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Multifunctional Carbon Foam Composite Core

by

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Abstract

The purpose of this study was to see if multifunctional attributes such as acoustical absorption, electrical shielding, low thermal conductivity, fire protection and other traits could be built into a single lightweight composite utilizing carbon foam. This study compares the performance of carbon foam core composite panels with other typical composite materials such as balsa, honeycombs, and other foams. Results of test panels utilizing multifunctional carbon foam cores indicate that cost and space savings can be realized when compared to sandwich panels fabricated from multiple single-property materials. Carbon foam cores presented in this study can have compressive strengths ranging from 500 psi up to 3,000 psi and also can be electrical or thermal insulators or conductors, depending on the application requirements. With such a wide range of properties to choose from in a single material, one major question is whether engineers would consider use of multifunctional materials such as this if the core densities are higher than their traditional lightweight cores. Overall, it may be possible to have a totally reduced panel density using such multifunctional materials because of the elimination of one or more of the other materials.

Advanced Composites

The demand in the aerospace industry for lighter materials has facilitated the acceptance of composites for airframe construction. The critical nature of composite aerospace structures requires significant analysis and design of the laminates. The stresses and loads associated with aerospace structures are quite different than marine structures. Now, however, because of the demand for better performance, the marine industry finds itself in a similar situation needing better and more cost-effective material solutions. Advanced composite materials have been making steady inroads into military systems for the last 40 years. As a result of recent requirements for faster and more agile ships, the Navy has been developing and is now starting to use polymer matrix composites in primary and secondary structures. Some examples include lightweight foundations, deckhouses, and masts; machinery components, such as composite piping, valves, centrifugal pumps and heat exchangers; and auxiliary or support items including gratings, stanchions, vent screens, ventilation ducts, and louvers.[i] High strength and weight remain the winning combination that propels composite materials into new arenas, but other properties are also gaining recognition. Composite materials that offer good acoustical absorption, electrical shielding, low thermal conductivity, fire protection, low coefficient of thermal expansion (CTE) and other attractive properties are also being considered by designers. This is being driven by more demanding system requirements for multifunctional materials. Defense-related applications that combine excellent fire properties with those of low weight and radar/electromagnetic shielding and absorption in one low- cost material system have gained increased attention in recent years. These applications have focused on bringing high-volume, low-cost carbon foam into the competitive marketplace as improvements and replacements of current state-of-the-art.

Multifunctional Cores

Currently, there are many sources of composite core materials that are used in various applications. These applications would include aircraft and ship panels and non-structural bulkheads, structural insulation or sound absorption panels, and radar or electromagnetic shielding/absorption panels for ship topside structures. While there are many materials that may offer one or two particular properties that exceed any other material for these applications, it is rare that a single material will provide more than a couple of the requirements. For example, polymer foams, honeycombs (polymer, paper, or metal) or balsa wood exhibits excellent specific strength (high ratio of strength to density). However, if the application is to be fire or chemically resistant, then only metal honeycombs might be selected. However, high cost and corrosion concerns would need to be taken into consideration. Carbon foams may show promise in replacing existing core materials where stringent fire, smoke and toxicity (FST) regulations are not met with other materials. However, these foams typically are more expensive and heavier than other core materials. The question is can multifunctional materials such as carbon foam be the right choice when compared with other composite materials such as balsa, honeycombs, and other foams.

Required Properties

As mentioned above, a designer must know the field of application before any decision is made regarding which material to use. Some of the properties which might be required include low cost, low density, resistance against low / high temperatures, resistance against moisture or chemicals, good formability, easy machining Usually, there is no basic material which serves all purposes, and often there are many proper choices.

