INVESTIGATIONS ON STRENGTH AND SUSTAINABILITY OF NONMETALLIC LAMINATED COMPOSITE SHIP STRUCTURE

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CERTIFICATE

I hereby certify that, to the best of my knowledge, the thesis entitled ***'Investigations on Strength and Sustainability of Nonmetallic Laminated Composite Ship Structure'*** *is a record of bonafide research carried out by* **Manju Dominic***, Part time research scholar, Reg. No.3955 under my supervision and guidance, as the partial fulfilment of the requirement for the award of PhD degree in the faculty of technology. The results presented in this thesis or parts of it have not been presented for the award of any other degree.*

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ABSTRACT

Composite materials have emerged as a superior structural material having application in all spheres of life. These have applications in every sector and essentially in marine environment, where high strength to weight ratio and noncorrosive nature of the material has great importance. Subsequently there has been a major shift in use of structural materials from steel to composite materials in marine structures. Composite materials are engineered materials made from two or more constituent materials that are combined at a macroscopic level to produce a material with characteristics different from the individual components. When both the matrix and fibre are not of metallic origin, such composites are called as nonmetallic composites. Glass Fibre Reinforced Polymers (GFRP), Carbon Fibre Reinforced Polymers (CFRP) and Aramid Fibre Reinforced Polymers (AFRP) are common nonmetallic composite materials used for marine structural applications. These are used in laminate form in ship hull construction.

In the present study, a design philosophy based on strength and sustainability of composite laminates has been proposed for selection of composites for ship hull construction. For this purpose, an index based on strength of composite laminates and an index based on sustainability of composites has been tabulated and materials need to be selected based on these indices. Both the indices had been constructed as a *composite indicator*. Index based on strength called as ‘Strength Index’ has been developed based on the index values of various strength parameters. Index based on sustainability called as ‘Sustainability index’ has been developed based on the index values of the composites based on the environmental impact of various phases of a ship’s life cycle. Nine non metallic composites have been considered in the present study. Accordingly strength parameters identified are bending strength, buckling strength and impact strength have been found out. Environmental impact during the manufacturing phase and disposal phase of composites has been found out. Based on these index values, indices based on strength and sustainability has been constructed respectively. Based on these indices, ranks have been assigned in such a way that, lower rank corresponds to higher strength and lower environmental impact. This also means lower the rank, higher the acceptability of the composite laminates. Using these two indices a two dimensional assessment of composites has been conducted. In this study both the indices have been superimposed to get strength index versus sustainability index plot. Analysis of this plot is the core of the design philosophy, ‘Design for strength and sustainability’. According to this design philosophy, the composite which has the least strength index and sustainability index rank should be selected for designing so that the structure will be strong and at the same time have a low impact on the environment. This procedure can be extended to any number of composites in the marine area or to composites that has application in other areas.

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NOTATIONS AND ABBREVIATIONS

A	Aramid
AE-F	All Edges-Fixed
AE-SS	All Edges-Simply Supported
AFRP	Aramid Fibre Reinforced Polymer
AFRP-E	Aramid Fibre Reinforced Polymer-Epoxy
AFRP-P	Aramid Fibre Reinforced Polymer-Polyester
AFRP-VE	Aramid Fibre Reinforced Polymer-Vinyl Ester
ASTM	American Society for Testing and Materials
A_f	Total cross-sectional area of fibres in a ply
A_m	Cross-sectional area of matrix in a ply
C	Carbon
CFRC	Carbon Fibre Reinforced Composites
CFRP	Carbon Fibre Reinforced Polymer
CFRP-E	Carbon Fibre Reinforced Polymer-Epoxy
CFRP-P	Carbon Fibre Reinforced Polymer-Polyester
CFRP-VE	Carbon Fibre Reinforced Polymer-Vinyl Ester
CI	*Composite Indicator*
CLPT	Classical Laminated Plate Theory
CO2	Carbon dioxide
DNV	Det Norske Veritas
E	Elastic modulus of the material
ECC	Engineered Cementitious Composites
EU	European Union
E_1	Elastic modulus of laminate in the longitudinal direction
E_2	Elastic modulus of laminate in transverse direction
E_3	Elastic modulus of laminate in ‘z’ direction
E_f	Elastic modulus of fibre
E_m	Elastic modulus of matrix
FEA	Finite Element Analysis

