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Building a Lightweight Future for American Transportation

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Abstract

New materials are being sought out to replace steel in conventional American vehicles as a way to increase fuel efficiency. Carbon fiber composites are lightweight materials that could replace steel without decreasing strength or safety of a vehicle. These new composites have the possibility of reducing carbon dioxide emissions and increasing overall efficiency of a vehicle throughout its lifetime. Carbon fiber production has the potential to be less carbon intensive than steel production, and it could increase the efficiency of a manufacturing plant due to its compactness and to new technology. Fuel efficiency can be improved by using many techniques to reduce the weight of the car and to improve aerodynamic properties. Increased efficiency leads to less carbon dioxide emissions during the use of the vehicles, which accounts for a huge portion of the carbon dioxide emissions in the United States. Current barriers to implementation of carbon fiber in passenger vehicles include safety and cost. The carbon fiber prototypes were found to be safe in terms of side wind resistance due to its aerodynamic shape and also good in impacts. Carbon fiber is a new technology and still fairly costly, but it definitely has the potential to be cost competitive with steel in the future.

Introduction

Throughout a vehicle's lifetime, it is manufactured, transported, sold and driven for quite a few thousand miles. There is data available for every vehicle manufactured in the America, and it is proven that overall, the vehicles are not very efficient with energy use. But, by changing the norm of manufacturing, the efficiency could significantly increase. Steel has always been thought of as a superior material in the automobile industry, but rising gasoline prices, oil independence, and global warming has left Americans searching for better methods to build vehicles. One of those methods is using a lightweight material such as carbon fiber to increase the overall efficiency of a vehicle.

Overall efficiency is compared by analyzing the amount of energy used throughout the vehicle's lifetime, from mining the raw materials to driving down the highway. This study includes analyzing the energy and emissions use during manufacturing and during use. The manufacturing process includes the amount of raw material used and the efficiency of the assembly line and production process.

Steel production emits a lot of carbon dioxide, and using alternate materials has the possibility of reducing those emissions significantly. The amount of energy use per an amount of raw material is also important, as the world is searching for new ways to conserve raw materials or reuse and recycle them. Manufacturing vehicles will always have some greenhouse gas emissions, but these can be reduced by making products and processes more efficient in the long run.

Mechanical properties are important to understand how the efficiency of the vehicle can be improved, but cost is also an important consideration in implementation of carbon fiber products. The mechanical properties define how a vehicle can be made lighter and how that affects the fuel efficiency. They are also important to define strength and safety of a vehicle. The benefits of carbon fiber are analyzed in many areas, and these are compared to cost to see if implementation would be effective.

There are a lot of different vehicles available to the American public. The many shapes and sizes produce a wide range of efficiencies and every company has their own unique parts and methods. Throughout the paper, the term vehicle is used in reference to any vehicle of any size and shape. The term car is used in reference to a typical mid-size American car. Most of the numbers given refer to cars rather all vehicles in general.

Building a conventional steel vehicle

65% of a conventional American vehicle is made from steel (Environmental Protection Agency), Steel is made out of iron ore and pure carbon extracted from coal, which are mined from the earth as a raw material. These items are smelted together in a very hot and high energy blast furnace. Almost all out of commission vehicles are recycled according to the EPA, and some of the recycled steel can be melted in with the new steel. A minimum of 25% of all new vehicles are made from recycled steel with different components of the vehicle containing different amounts depending on strength requirements.

129 million tons of steel were produced in Japan which resulted in 184.7 million tons of carbon dioxide emissions (Japan Iron and Steel Federation, 2005). So for every ton of steel produced, 1.4 tons of carbon dioxide is produced, which proves that steel production is not very good for the environment. Similar statistics exist for the United States, but through improving

equipment and operations processes, small energy savings and reduced carbon dioxide emissions occur.

The engine and transmission are made out of cast iron, which is also very heavy metal. It is made through almost the same process as steel and is carbon intensive. The engine accounts for much of the weight of the car besides the frame. Typically an engine is six or eight cylinders of power, with more power from more cylinders. The transmission and drive train enable the driver to switch gears and transfer the power to the wheels. T his is all located under the vehicle frame.