Wood

End-grain balsa is still one of the most popular core materials. End-grain balsa with elongated vertical cell structure provides very high compressive stiffness and resistance to crushing. It has a great capacity for handling cyclic loads, and it is possible to obtain very strong skin-to- core bonds. End grain balsa is very cost effective and can withstand high operating temperatures unlike many other foam products. It is a good thermal and acoustic insulator and is easily worked with simple tools and equipment. As a natural material it is susceptible to moisture attack. It will rot if it is not well protected. Another disadvantage is the absorption of large quantities of resin during lamination. Although it can be reduced by pre-sealing, use of balsa is often avoided in weight-critical applications.

Honeycombs

Honeycomb cores are also available in various materials for different applications. They range from cheap cardboard honeycombs to aramid and aluminum honeycombs. All types are supplied in a different densities, thicknesses and cell-diameters and shapes. Nomex and aluminum honeycombs are often used in high-temperature applications where cheap foams are not suitable. Honeycombs are formable and can be used in vaulted structures but not in structures where a variable core thickness is required. Due to the open-cell structure, there are some difficulties when used in liquid resin manufacturing which can be partly avoided by filling the cells with foam.

Nomex honeycomb is made from Nomex paper - a form of paper based on aramid fiber rather than cellulose fibers. Nomex honeycomb is widely used in airspace applications but is primarily used in other applications due to its high mechanical properties. Compared with other core materials, it is expensive.

Aluminum honeycomb is cheaper than the Nomex counterpart but offers similar strength and stiffness. In marine applications and in laminates with carbon skins, it must be used with care due to corrosion problems. Because of the difficulty to achieve good core-skin bonds, high quality resins should be used to avoid delamination.

Thermoplastic honeycombs usually have low densities but also low stiffness. Some of the often used polymers are ABS, Polycarbonate, Polypropylene and Polyethylene. They are resistant against many chemicals and are not affected by moisture. The main problem is getting a good bond layer between the core and the skin.

Foams

Foams are manufactured from a variety of polymers and other precursors. These foams can be supplied in various densities. Because of the great variety, foams can used in a variety of applications. They are especially appropriate for constructions with complex core surfaces. Some foams can be applied as a liquid material into a mold, where it expands and cures. Foams are often supplied with a resin coating. This improves the thermal stability. If prepregs are used, the absorption of liquid resin during lamination can be reduced. Nevertheless, if thermal stability is required, balsa wood, honeycombs or carbon foams should be preferred.

Polyvinyl Chloride Foams (PVC) are widely used in high-performance sandwich structures. They have good static and dynamic properties, a large operating temperature range and are resistant against many chemicals. Two different types of PVC foams are available: crosslinked and uncrosslinked foams. The crosslinked foams are harder and stiffer, while the uncrosslinked types are tougher and more flexible. A new type, toughened PVC foams, is a combination of crosslinked and uncrosslinked PVC.

Polystyrene Foams (PS) are cheap foams with low physical properties. They are often used in sporting goods. Because they are dissolved by styrene, they cannot be used with polyester resin.

Polyurethane Foams (PU) can be used for lightly loaded sandwich constructions and thermal insulation. They have moderate properties. One problem with PU is that the bonding foam-skin deteriorates with age.

Polyetherimide Foams (PEI) are relatively new. They have outstanding fire performance and can be used over a wide temperature range. They are expensive but highly suitable for applications in aircraft and trains.

Polymethyl Methacrylamide Foams offer superior specific strength and stiffness and can be used with elevated temperature curing prepregs due to their high thermal stability. However, the high price limits their application to aerospace and other high-tech constructions.

Styreneacrylonitrile Foams (SAN) have similar properties like the PVC foams but offer higher elongations and toughness, higher temperature performance and better static properties. In many fields, SAN Foams are replacing the PVC foams.

Carbon Foams are relatively new. They have outstanding fire performance and can be used over a wide temperature range. They are expensive but highly suitable for applications in ships, aircraft and trains. This study will take a look at this material in comparison with other cores.

