded sections as a core material was motivated by the bonding quandary between composite and metal sections, the joining challenge to eliminate bolting and fastening methods, and a method to provide a lightweight, strong, and low cost way to produce a structurally sound and easily manufactured panel design. In this study, aluminum extrusions tubes as the load bearing component. The height of the tubes will be kept at 0.10 m so that the total height of the floor will be the same as in the current design. The aluminum tubes core is enclosed by composite face plates. Additionally, paper honeycomb, ribbed sections were used as a filler between the core members. Such a sandwich composite which implements a core structure enhances the bending stiffness and the geometry of the face plate creates a joining solution between the metal core and composite face plates. Two alternatives for the composite face plates are considered:

1. Fiber glass Composite face plate and this design will be called "FIBERPLATE".

2. Carbon fiber Composite face plate and this design will be called "CARBONPLATE".

FIBERPLATE



CARBONPLATE

Figure 4.17 Sandwich Panel Design Configurations for Trailer Floor.

To further illustrate the concept, 1:4 scaled models of structural design concepts for floor assemblies have been developed and prototyped as shown in Figure 4.17, as a means to predict and understand the actual performance of the new floor design configurations. For this purpose, the scaled models were instrumented, and tested in the laboratory environment, in order to validate the predictions of the theoretical models.

In FIBERPLATE design prototype, the face plates are made of fiber glass composite. The fiberglass and aluminum tube core panel is a complex design that involves ribbed paper honeycomb, sheet aluminum stiffeners, E-glass 18 oz/sq. yd woven fabric, fiber content 52 vol-% and five 19 mm (¾ inch) extruded aluminum tubes. The illustration of the design and basic manufacturing process is depicted in Figure 4.18.

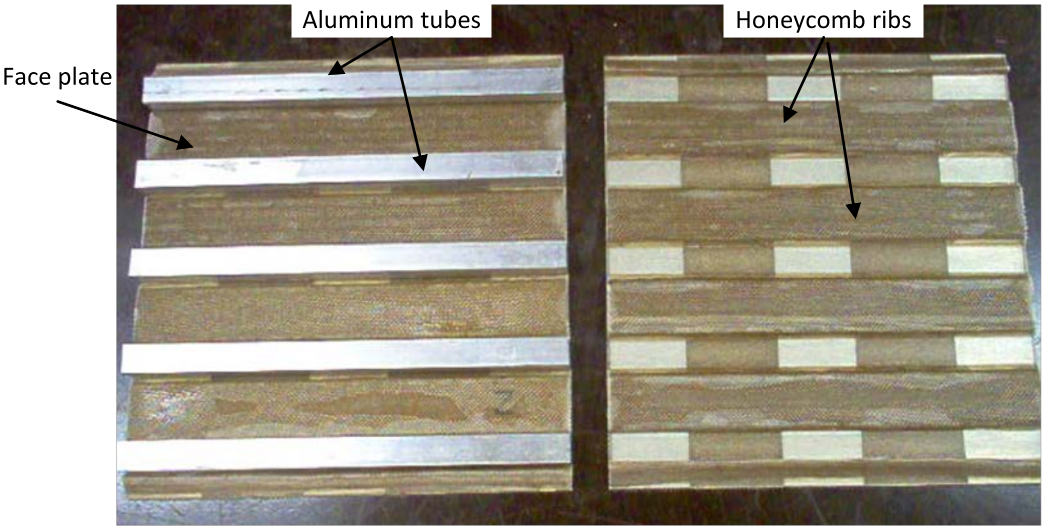


Figure 4.18 FIBERPLATE Design with Aluminum Tube Cross Members, Fiberglass Top and Bottom Face plates, and Paper Honeycomb Rib Stiffeners.

The geometry of the ribbed top and bottom plates is an effective feature to incorporate the extruded aluminum tubes in the core of the panel. The paper honeycomb ribs between the tubes will enclose and secure the positioning of the core cross tube members. The bond or connection between the aluminum tubes and the composite top plate is important for the overall panel bending resistance.

The method of manufacturing required that the top and bottom plates be made separately for two reasons. First, the vacuum bagging technique would not have applied pressure on the on the top surface of the paper rib stiffeners if the plate was completely assembled and then pressurized. Second, the top and bottom edges of the top plate would have not cured in a flat position but would take on a curved shape from the pressurization.

The carbonplate was manufactured in the same manner as the fiberplate except using carbon fiber sheets instead of fiberglass. Also, the carbonplate layup process was done in one single step instead of manufacturing the top and bottom face plates separately. A single phase manufacturing process was intensive and critical for proper alignment of the cross members in relation to the top and bottom face plates. Reinforced foam inserts were placed in the spacing between the core cross members. Pressure was provided from the foam inserts onto the paper honeycomb ribbed sections when the entire panel was vacuum bagged. A release agent was placed on the surfaces between the face plates and core also between the foam inserts and face plates so the parts could be removed after the curing procedure.