FEM	Finite Element Method
FRP	Fibre Reinforced Polymer
FSDT	First order Shear Deformation Theory
G	Glass
GFRP	Glass Fibre Reinforced Polymer
GFRP-E	Glass Fibre Reinforced Polymer-Epoxy
GFRP-P	Glass Fibre Reinforced Polymer-Polyester
GFRP-VE	Glass Fibre Reinforced Polymer-Vinyl Ester
GNLA	Geometric Nonlinear Analysis
G_{12}	Inplane shear modulus of laminates
G_{23}	Inplane shear modulus of laminates
G_{31}	Inplane shear modulus of laminates
G_f	Shear modulus of fibre
G_m	Shear modulus of matrix
HCF	High Cycle Fatigue
HMS	Her Majesty's Ship
HSwMS	Her Swedish Majesty's Ship
IMO	International Maritime Organization
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LCF	Low Cycle Fatigue
LE-F	Long Edges-Fixed
LE-SS	Long Edges-Simply Supported
$\overline{\overline{N_x}}$	Buckling pressure due to inplane compressive load
P	Polyester
PAN	Poly Acrylo Nitrile
RTM	Resin Transfer Moulding
SE-F	Short Edges-Fixed
SE-SS	Short Edges-Simply Supported
SOLAS	Safety Of Life At Sea
UHMWPE	Ultra High Molecular Weight Poly Ethylene
UN	United Nation

VARI	Vacuum Assisted Resin Infusion
VARTM	Vacuum Assisted Resin Transfer Moulding
VE	Vinyl Ester
V_f	Volume fraction of fibre in a ply
V_m	Volume fraction of matrix in a ply
a	Length of the composite plate
b	Breadth of the composite plate
p	Transverse load
q	Inplane compressive load
wt	Weight
t	Thickness of the plate
w	Deflection
w_{max}	Maximum deflection
ν_{12}	Poisson’s ratio of laminate when inplane load is applied parallel to longitudinal direction
ν_{23}	Poisson’s ratio of laminate when inplane load is applied perpendicular to longitudinal direction
ν_{31}	Poisson’s ratio of laminate when inplane load is applied perpendicular to longitudinal direction
ν_m	Poisson’s ratio of matrix
ν_f	Poisson’s ratio of fibre
λ	Critical buckling pressure due to transverse load
σ_{matf}	Stress at matrix failure
$\sigma_x(max)$	Maximum stresses in the ‘x’ direction
$\sigma_y(max)$	Maximum stresses in the ‘y’ direction
ε_x	Strain at matrix failure in ‘x’ direction
ε_y	Strain at matrix failure in ‘y’ direction

CHAPTER 1

INTRODUCTION

1.1. General

Composite materials have emerged as a superior structural material having application in all spheres of life. They have applications in every sector and essentially in marine environment, where high strength to weight ratio and noncorrosive nature of the material has great importance. Subsequently there has been a major shift in use of structural materials from steel to composite materials in marine structures. Marine composite structures exhibit longer life span, better fatigue strength and less maintenance when compared to their metallic counterparts. Composite materials have also emerged as a cost saving material in recent years.

In the early days composite materials have been used to construct components of marine composite structures. In floating structures, application of composite materials as components vary from the manufacture of superstructures, decks, bulkheads, advanced mast systems, propellers, propulsion shafts, rudders, pipes, valves and machinery on large warships such as frigates, destroyers and aircraft carriers. In sailboats composite materials are used for making wing masts and sail cloths. Later composite materials have been used to construct the hull of floating structures. Some early applications of composites are found in recreational and commercial fields. In recreational field use of composites includes racing powerboats, racing sailboats, canoes and kayaks. In the commercial field, boats build with fibre reinforced polymer are used as lifeboats, buoys and floats, utility vehicles, passenger ferries, deep sea submersibles, navigational aids, fishing vessels, life boats etc. Naval applications in the present day include use of composites in submarines and surface boats.