Carbon Foams

Materials engineers today can select foams made from a wide variety of materials including organic polymers, metals, and ceramics. These foams find widespread use over other material forms based on specific criteria required for the application, such as density, insulating value, selective absorbing properties, or air/liquid flow. Recently, much attention has been focused on carbon and graphite foams due to the unique properties that carbon can offer, such as chemical inertness, use at ultra high temperatures, low coefficient of thermal expansion (CTE), and electrical/thermal conductivity. Carbon foams generally fall into two categories – graphitic or non-graphitic. The graphitic carbon foams offer high thermal and electrical conductivity but considerably lower mechanical strength. The non-graphitic carbon foams are generally stronger, act as thermal insulators, and cost far less to manufacture. To a large extent, the type of carbon foam produced is highly dependent on the precursor material, which may be coal, petroleum or coal tar pitches, highly refined synthetic pitches, or organic resins.

The earliest carbon foams are simply carbonized organic foams or sponges and are currently used as substrates for producing other ceramic or metal foams. Materials are deposited onto the skeleton of these reticulated or "glassy" carbon materials, and then the carbon is removed by heat treatment in an oxidizing atmosphere. These carbon forms tend to be very weak and have limited use beyond the applications mentioned.

Graphitic foams typically are produced from petroleum, coal tar, or synthetic pitches due the ability of these precursors to be converted to the highly ordered graphitic crystal structure during the manufacturing process. Carbon foams produced directly from coals or organic resins generally have crystal structures that are highly amorphous and thus will not form the graphitic structure. Depending on the application, graphitic or carbon foams may be selected due to their vastly different properties. Although the highly graphitic foams offer unique properties such as high thermal and electrical conductivity and low density, they are currently not produced competitively either on a cost or volume basis. As such, currently these foams are best suited for the low volume, high-end applications such as heat exchangers, and thermal management.

Carbon foams made from less expensive precursor materials such as coal or similarly novel materials are currently made on a larger scale and are now competitively priced in such applications as composite core materials, fire and thermal protection, composite tooling, electromagnetic shielding, and radar absorption. To compete in these applications, carbon foam must be produced in large volumes in standard sizes up to 4 ft. wide. Competing materials may be PVC or PMI foams, various honeycombs such as phenolic resin or polypropylene, and various metals and ceramics. In each of these applications, critical characteristics such as weight, mechanical properties, ability to pass fire or smoke toxicity (FST) tests, or CTE may be used to determine that one material is better suited than another

Unique properties of the coal-based carbon foam material include:

- *Precursors*: coal is inexpensive and readily available.
- *Mechanical and Electrical Properties* can be engineered to meet different requirements. The density, compressive strength, and ability to absorb energy can be tailored to meet specific requirements by varying the processing conditions. Materials with densities from <10 lbs/ft^3 to >30 lbs/ft^3 have been produced. Compressive strengths of over 3000 psi have been achieved for high-density foams. Electrical resistivity can be tailored for Low Observable (LO) applications.
- *Low bulk thermal conductivity:* Normally less than 1.0 W/m/K, but there is a potential for heat exchange application by convection (gas flowing across high surface area graphitic ligaments if the foam is converted to graphite through heat treatment).
- *Fire resistance*: once carbonized the foam does not contain a sufficient volatile material with which to support combustion and produces no noxious or hazardous fumes when heated.
- *Integration with other materials*: examples include impregnation with phenolic or other resins and lamination with aramid fiber tape. Attaching fiber-reinforced polymer or metallic face sheets allows joining to other components by more conventional methods, protects the foam from localized damage or abrasive wear, and transfers loads uniformly to the foam.
- *Machinability*: can be machined into complex surfaces and joints.
- *Formability*: foam assumes shape of mold in batch operation.

Carbon Foam/Balsa for Ship Panels

Balsa has been the standard core for naval vessels. This is primarily due to its ability to provide very high compressive stiffness and resistance to crushing. It has a great capacity for handling cyclic loads, and it is possible to obtain very strong skin to core bonds.