Each individual steel part is rolled or forged into the shape needed for the vehicle. Not all parts of made of steel; a lot of the interior is made from plastics or other lightweight materials. The parts are bolted or welted together through an assembly line at a production plant. According to Dauncey and Patrick (2001), approximately 5.25 tons of carbon dioxide are released in manufacturing a car. This includes the emissions from steel production, electricity use, and all the processes throughout a plant including welding. The assembly line has been updated over time to be as efficient as possible, but much of the process could be reduced in terms of carbon dioxide emissions.

Building a carbon fiber vehicle

Carbon fiber is made from organic polymers like poly. A feedstock like ethanol, hexane, methane or diesel can all be used to make carbon fiber (Rincon, 2007). One of these is injected into a furnace along with a small amount of iron, and the furnace breaks the feedstock down into hydrogen and carbon. The carbon particles will stick to the iron particles and a very tiny fiber is formed. These fibers are wrapped, woven, and pulled on to create greater strength in the particles (Fitzer, 1985). The carbon fiber created from this process results in a fabric mesh. To obtain body panels or engine parts, the fabric is used as reinforcement in a plastic or epoxy mixture.

It is not known how the assembly line process will be changed since carbon fiber vehicles are still only a prototype and have not been produced in mass quantities. Carbon fiber body panels and car parts can be attached to the base frame by snap on plastic connections. These pieces are strong enough to support the weight and make it easy to snap on pieces. So, the process of assembling a vehicle could be a lot shorter with carbon fiber parts, because less manpower and production power would be needed.

Emissions and efficiency of the manufacturing is unclear, but new technology is generally more efficiency. Assembly line changes are less carbon intensive because newer technology is almost always more efficient. GM is designing new plants that use less electricity because they are smaller than conventional plants (Elson, 2003). The assembly lines are more automated and concise and therefore consume less energy.

Carbon fiber reinforced composites (CRFP) use very low raw material and energy consumption compared to conventional metals like steel. Steel uses 6.8 kWh per kg of raw material and CRFP uses 3.7kWh per kg of raw material (Fitzer, 1985). But steel is a lot heavier than CRFP, so when comparing the two on a per volume basis, steel uses 53.6 kWh/L and CRFP uses 5.6 kWh/L (Fitzer, 1985). It is more practical to compare on a volume basis, because the steel parts being replaced on a vehicle would be approximately the same volume as the equivalent carbon fiber part.

Based on the manufacturing process of a carbon fiber vehicle versus a steel vehicle, the carbon fiber composites consume fewer raw materials, and the carbon fiber would reduce emissions because it uses almost 10 times less energy than the steel. A deeper analysis of carbon fiber is needed to understand all the benefits.

Comparison of the Materials

The density of carbon fiber is significantly less than steel which makes it a lot lighter. The density of steel is 490 pounds per cubic foot whereas the density of carbon fiber fabric is 110 pounds per cubic foot. The weight of steel is one of the reasons why it is so strong.

Two of the most important properties of a material to determine its strength are the modulus of elasticity and the tensile strength. Steel is known to be a very strong material which makes it suitable for about any type of structural applications. Steel has a modulus of elasticity of around 200 GPa depending on the exact type. Steel has a tensile strength in the range from 400 to 800 MPa.

Carbon fiber has the possibility to have a maximum modulus of elasticity of 1060 GPa based on the modulus for a graphite crystal. Practicality in testing carbon fiber suggests its modulus of elastic is around 200 to 700 GPa (Fitzer, 1985). Carbon fiber has a tensile strength in the range from 2000 to 5000 MPa. The strength and modulus of steel and carbon fiber are shown in Figure 1 in the appendix.

Carbon fiber has other properties that are advantageous including a low thermal expansion, good fatigue resistance and high corrosion resistance (Fitzer, 1985). These properties of CRFP and steel are shown in Figure 2 in the appendix. Thermal expansion is not of high concern in automobiles, but the other two properties are important. Good fatigue resistance implies that the longer the vehicles are in use, the better the quality the parts will remain throughout its life. Maintenance is needed on all vehicles, but better fatigue resistance may help reduce the cost and frequency of maintenance. Many older vehicles today have rust developing, but since carbon fiber has a very low metallic content, it is very resistant to corrosion.

Carbon fiber has a modulus of elasticity equal to or greater than steel and a tensile strength significantly greater. The strength properties show that carbon fiber has the possibility of being stronger than steel and the density indicates that it is significantly lighter. Although, carbon fiber has a high tensile strength, it is brittle and breaks easily rather than deforming. The properties of carbon fiber play an important role in increasing the efficiency of a vehicle.