Among floating structures composite materials are presently used in construction of vessels that cruise through waters that is shallow i.e. depth of water is less than 200m. Such structures that are made of composites are shallow draft cruisers, littorals, patrol vessels, trimarans, corvettes, mine counter measure vessels etc. Some floating structures made of composites are given in Table 1.1.

Table 1.1. Floating structures made of composites

Type of floating structures	**Name of the structure**	**Features**
Littoral combat ships	M80 Stiletto	Length – 27m Made of CFRP
Patrol vessels	FPB 15M	Length – 15m Made of FRP
Trimaran	Tricat 23.5	Length – 7.11m Made of bio composite
Corvettes	Visby Class	Length – 72.7m Made of CFRP

1.2. Relevance of composite materials

Advantages of FRP(Fibre Reinforced Plastic) composite materials over steel and other metals used for the construction of marine structures are high specific strength , high specific stiffness, good fatigue properties, low magnetic properties or high stealth properties, low electrical conductivity (for glass-reinforced plastics), resistance to corrosion, resistance to rot and marine growth, relatively high sonar transparency, maintenance of properties at low temperatures, and manufacturability to near net-shape. The structures made of composites have larger life span and need low maintenance. The life span of steel ships is taken as 20-25 years and that of a composite ship can easily go up to 30 to 35 years. All these advantages make composite material a cost effective material for the construction of marine structures. One of the main advantages of construction using composite materials is the ability to choose the material, laminate and manufacturing method to suit the design requirements. By using composite materials and moulds, complex shapes can be made with high rate of geometric tolerances.

Composites consist of reinforcing fibres and a matrix. The reinforcing fibres give strength to the composites and the matrix made of resin transfer the stresses developed and act as a barrier to corrosion. Cost advantage is high while using composites due to its anticorrosive nature as composites can replace expensive corrosion-resistant metals such as copper-nickel alloys, duplex or super duplex stainless steel or even titanium. Resins in general possess anticorrosive features. Also composite surfaces provide a smooth surface which prevents or reduces the growth of algae and other microorganisms.

Stealth characteristics of composite materials make them a favourite among the sea going vessels in the defence sector. In a mine affected sea, a mine can detect the change in magnetic fields when a vessel move by, which will lead to detonation. Hull material is of great importance to counter act this. Steel is very magnetic and high degaussing energies are required to reduce it’s magnetic signature. GFRP (Glass Fibre Reinforced Plastic) composites have very low magnetic signature and therefore they are used in mine-countermeasure vessels. The shape of the vessel has been designed to reduce radar signature. Metal parts have been covered with radar absorbent material, and the composite parts have radar absorbent material embedded in the structure. Radar transparent materials (kevlar, balsa) have been used in stealth vessels. Unlike glass fibre, carbon fibre blocks radio waves. This protects ship's electronics against electromagnetic pulse. In addition, it stops any radio frequency signals generated by ships electronic devices that try to escape outside. Due to lightweight of composites, the vessels will have higher speed, low displacement and shallow draft.

Tribological features of composites are different from those of metals. The tribological interactions of a solid surface's exposed face with interfacing materials and environment may result in loss of material from the surface. In composites the abrasion resistance performance depends on its bulk and surface properties and the wear mechanisms. Abrasion in nonmetallic composites depends upon the resin and the fibres used. It is found that the abrasive properties of reinforced polymers are better than polymers alone. The wear resistance of epoxy is lower than carbon fibre reinforced epoxy and glass fibre reinforced epoxy. Among the reinforced epoxies, glass fibre reinforced epoxy exhibit better wear resistance than carbon fibre reinforced epoxy. (Vasconcelos et. al., 2004)