The carbon fiber alternative to fiberglass is effective for adding strength and stiffness to the sandwich composite along with weight saving capabilities. The fatigue life of the carbon fiber is superior to that of the fiberglass and is effective for cyclic loading that may occur in structural use of the sandwich composite.

4.5 Testing and Finite Element Modeling

Static loading was performed on each of the test panels to determine the strains occurring at critical locations and the overall displacement that each panel will yield under the testing procedure. Each panel was simply supported along its respective side edges and loaded at its center of the panel with pressure that reaches 0.70 MPa acting upon a 50mm×75mm area as illustrated in Figure 4.19. The experimental results are used to validate the theoretical finite element models. Thus, all the panels were fitted with strain gages as shown in Figure 4.20, to measure that their structural response and at the critical location, to generate reliable data for correlations with the theoretical predictions.

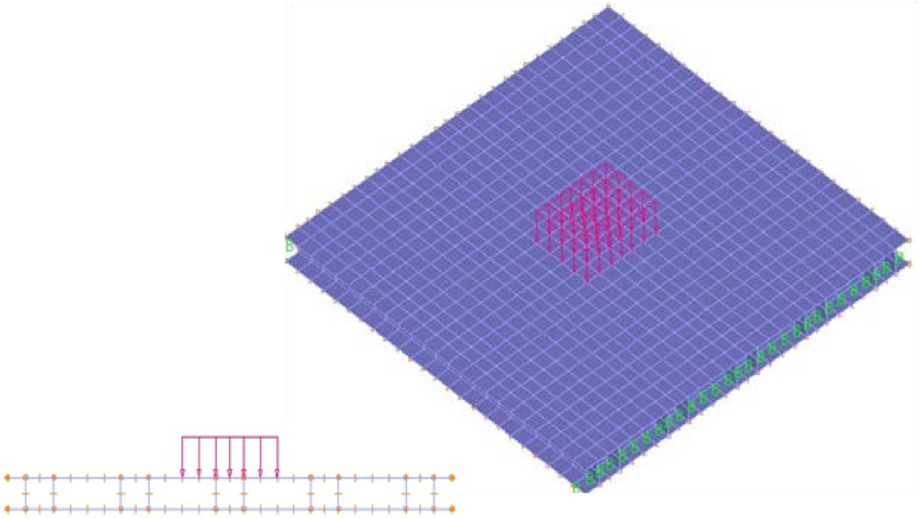


Figure 4.19 Finite Element Model with Cross Section View.

A detailed 3D finite element model was created for the fiberplate panel to most accurately define the panel geometry, materials, and contact characteristics. The face plates were modeled using multilayer shell elements. Figure 4.21 displays a schematic representation of one of the two face sheets used in the sandwich composite panel. The various surface configurations require a detailed finite element modeling process. There are four different subdivisions of material configurations, which represented a complexity in the modeling process.

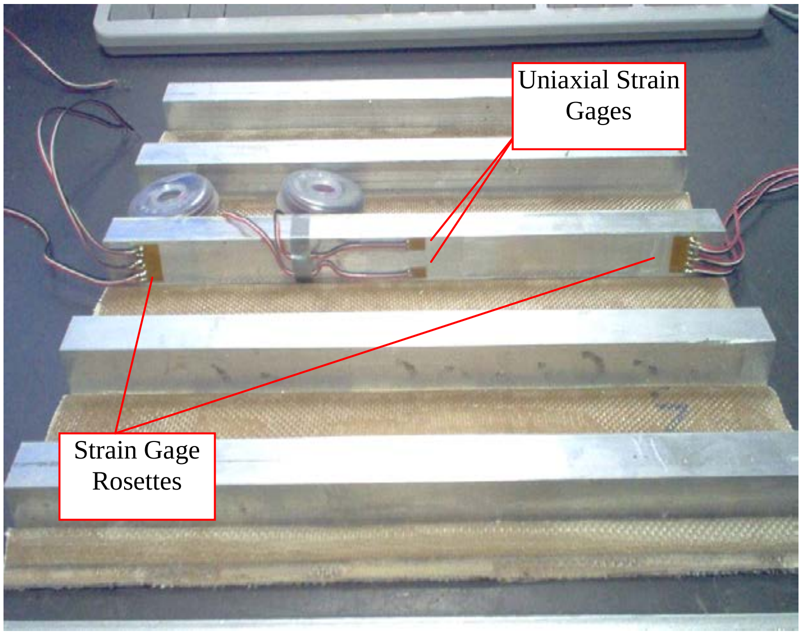


Figure 4.20 Instrumentation of the FIBERPLATE Panel with Uniaxial Strain Gages Centered on the Middle Cross Member and Strain Gage Rosettes along the Cross Member Edges.