Unlike balsa, carbon foam is electrically conductive. This can be a very interesting benefit for electrical shielding. These properties are suitable for naval and other military applications. The question is whether a carbon foam multi-functional panel will increase stiffness, reduce weight, and be a more reliable and reproducible system compared to the current panel configuration. Will the panel be less complex than the current system, which leads to easier fabrication and assembly? Will the EMI performance of a carbon foam panel be more reliable and have less risk for damage?

EMI Shielding

Carbon foam has a high electrical conductivity enabling it to be used as an effective EMI shield. The results of EMI shielding effectiveness testing are shown in Figure 1. The test was performed on a ½" thick, joined panel in a reverberation chamber in the frequency range of 400MHz-18GHz. A ½" thick panel is capable of shielding greater than 60dB for the entire frequency range, as illustrated in the figure. The two curves represent carbon foam and a solid aluminum plate. The tested carbon foam panel proved to be equivalent to the aluminum plate in terms of EMI-shielding effectiveness.

Lightning Protection

Carbon foam was attached to an arch wire which transferred an electrical charge of 200 kA and 8 KV to simulate a lightning hit. The high surface conductivity of the carbon foam core allowed it to withstand a lightning strike by carrying the current to ground, as seen in Figure 2. This unique ability to carry energy is an enabling feature that could be very useful to a designer.

Corrosion

Unlike metals, carbon foams will not corrode in a salt-water atmosphere, have a very low galvanic activity, and have been tested in a salt fog chamber according to ASTM B 117. The results show no change in physical properties after a 3,072-hour exposure to salt fog, which demonstrates stability in a corrosive environment. Metals, even those with protective coatings, show severe corrosion after exposure to salt fog, thus creating a maintenance burden when used in many applications.

Mold Growth

Carbon foam was tested in accordance with ASTM D 3273, Standard Test Method for Resistance to Growth of Mold on the Surface of Interior Coatings in an Environmental Chamber. The results show that it does not support mold growth, and the ASTM rating for mold growth after a four-week exposure is zero.

Fire, Smoke & Toxicity (FS&T)

Coal-based carbon foams have been tested for ISO 1182 Non-Combustible, ASTM E 162 Low Flame Spread, and ASTM E1354 Cone Calorimeter. The material passed ISO 1182 fire testing and met Underwriter Requirements for commercial and international marine applications. It also passed ASTM E 162. It received the highest rating possible, with a flame spread index of one. Figure 3 shows the cone calorimeter test setup. It also underwent no ignition (NI) when exposed to successive heat fluxes from 25-100 kW/m^2; therefore, no heat release, ignition or smoke was detectable.

Flexural Strength

Three- and 4-point bending tests were done in accordance with ASTM C393, "Standard Test Method for Flexural Properties of Sandwich Constructions." The tests are performed in order to quantify how much the carbon foam composite core will bend when in a beam configuration. The samples are simply supported beams of 10"x2"x1" with an applied mid-span load (3 Point) or an applied quarter point load (4 Point).

A 4-point bending test (see Figures 4 & 5) was done in accordance with ASTM C393 on a 1" thick balsa core, and a 1" thick carbon foam /E-glass/balsa core (2 layers - 1/4" balsa, 2 layers - 10mil E-glass, and 1 layer - ½" carbon foam of 17 lb/cu ft). Each sample was 1"x2"x10" with a load span of 4 inches and a support span of 8 inches. Four-point bending was chosen because the loading causes shear failures, and shear strength, modulus and stiffness can be calculated. Figure 6 shows the results of the test: a load-versus-displacement curve comparing the two systems. The carbon foam composite panel withstood over six times more load than the balsa by itself. The change in slope around 175 lbs was caused by delamination, and the subsequent leveling was caused by balsa failure. The sharp drops represent total failure. Mechanical testing of carbon foam/balsa panels are in the initial stages, but will be completed within two months.