Increasing the Efficiency of a Vehicle

The fuel used in vehicles is obviously a very powerful energy source. But a lot of the efficiency of fuel is lost throughout different portions of a vehicle. According to Lovins (2005) in Winning the Oil Endgame, about 85-87% of energy in fuel is lost as heat and noise in the powertrain or in idling. Only about 12-13% of the energy in fuel reaches the wheels of a car while driving, so that energy powers a mass that is 95% car and about 5% driver. When calculating 12% of the fuel used to carry 5% driver, the fuel energy used to move the driver is less than 1% (Lovins, Winning the Oil Endgame, 2005). The whole purpose of having a car is to move the driver, so when less than 1% of fuel is actually used for the purpose, the overall efficiency of a car is very low. When the overall efficiency of a car is increased, the fuel efficiency is also increased, which seems to be the ultimate achievement in today's world of high priced gasoline.

There are many limitations of vehicles that are preventing them from reaching higher efficiencies. There are three main tractive loads that affect the overall efficiency of a vehicle

(Lovins, Winning the Oil Endgame, 2005). First, the shape of the body creates aerodynamic drag on the vehicle. The way that air hits the vehicle can significantly affect how hard the vehicle has to push to overcome the air effects, which decreases the efficiency when the vehicle has to push harder. Even in a perfect design, a vehicle will also have some aerodynamic drag. Second, the rolling resistance of the tires on the pavement is affected mostly by the weight of the vehicle. When the weight of the vehicle pushes down on the tires, the friction between the tire and pavement is greater, which is another resistance that the vehicle has to push harder to overcome. Third, acceleration and braking effort also contribute to reduce efficiently. The faster the acceleration and braking, the more energy that is lost. A larger weight on the drivetrain also inhibits acceleration and braking efforts, so more energy is dissipated from weight as well.

The engine is the power generator in a vehicle. Most of the vehicles today have internal combustion engines. Most engines are run at 8-11% of their total capacity, because the speeds driven produce power that is much lower than the potential power of an internal combustion engine (Lovins, Winning the Oil Endgame, 2005).

The efficiencies of car could be improved by improving aerodynamic drag, rolling resistance, acceleration effort, and the engine. A major factor in improving these is the weight of a car. A key to reducing weight is to reducing the amount of steel in a car, which has a high density. Carbon fiber is almost five times less dense than steel, which implies five times lighter than steel. This substitute would provide significant weight improvements to a car. Reducing the weight in the car implies that there is a smaller load to pull, so the size of the engine can be decreased as well as the drivetrain. This further reduces the weight of the car. An analysis of carbon fiber is needed to compare durability, safety, and cost, which are important factors that would need to be considered to replace a proven material like steel.

Replacing half of the steel in a car is very feasible. The vehicles weight would be reduced by 60%, and the fuel consumption would be reduced by 30% from just weight alone (Oak Ridge National Laboratory, 2006). Greenhouse gases from this change would be reduced by up to 20%.

Hybrid cars are another possibility to increase efficiency in cars. They do so by overcoming the mismatch of the power of the engine and the tractive load by varying the power source: either an electric motor or gasoline. The electric motor boosts power to the engine under acceleration or up-hill climbing, with up to 25% efficiency savings during these times (Lovins, Winning the Oil Endgame, 2005). Then the normal gasoline fuel source is used under normal use.

Implications of Using Carbon Fiber

The biggest concern with having a totally new vehicle design is safety. There is concern over how the material will react in an impact in terms of strength and durability as well as how the lighter weight will react under different conditions.

Carbon fiber is a high strength material, but it is also very brittle due to the high carbon content. An optimally shaped CFRP panel can absorb 10 times as great of an impact as steel because of the way the impact is absorbed through crushing. Metal crumples jerkily, but carbon fiber can crush to dust making it almost 1.5 to 2 times as efficient in the event of a collision (Lovins, Winning the Oil Endgame, 2005). Carbon fiber is lighter, but stronger, and more weight does not imply more safety.

Steel is made almost entirely of raw materials, but due to the fact that CFRP is engineered, it has a lot of opportunity to be safer. Different types of CFRP have been manufactured to have different lengths of crush zones, and these in turn made the car safer in impacts situations (Lovins, Winning the Oil Endgame, 2005). Formula One racecars are fabricated from a high strength CFRP and can withstand an impact at 220 miles per hour safely.