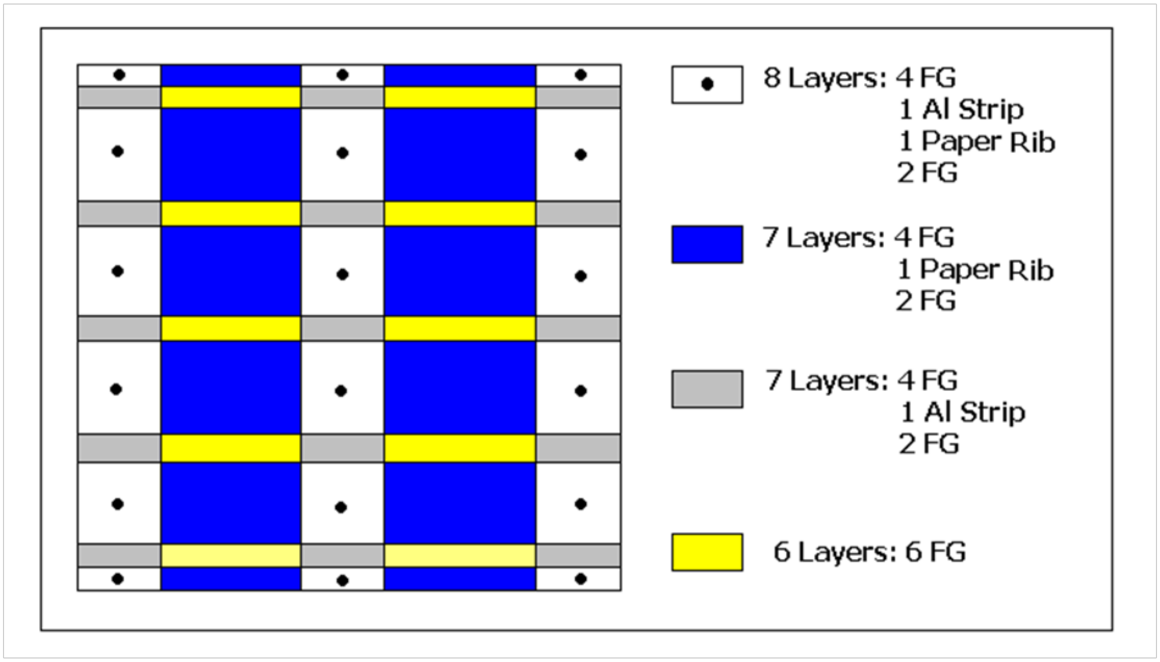
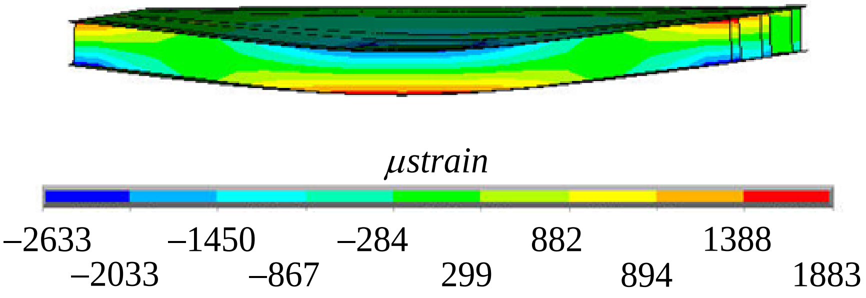


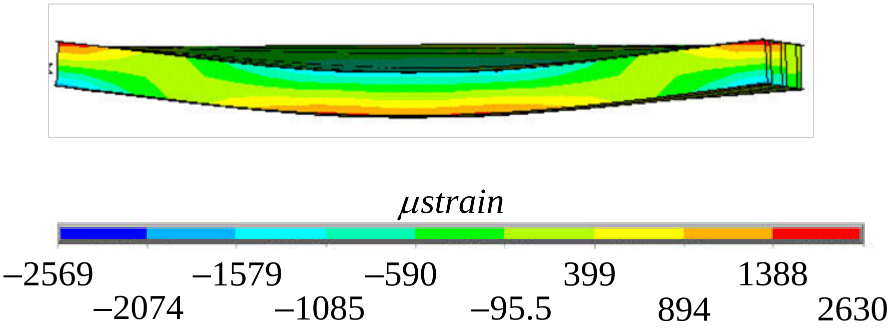
Figure 4.21 Various Layer Configurations for the FIBERPLATE Design.

The prototype contained 5 aluminum tubes 305 mm×19 mm×19 mm with a thickness of 1.6 mm. 50 mm wide, 0.5 mm thick aluminum metal strips were also used between the fiber glass layers and tubes. The aluminum modulus of elasticity E= 68.9 GPa and its Poisson's ratio=0.33. The paper ribs used are 44.5 mm wide and 4 mm thick (E=4.5 GPa and ν=0.3). Six layers of glass/epoxy fabric whose fiber volume fraction is 0.5 were used. The thickness of each layer is 0.635 mm and its density is 1,660 kg/m3 and E11=E22=29.6 GPa, G12=5.3 GPa and ν12=0.17.