The E-glass certainly could have been added to the balsa core and would have shown similar increased shear properties. The point of the comparison is to show that a multifunctional core could meet or exceed the current physical properties of a strong material like balsa. The difference is that he multifunctional carbon foam composite core material is also providing EMI shielding, fire protection, lightning protection, etc.

Fatigue

Testing was done based on ASTM C297, "Standard Test Method for Flatwise Tensile Strength of Sandwich Constructions." The sample preparation of the fatigue samples is the same as the flatwise tensile test (1.94" diameter, 1.5" long cylinders). The samples are bonded to round grips that are pinned in a self-aligning fixture.

Initially, three samples were tested for tensile strength in order to get a baseline for the fatigue tests. The average tensile strength of the samples was 288 psi. The fatigue test is a tensile-tensile fatigue in which the sample is cycled between two tensile loads with a 0.1 ratio. Several stress levels were chosen to run this test. For example, the first test was run at 50% of the ultimate stress level at a 0.1 ratio. The sample was cycled between 424 lb and 42.4 lb at 20Hz (ultimate breaking load of ~ 850 lbs). The sample cycled over 593,000 times before failure occurred. The next sample was run at 40% stress level, thus being cycled between 340 lb and 34 lb at 20Hz. The sample ran for 2,000,000 cycles and did not break. Table 1 shows the results of the initial fatigue testing performed.

Carbon foam can undergo numerous tensile loadings up to a certain percent of its ultimate strength. This study found that the tensile load limit to be approximately 90% of the ultimate strength. Perhaps, the most amazing part of the fatigue testing is that the material shows no degradation in its residual tensile strength after undergoing 2,000,000 cycles at 90% of its ultimate strength. When cycled at stress levels greater than 90% of the ultimate tensile strength, the material fails in less than 100 cycles. Originally, a S-N curve was to be generated that plots cycles to failure versus stress level for carbon foam that will allow designers to better understand not only what types of loads, but how many times those loads can be applied before failure. However, it appears there will not be a defined trend, just an upper limit of how many times it can be cycled at high stress levels.

Coefficient of Thermal Expansion

The coefficient of thermal expansion (CTE) is done in accordance with ASTM E 288. The test is done using a horizontal Anter Dilatometer that records expansion or contraction under various temperatures. Five test specimens were tested from -150°C to 500°C. The average CTE was 5.0 ppm/°C, which is a fairly low, but typical value for carbon foam. In comparison, the CTE of end-grain balsa varies from 1 to 12 ppm/°C, but is typically overshadowed by shrinking and swelling due to moisture changes, not temperature changes.

Water Absorption

The water absorption of coal-based carbon foam was measured in accordance with ASTM C272 – Test Method B, "Elevated Temperature Humidity." Three specimens were tested in a chamber at 160°F and 90% relative humidity for 30 days, and the mass change was recorded. The material gained only 0.5% mass due to the elevated temperature/humidity environment, which may be advantageous over balsa in this regard due to balsa's dimensional instability caused by a high rate of moisture absorption. High moisture content degrades properties of balsa.

Thermal Conductivity

The thermal conductivity measurements were conducted using a Guarded Hotplate method per ASTM E1225. The thermal conductivity of coal-based carbon foam at 25°C is approximately 0.25 W/m-K.

Core Price Comparison

Generally, in higher-end applications performance is the most important consideration when selecting the right core. In today's competitive marketplace, an ever growing determining factor is price. When comparing the price of different cores, engineers will generally look at core pricing per pound or cu. ft. Figure 7 shows a relevant cost comparison of some of the core materials described above.