But since carbon fiber weighs a lot less, the effects of a lot less weight need to be analyzed as well. Many SUVs have a high rate of rollover due to wind loads or turning too sharply. With a significantly lighter load, a carbon fiber vehicle would not have as much pushing down on the vehicle, so many of today's car styles would have a higher risk of rollovers. But the solution to that problem is simple: aerodynamics. Aerodynamics was mentioned previously as a way to reduce drag on the car. By designing the car body to have smooth curve up the front, back, and both sides, aerodynamic drag is reduced. As long as there is smooth transition from the sides of the car to the roof, laminar flow will occur from a perpendicular wind load. The problem with wind flowing from side to side of a car is that it the downdrag pulling down on the opposite side of the car may cause it to roll over. A possible solution to this problem is to create turbulent flow once the wind reached the top of the car. A small channel or extrusion running lengthwise with the car would be enough to create turbulent flow (Lovins, Winning the Oil Endgame, 2008). This would protect the car from tipping over during wind loads or during turns.

One safety issue that still needs to be addressed is how the car would perform under an extreme weather event like a tornado or hurricane. It is not safe to be in any car during a tornado or hurricane, so the same would still apply with a lightweight car. Most hurricanes and some of the stronger tornadoes can pick vehicles up and throw them some distance. The same would still apply, only with a higher probability, in a lightweight car. More research needs to be done to analyze the full impact of extreme weather events on lightweight cars to see if they create a significant safety concern.

Saving a pound of weight through lightweight materials costs one to three dollars per pound, but only saves a gallon of gasoline every 12 years, which is ineffective when gasoline prices are low (Lovins, Winning the Oil Endgame, 2005). But since gasoline prices are still continuing to increase, lightweight materials become a more plausible solution. Within the last 30 years, the price of carbon fiber has decreased by over 20 times. So, if this trend continues, as is expected, the price of lightweight cars will be competitive in the near future.

According to Dauncey and Mazza (2001), approximately one pound of carbon dioxide is released per mile in a car that can go 20 miles per gallon of gasoline. If the fuel efficiency of the car was reduced by decreasing the weight by 60%, then carbon dioxide emissions could be reduced by 20%. Coupled with other methods of efficiency savings, 50% of the carbon dioxide emissions could be reduced, which would play a significant role in reducing emissions in the United States.

Implementation Limitations

The government has not supported modifying the American vehicle fleet due to three main reasons: a lightweight vehicle must be unsafe, it would not look stylish, and it would cost a lot more than a typical vehicle. But these stereotypes have proven to be just that: stereotypes. Lightweight fibers have been successfully and safely used in race cars and airplanes due to the strength of carbon fiber. All newer lines of vehicles look more modern and edgy, and the appearance of a carbon fiber body can be very similar to the new lines of vehicles. Also, the cost has the potential to be very competitive with current vehicles in the future.

The two greatest reasons opposing implementation of the carbon fiber cars currently is cost of carbon and ironically the great strength of the material.

Commercial-grade carbon fiber that is used for automobiles is currently around $8 to $10 per pound and steel costs around $.40 per pound. Carbon fiber could be competitive at around $3 to $5 to break even with fuel savings, but would be more effective at $1 to $3 per pound (Oak Ridge National Laboratory, 2000). Boeing currently is manufacturing planes that are made from carbon fiber in 50% of the structural mass (Lovins, Winning the Oil Endgame, 2005). But Boeing can afford to pay up to $100 per pound for the carbon fiber, because it is a civilian aircraft and carries many people during one flight.

JetBlue reported that a 1000 pound lighter load on a 3 hour flight saves approximately $16000 in fuel costs (Associated Press, 2008). This is a significant cost effect in the airline industry, so it would have the potential for cost savings in the automobile industry as well. The only problem is that the upfront cost is greater, and the fuel savings takes longer to cut even as a conventional vehicle.

When a carbon fiber car is hit during a collision, the panels are so strong and brittle that they would crumble instead of crumple like sheet metal does (Lovins, Winning the Oil Endgame, 2005). During a low-force impact, the carbon fiber is almost impossible to break. As demonstrated by Amory Lovins (2008) in his presentation at the University of Nebraska – Lincoln, even when CFRP is hit with a high force with a hammer, it does not dent or break. Carbon fiber has really great tensile strength, but if the panels crush under a large force, there would be the need to completely replace panels in the event of an accident.