Modeling of the carbonplate was performed in the same manner as the fiberplate. The properties of the fiberglass layer were changed to those of twill weave graphite fabric sheets. Each layer thickness is 0.3 mm and the density is 1430 kg/m3 and E11=E22 = 54.5 GPa, G12=4.07 GPa and ν12=0.17.



FIBERPLATE



CARBONPLATE

Figure 4.22 Contours of Uniaxial Strain in Sandwich Panels.

Figure 4.22 shows the contour plots of the uniaxial strains developed in the FIBERPLATE and CARBONPLATE panels as the load is applied. To validate the response of the FE model, the strain values were obtained at the elements corresponding to the locations of the uniaxial strain gages. Table 4.4 shows comparison of the 3DFE-calculated strains and the experimentally measured one. Table 4.4 demonstrates excellent agreement between the 3DFE and experimental results for both FIBERPLATE and CARBONPLATE panels. The difference in the 3DFE-predicted load values and the measured ones is less than 10%. This is a reasonable result taking into account that the experimental errors in material characterization as well as the errors in positioning the strain gages during mounting.

Table 4.4 Maximum Measured and 3DFE-Calculated Uniaxial Strains

	FIBERPLATE			CARBONPLATE		
	3DFE	Measured	Difference	3DFE	Measured	Difference
Top strain	-1050	-1003	4.6%	-1007	-1025	-1.8%
Bottom strain	1003	1069	-6.1%	992	1056	-6%

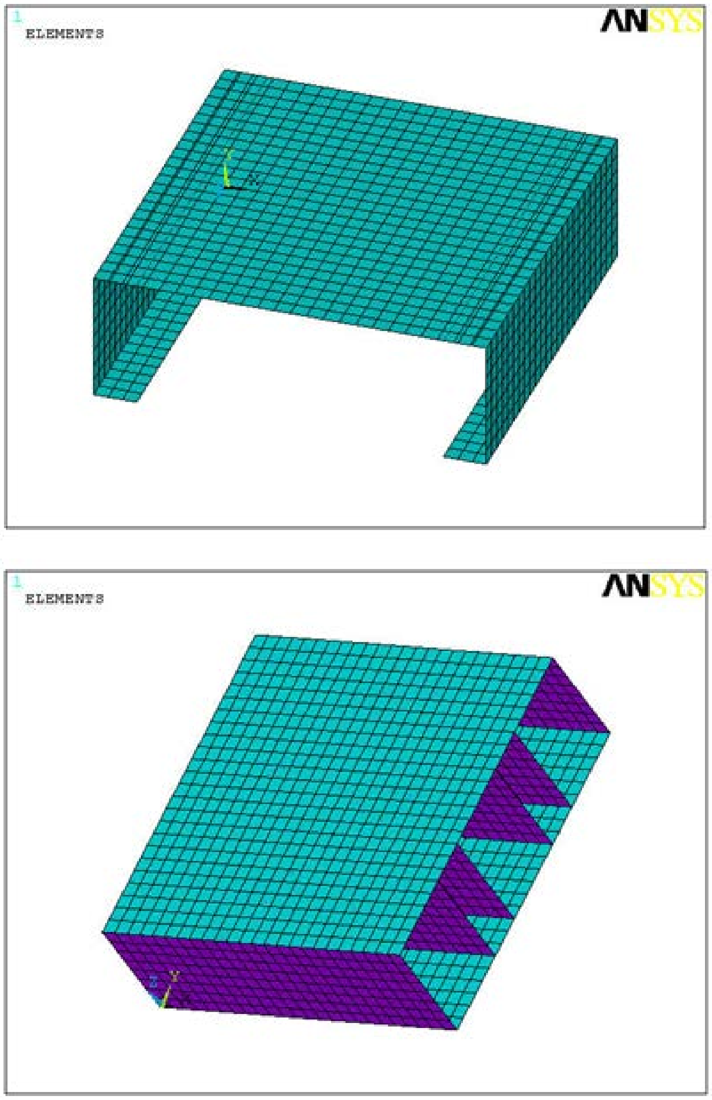
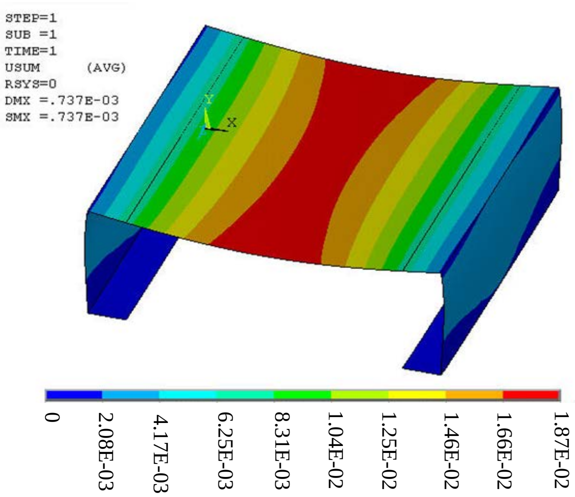
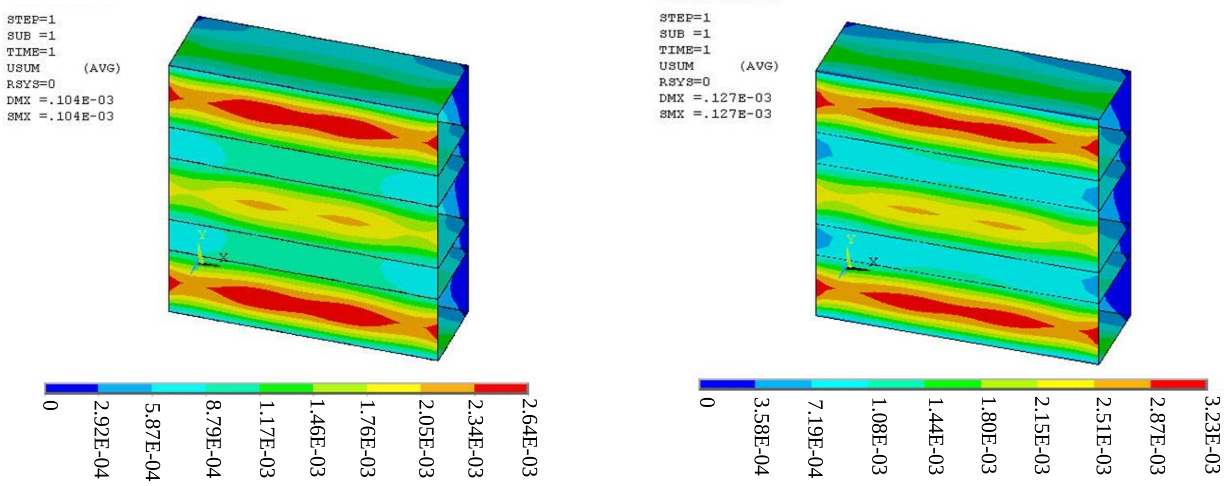