The real cost associated with selecting a core should include not only the core price but also everything else in the system that could be affected if a multifunctional core is selected. This point was demonstrated on a fire barrier panel used on small aircraft. In general, aircraft designers will not consider higher density cores because of weight limitations. The current core of the panel was much lighter than any carbon foam cores (<3lbs/cu.ft.) and initially didn't appear to be a viable solution because of weight issues. Because of the core temperature limitations, additional thermal and heat protection was necessary for fire protection. The fire and combustibility properties of the carbon foam eliminated the need of glass inserts normally required to protect the core at critical penetrations. Additionally, other protective materials like stainless steel were not needed resulting in a sandwich panel assembly with more than a 30% weight reduction. The reduction in additional assembly time associated with installing the inserts and seals combined with the elimination of unnecessary components because of carbon foam would result in a 10% savings in the panel costs. It is important that all the significant properties of the system are carefully considered and not just the core pricing when designing a product or material system.

Conclusion

The results of this study show that design engineers need to look at the total system requirements before selecting a core material. Weight will always be one of the major criteria for selection; but when the panel or structure requires multifunctionality, a carbon foam core should be given ample consideration. To a large extent, the type of carbon foam produced is highly dependent on the precursor material, which may be coal, petroleum or coal tar pitches, highly refined synthetic pitches, or organic resins. Because of cost, use of carbon foams will be initially limited to high-end applications. Coal-based carbon foams represent an opportunity to significantly reduce costs because of an inexpensive precursor, thus opening the door for this material for higher volume applications.

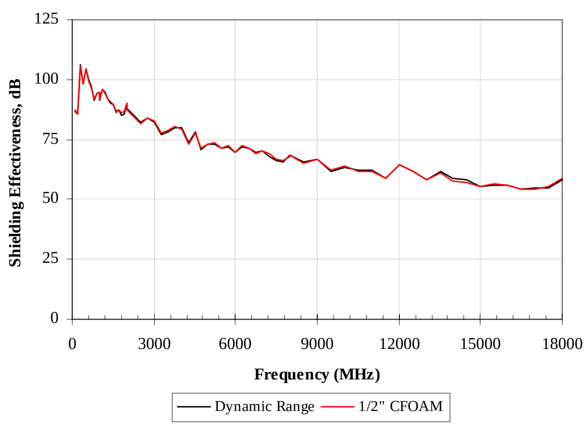


Figure 1 – Carbon Foam EMI Shielding Effectiveness Data

Figure 2 – Lightning Test (EMI Material)