Carbon fiber has been used in small amounts in almost all new cars produced in America today and some manufacturers are starting to produce their concept cars with large amounts of carbon fiber. McLaren made a few hundred cars built mostly from carbon fiber, but these are top of the line, top dollar sports cars. BMW has also started producing around a hundred carbon fiber cars a year (Kanellos, 2006). GM and Ford are using carbon fiber in smaller ways like hoods and trunk lids.

Conclusions

The implementation limitations mentioned are current challenges to carbon fiber cars, but they will not be limitations in the future. Just because a car is lightweight, does not mean it is unsafe. Although the cost of carbon fiber is not competitive right now, it has the potential to be so in the near future, and production is ready to begin when the price is right. Carbon dioxide emissions could be significantly cut by carbon fiber cars, and there will also be numerous energy savings as well. Not only will the effects be good for the environment, consumers will also save money with fuel efficiency.

Lightweight does not imply unsafe. Carbon fiber reinforced composites are just as strong as or stronger than steel in terms of tensile strength and the modulus of elasticity. It absorbs an impact more efficiently than steel, which protects the driver and passengers more in a collision. Cars can be more aerodynamically shaped to prevent uplift from wind loads. More intensive research on the safety of carbon fiber needs to be analyzed to reassure any doubts that it is an inadequate material.

The cost of carbon fiber could be competitive within the next few years, and since technology is already being developed to implement carbon fiber into cars, mass production of lightweight cars could be seen in the near future. Carbon fiber has decreased in price by over 20 times within the last few years, so it could be cost effective sooner than later. With new and better processes for creating carbon fiber, it is becoming cheaper to make, and will be cheaper to implement in automobiles.

Using carbon fiber to replace steel in car would save a lot of energy and emissions. Not only reducing the weight, but improving aerodynamics and engine and drivetrain efficiency could result in significant energy and carbon dioxide emissions savings. With a new assembly line process and new automobile plants, the plants would be smaller and consume less electricity. There is also the potential to reduce the number of man hours and machine hours, since carbon fiber reinforced composites are significantly lighter and have different mechanisms to attach them.

The raw materials savings in making carbon fiber are almost ten times as much as steel on a per volume basis, so this is also extremely good for conserving natural resources. Carbon fiber cars also save a lot of raw material in terms of oil savings from increased fuel efficiency. Since most of the greenhouses gases are due to the transportation industry, even a 20% decrease in carbon dioxide would be very beneficial to the environment.

Not only is carbon fiber better for the environment, but individuals will also see cost savings with increased fuel efficiency. By reducing the weight of a car by 60%, there would be at least a 30% decrease in fuel consumption which implies much better fuel mileage. With the high gasoline prices in America, the public is searching for new solutions to the same problem. Through improving aerodynamics, reducing the weigh, and improving the drivetrain in a car, significant increases in efficiency can be made.

Fuel efficiency savings could result in the American public paying half as much as they do for gasoline right now. America's dependency on foreign oil would also decrease if half as much gasoline was used with the United States. Carbon fiber cars have shown promise in the present to be safe and fuel efficient, now the cost of carbon fiber in the future just needs to decrease for these cars to become a new reality for American transportation.