Figure 4.23 Finite element models of the trailer section and the carbonplate/fiberplate

In order to compare the FIBERPLATE and CARBONPLATE designs with the current trailer design, thickness and dimensions of each panel have been increased to create a 0.10 m high cross section thickness and will be noted as fiberplate-4 or carbonplate-4. 3D FE models were created to these two panels as well as to a section of the floor of the existing trailer design as shown in Figure 4.23. The objective of these models is to determine if the maximum displacement and strain values of the sandwich panel will be less than the existing trailer design of 0.10 m high steel I-beams and 35-mm thick solid oak platform. The FE models were subjected to the same distributed pressure and boundary conditions and the displacement and strain fields were obtained.



Existing Trailer Floor



CARBONPLATE-4

FIBERPLATE-4

Figure 4.24 Displacement Contours in Different Design Configurations.

Figure 4.24 illustrates the displacement contour plots for the trailer section and the comparative carbonplate-4 model and Fiberplate-4 models respectively. It is seen that the maximum displacement of trailer section is 1.87E-2 mm. The maximum displacements in the carbonplate-4 and fiberplate-4 are 2.64E-3 mm and 3.23E-3 mm respectively. These values are more than six times less than the maximum displacement of the existing trailer section. Comparing the stress and strain levels reveals that the two new designs would produce stresses that are about one-half of those induced in the current floor design.

The square-meter mass of the carbonplate-4 panel is 34.18 kg. If the I-beams and oak floor were replaced with the carbonplate-4 design, the weight savings per square foot would be 74 kg which correlates to a total of 2,633 kg saved for a 14.63 m (48 ft) trailer haul. This figure can be maximized by creating the panel thickness which exactly matches the displacements and strains of the current existing trailer. However, the estimated cost for this design is \$550/m2, which is about 4.3 folds of the cost of the existing floor design.

The fiberglass design is also an option to replace the existing current floor structure of steel I-beams and solid oak covering. The mass of the fiberplate-4 panel per square meter is 35.2 kg, which is slightly heavier than the carbonplate-4 design. The total weight savings for a 14.63 m long trailer floor using the fiberplate-4 design is 1,465 kg. The cost of the fiberplate design is estimated to be \$120/m^2, which is comparable to the cost of the existing floor design.

The aforementioned weight saving could be translated to fuel saving. Since the operators of long haul heavy trailers usually load them to reach the gross vehicle weight (GVW) in order to maximize the efficiency of every transport, structural weight reductions would not necessarily result in lower fuel consumption of the truck in terms of “kilometer per Liter”. Instead, the associated energy savings are best expressed in terms of fuel used by a heavy vehicle to transport one ton of freight over a certain distance, say 1,000 km. Assuming an average vehicle mass of 30,000 kg corresponding to 75 percent payload, the weight saving will be added as an additional cargo. Table 2 summarizes a comparison between the weight, cost and energy saving achieved by each design alternatives versus the current design configuration.