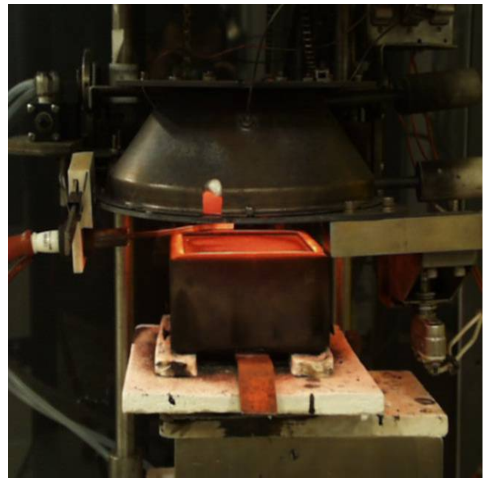


Figure 3 – ASTM E1354 Cone Calorimeter Test

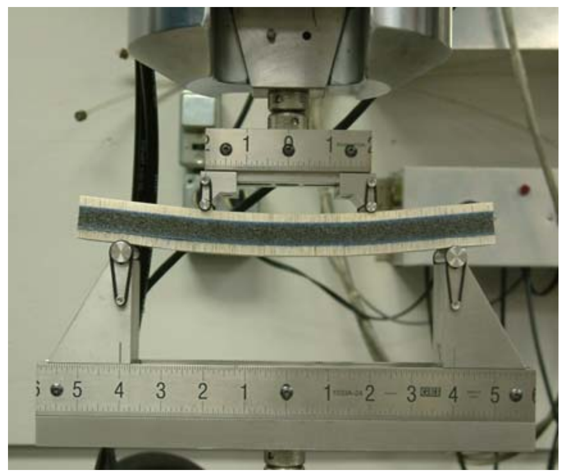


Figure 4 – Carbon Foam/E-Glass/Balsa Core

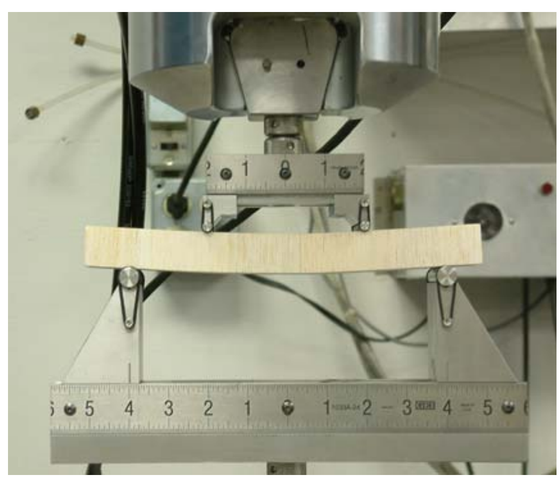
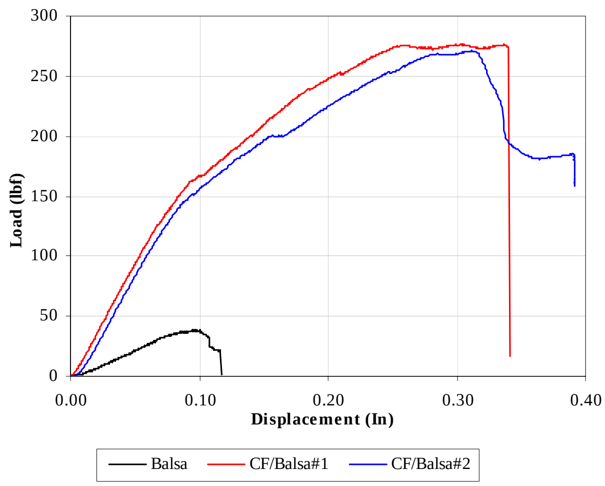


Figure 5 – Balsa Core



Figue 6 – Balsa & Balsa/Carbon Foam Composite – Load vx. Displacement

Table 1 - Fatigue Test Results

% UTS	Stress Level (psi)	Cycles to Failure*	Residual Tensile Strength (psi)
60	173	DNF	276
70	202	DNF	280
80	230	DNF	291
90	259	DNF	292
91	262	13	***
92	265	55	***
100	288	0	***

* DNF samples stopped at 2,000,000 cycles

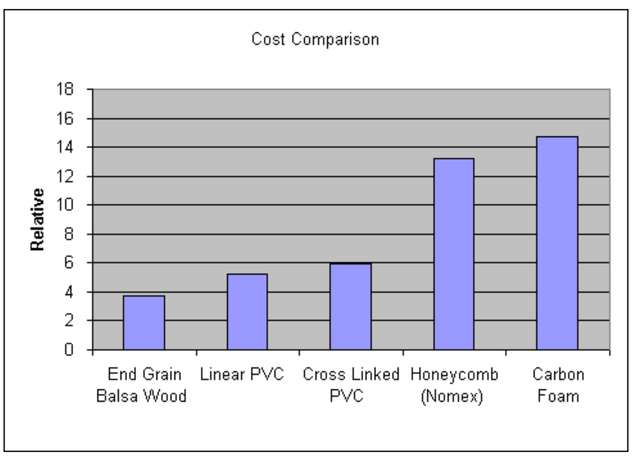


Figure 7 – Core Price Comparison

[i] J.E. Gagorik, J.A. Corrado and R. W. Kornbau, "An Overview of Composite Developments for Naval Surface Combatants," 36th International SAMPE Symposium and Exhibition, Volume 36, April 1991.

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