Appendix

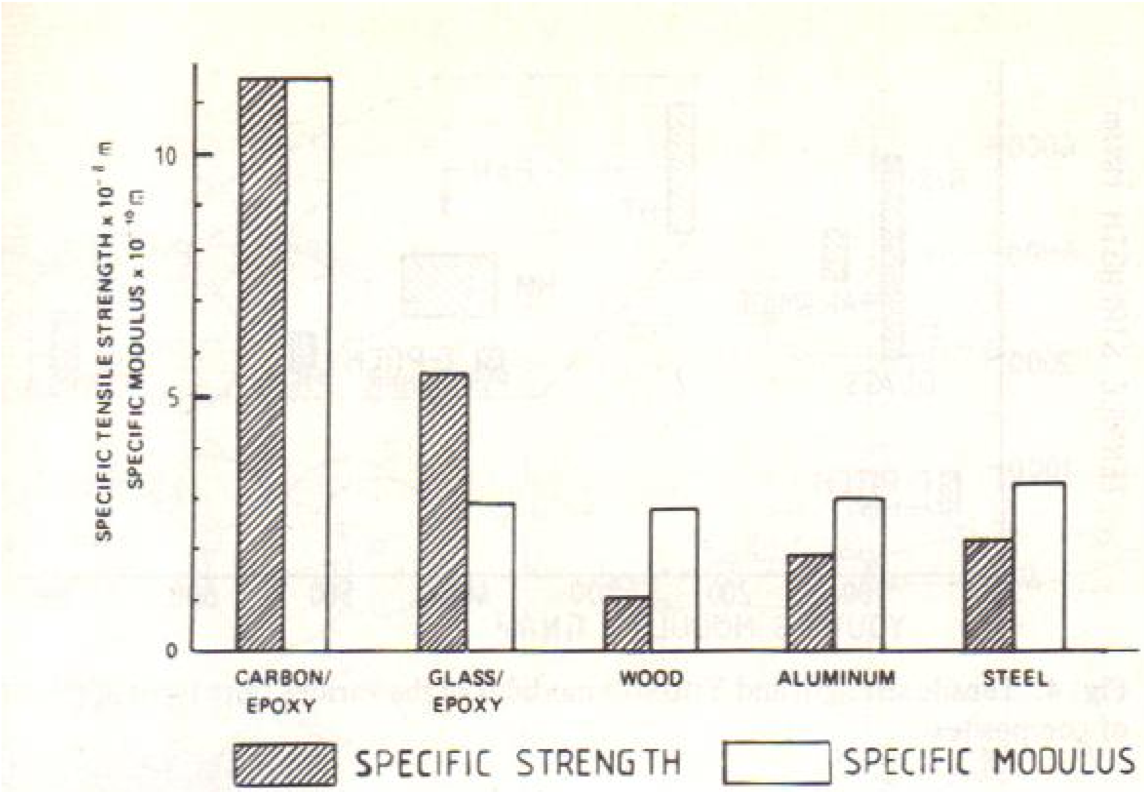

Figure 1. Specific strength and modulus of CFRP in comparison with conventional materials.
(Fitzer, 1985)

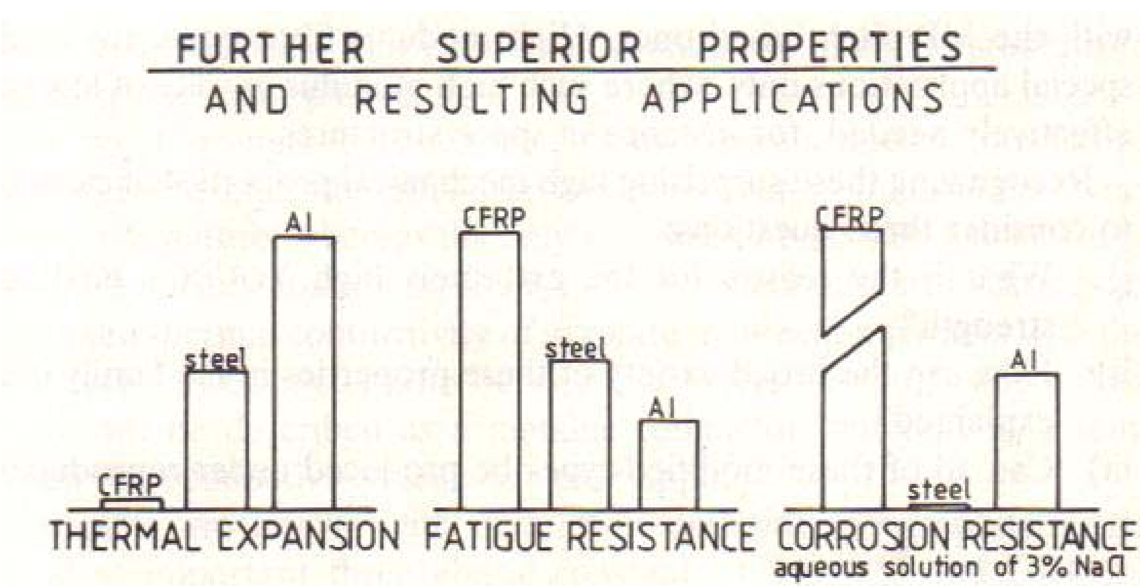

Figure 2. Further advantages properties of advanced composites (CFRP) in contrast to conventional materials.
(Fitzer, 1985)

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