Table 4.5 Weight and Energy Savings Through Floor Design Concepts

	Mass kg/m^2	Cost \$/m^2	Fuel Used to Transport One Ton of Cargo Over 1000 km (Liter/ton×1000 km)
Current Floor Design	76.23	126.4	20.053 (0%)
Carbonplate-4	34.18	550	18.584 (7.3%)
Fiberplate-4	35.2	120	18.617 (7.1%)

The weight and energy savings for both the carbon fiber and fiberglass designs are extremely significant. The carbon fiber design is superior for weight savings and load bearing capabilities, however, taking into account the slight margin of difference in performance and the cost of carbon fiber to fiberglass, equipping the trailer floors with a lower cost fiberglass design and sacrificing small weight and stiffness penalties may result in the most practical alternative.

4.6 Summary

The carbonplate and fiberplate design is a technology geared toward flooring applications in large trailer systems but can be applied to platforms or load carrying structures. In applications such as the aerospace industry and shipping industry where weight saving is crucial to the performance of the structure, composite sandwich technology with a load-bearing core structure, as shown in this work, is a promising solution. The particular composite sandwich structure studied in this work is revolutionary because it combines a core material which contributes to the bending stiffness as compared to a common sandwich structure with a core material of honeycomb, wood, or foam which does not contribute to bending resistance. The bonding and joining issues of a metallic core and fiber reinforced polymer faceplates has been solved by the combination of panel geometry and adhesive bonding. The application of applying composite material technology to the entire trailer structure has been tested by the manufacturing of a scaled trailer model. The following conclusions can be drawn from this work:

If replacement of the steel I-beams and oak flooring in an existing trailer is not acceptable within the trucking industry, an alternative arrangement of replacing the oak flooring alone with the fiberplate or carbonplate designs will also create respectable weight savings. The one-inch thick cross section panels will serve this design purpose.

The fiberplate and carbonplate designs were created with the objective of designing and manufacturing a sandwich composite structure with a core material that contributes to the bending stiffness. In theory, a sandwich composite is generally composed of a honeycomb, foam, or wood core. These core materials do not contribute to bending resistance. To create this type of design, issues of bonding between the faceplates and core had to be addressed. Developing an interlocking geometry between the core and faceplates assists the adhesive bonding and ultimately strengthens the design. The top and bottom faceplate structures implement a sandwich design between the core cross members by means of paper honeycomb ribbed sections. The ribbed sections serve to provide stiffness at the spaced intervals between the core cross member extrusions.

The composite structures within this work were produced by hand layup techniques. More advanced manufacturing processes can significantly increase the performance of the part and also further increase weight saving capabilities.

Several options for optimizing the design of the fiberplate and carbonplate are available if needed. The comparison of the cross section core members revealed that the tube extrusion is not the most effective for loading applications and replacing this extrusion with a more beneficial design will also increase the performance. Optimization of the carbon fiber and fiberglass layups can also be performed to strengthen the laminate.

5. LIGHTWEIGHTING TECHNOLOGIES FOR AIR CARGO CONTAINERS

5.1 Motivation

In the preceding chapters, it was shown that a reduction of about 50% in the structural weight of a 48 ft long heavy trailer will reduce by about 6% the fuel consumption of the vehicle. However, operators of long-haul highway transportation systems are expected to load always their vehicles up to the maximum allowable gross weight (for example 80,000 pounds), so that any reduction in the structural weight of vehicle is likely to result in the transportation of heavier cargo loads for the same amount of fuel consumption. Assuming that a typical long-haul vehicle travels, on average, 100,000 miles per year, a reduction of 3,250 pounds for example, in the empty weight of the vehicle would translate into an annual saving of 350,000 gallons of fuel for every1000 tons of freight cargo transported by that vehicle during the year.

Since most freight loads are usually transported within cargo containers that can be moved easily from one type of vehicle to another and can be loaded or unloaded expediently, energy savings similar to those described above can be achieved by reducing the structural weight of such containers. Therefore, the benefits of using lightweight composite materials for the manufacturing of cargo containers are equivalent to those associated with corresponding weight reductions in any structural component of the vehicle itself. The main objective of this sextion is to investigate the technical and economic feasibility of expanding the alternate manufacturing and assembly methods that were developed for vehicles structures to cargo containers.

The overall purpose is to devise innovative, lightweight design and joining concepts for air cargo containers that would allow for energy saving in transport sector. For this purpose, innovative design and assembly concepts of lightweight design configurations of air cargo containers have been developed through the applications of lightweight composite sandwich structures. A 1 to 6 scaled model prototype of a typical air cargo container was built to assess the technical feasibility and economic viability of creating such a container from fiber-reinforced polymer (FRP) composite materials as well as lightweight paper honeycomb and therefore using innovative bonding methods to join the design parts. This portion of work focused on using the process of designing and fabricating the model to have first-hand knowledge and experience on what bonding methods are possible and what types of materials and structures will optimize strength and weight saving characteristics. The new design concepts for structural weight savings are being refined, evaluated and validated from the standpoint of their manufacturing feasibility at reasonable levels of cost and quality control.

5.2 Current State of Air Cargo Containers

Air cargo containers are used to load luggage, freight, and mail on various types of aircrafts. Each container, also known as unit load device (ULD) allows a large quantity of cargo to be bundled into a single unit (Aircargoworld *2013*). The International Air Transport Association (IATA) reported that there were approximately one million united loading devices in commercial service in 2008, at an asset value of $1.3 billion (Roongrat *et al. 2008*). The current containers are closed containers made of aluminum or combination of aluminum (frame) and Lexan (walls). About 90 percent of freight loads are transported within cargo containers that can be moved easily from one type of vehicle to another and can be loaded or unloaded expediently. Fuel cost is the largest contributor to the total cost of ownership of an air cargo container. Therefore, a better fuel economy could be achieved by reducing the structural weight of such containers.

It is expected that the worldwide freighter to almost double in the next 20 years (Aircargoworld 2013). Global airfreight traffic will grow by an average of 4.8 percent annually over the next 20 years. This projected growth is driven by positive global trends in economic activity, including world trade, private consumption and industrial production (Aircargoworld 2013). As a result, developing lighterweight air cago containers that will reduce the fuel cost and greenhouse gas emission is becoming more essential.

This Chapter aims at extending the lightweighting concepts developed at West Virginia University for heavy duty vehicles and described at the preceding chapters to be applied for air cargo containers. The work also aimed at providing quantitative measurements of physical, structural, cost and performance characteristics of the scaled models of lightweight cargo containers and floor pans, as compared to the similar models of the currently used corresponding structures.

5.3 Prototyping

A prototype of an air cargo was constructed at a 1 to 6 scale. The main purpose of building a solid model is to explore the potential benefits and drawbacks of various joining configurations and sandwich composite implementation. The construction of such a model provides reliable, extensive data for comparative assessments of alternative joining methods and material selection. The manufacturing and close examination of such a scaled model is necessary in order to reduce the cost of tooling and materials that have to be used at a later stage, for producing full-scale prototypes.

The primary design criteria guiding the fabrication of a scaled trailer prototype are the achieving of optimal tradeoffs between structural weight and performance, based on extensive use of lightweight, strong and durable components, connected by fastener-free joints that allow easy assembly and maintenance. This approach has been proved to be cost effective and provide the means to implement high performance advanced sandwich structures into the model design after the initial fabrication process has been completed and studied.

Lightweight, high strength composite sandwich panels were developed and utilized to build the scaled model air cargo prototype. The panel utilizes two epoxy-carbon fiber composite skin plates bonded to a Nomex aramid fiber reinforced honeycomb core. Nomex honeycomb core is an extremely lightweight, high strength and non metallic product manufactured with aramid fiber paper impregnated with a heat resistant phenolic resin. Aramid paper has been used in boat hulls, auto racing bodies and military shelters. This core was selected based on a survey of various available core materials as it offers a unique combination of properties incluing:

- High strength to weight ratio
- High toughness
- Corrosion resistance
- Good fatigue and impact resistance
- Fire resistant (self-extinguishing)
- Good dielectric properties
- Good thermal stability
- Good formability for curve forming
- Good thermal and electrical insulating properties

Figure 5.1 shows a part of the Nomex honeycomb core utilized in the base of the scaled model.

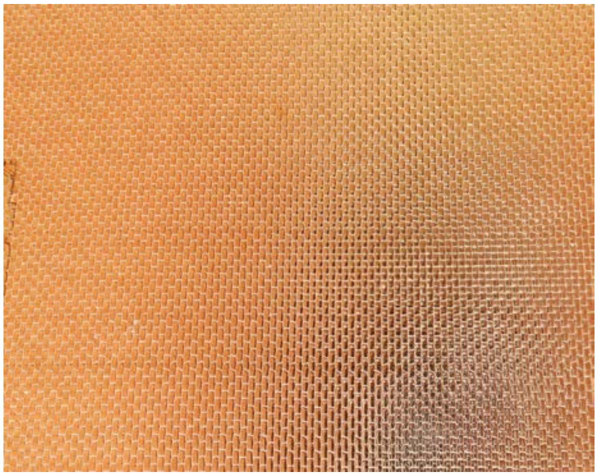


Figure 5.1 Nomex Honeycomb Core Used in Prototyping.

Figure 5.2 Sidewall of the Scaled Model.

The side walls of the prototype were made as a thin epoxy-carbon fiber composite laminate, however they could be also made of sandwich composite similar to the base as illustrated in Figure 5.2. The two sides were made flanged as shown in order to be clamped to the main side wall for the ease of assembly. The assembled sides of the scaled model are shown in Figure 5.3.

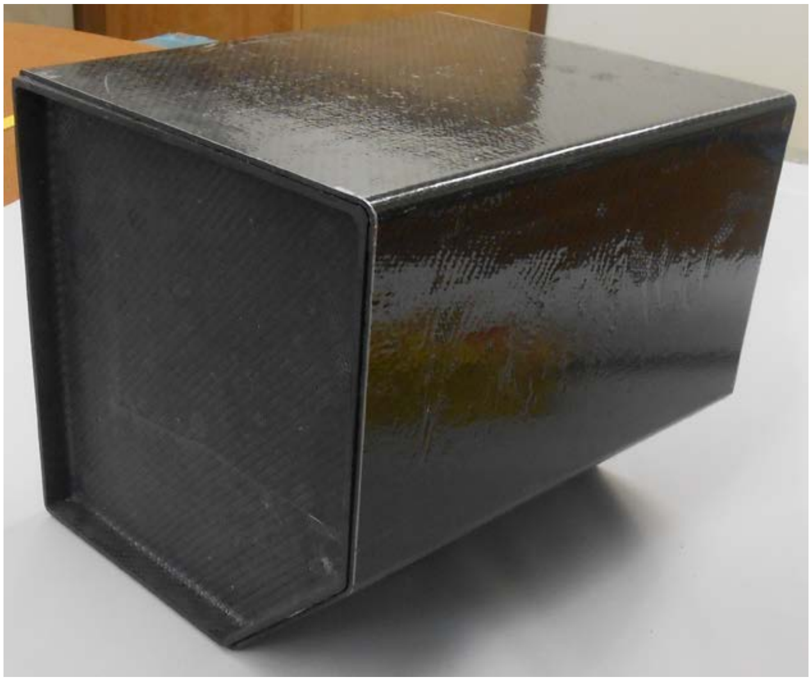


Figure 5.3 Full Scaled Model of Air Cargo Container

The building of the prototype model was performed in distinctive phases in order to allow continual assessment of the feasibility, potential advantages and disadvantages of different design configurations. Phasing of the fabrication process allowed incremental improvements in the design and fabrication concepts. The first phase was the construction of the base of the container using the lightweight sandwich panel. The process of fabricating this section progressed into the side walls and provided an effective method to culminate the full model design.

The side panels have been bonded to the base through the flanged edges in order to secure the integrity of such joints. Furthermore, this approach would allow structural flexibility and effectively absorb typical static, thermal, and dynamic forces associated with typical loading scenarios.However, other mechanical joining options by clipping were investigated in order to make the container collapsible as needed for more flexibility.

The new design is expected to lower the structural weight of the cargo containers from 83 kg for a typical aluminum container to about 55 kg, which represents a weight reduction of 34 percent. According to CargoComposites (2013), it costs approximately $134 USD per year to fly 1 kg. This would achieve significant savings in fuel cost that would recover any additional cost in the original container price.

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6. CONCLUSIONS

The work presented in this report summarizes the current state-of-the-art in reducing the structural weight of heavy-duty vehicles and its contribution to increase the fuel efficiency and reduce green gas emissions. Finite-element stress analyses were performed on the chassis assembly of a Great Dane P-Series Heavy-Trailer. In the current trailer configurations, floor assembly constitutes 70% of the overall weight. Based on the available lightweighting technologies searched, several alternative structural arrangements for the floor of a heavy van trailer have been devised and analyzed within the scope of this study. The results indicated that sandwich panels allow minimum weight designs for a variety of core configurations. Based on the finite element analysis of such design alternatives as well as the baseline steel design, the following conclusions could be made:

Alternative material selections have been considered for the structural floor of a heavy van trailer, leading to the conclusion that sandwich composites enable the largest weight savings, depending on the specific floor design configuration.

The predicted energy savings enabled by the lightweight floor design and joining configurations of a typical van trailer were estimated. Although these numbers appear to be small for transporting one ton of cargo, they become enormously significant considering the thousands of freight loads that any given trailer is likely to haul during its life in service.

The carbonplate and fiberplate design is a technology geared toward flooring applications in large trailer systems but can be applied to platforms or load carrying structures. In applications such as the aerospace industry and shipping industry where weight saving is crucial to the performance of the structure, composite sandwich technology with a load-bearing core structure, as shown in this work, is a promising solution.

The particular composite sandwich structure studied in this work is revolutionary because it combines a core material which contributes to the bending stiffness as compared to a common sandwich structure with a core material of honeycomb, wood, or foam which does not contribute to bending resistance. The bonding and joining issues of a metallic core and fiber reinforced polymer faceplates has been solved by the combination of panel geometry and adhesive bonding.

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