Composites provide a smooth surface but it is not hard compared to steel. Therefore composites can abrade in the presence of high loads. Even due to the suspended materials moving with high velocities in a fluid, composites can abrade. Slurries and coarse particulates will also cause abrasion. The wear rate of composites depends on the fibre orientation. When the fibres are normal to the plane of sliding because of the force applied the composites exhibit superior wear resistance. The effect of fibre orientation to wear resistance decreases as the fibre content increases. The wear resistance increases as the fibre content increases in composites (Arivalagan et. al. 2012). Among the three strong reinforcing fibres like glass, carbon and aramid, using aramid as the reinforcing fibre increases the wear resistance properties of composites. (Kukureka et. al., 1999)

1.3. Composite ships and boats

Traditionally steel has been the widely used material for ship construction from nineteenth century. A stronger focus on both energy efficiency and environmental competitiveness and increasing fuel costs have created a large interest world-wide for using lightweight materials in shipbuilding. Lightweight hull construction can be achieved by using composites as construction materials. Use of composite materials will increase the operational efficiency and reduce ownership costs of ships and boats. Operational efficiency is increased due to increased range, stealth, payload and stability. Ownership costs will be reduced due to reduced operational and maintenance cost. Advances in composite materials and manufacturing technology during the recent years have strengthened the trend of increased use of composite materials in hull construction. (Evegren et.al. 2011)

FRP boats were the composite vessels that were built in the initial years of composite construction. Boat builders identified many benefits gained from using composites instead of conventional shipbuilding materials. Such construction being low cost and almost maintenance free received a mass appeal. The fibreglass boatbuilding began after World War II. During the 1960's, the boat building industry found a rapid increase in the number of fibreglass boats. Early FRP boat builders relied on "build and test" methodology or empirical methods to guarantee that the hulls produced by them were strong enough. Later composite mine hunters were constructed extensively for defence applications owing to high strength to weight ratio and low magnetic properties of composites.

The replacement of naval structures, components and machinery made with steel, aluminium alloy and bronze with composites has been a difficult and slow process.

Metals perform extremely well in most applications. Designers, builders and operators have a great deal of confidence in the performance of metals. Thus only applications where composites have the strong potential is where there will be a reduced acquisition and through-life maintenance costs and improved ship stability and performance. (Eric Greene Associates 1999)

Marine vessels can be fully or partially made of composites. In early applications certain parts of superstructure alone or parts was made of composites. When they are fully made of composites, then hull and superstructure are made of composites. When vessels are fully made of composite then the total weight of the vessel gets reduced by 50% than when they are made by steel. The first all-composite mine hunter that plied the seas was the British warship HMS Wilton in 1972 (Mohan 2008). It's length is 47m and was made of GFRP. At present the longest all-composite vessel is HSwMS Helsingborg. It is a Visby class 72.7m long corvette launched in 2009.

1.4. Constituent materials of marine composites

Composite materials are engineered materials made from two or more constituent materials that are combined at a macroscopic level. The constituent materials with significantly different physical or chemical properties, when combined, produce a material with characteristics different from the individual components. The synergy that can be acquired in material properties of composite materials by using a matrix reinforced with fibres over using fibres and matrices alone is main reason for such a construction. FRP's are composite materials which consist of a matrix reinforced with fibres. When both the matrix and fibre are not of metallic origin, such composites are called as non metallic composites. Glass Fibre Reinforced Polymers (GFRP), Carbon Fibre Reinforced Polymers (CFRP) and Aramid Fibre Reinforced Polymers (AFRP) are common non metallic composite materials used for marine structural applications. These are used in laminate form in ship hull construction.

Constituent materials form an integral part in the way composite structures perform. Strength of the composite is defined by the strength of the **reinforcement** used. Different types of reinforcements used in marine construction are Glass fibres, Carbon fibres, Aramid fibres and Ultra High Molecular Weight Poly Ethylene fibres .

Glass fibre reinforcements are made from varying combinations of SiO_2, Al_2O_3, B_2O_3, CaO, or MgO in powder form. These mixtures are then heated through direct melting to temperatures around 1300^0C, after which dies are used to extrude filaments of glass fibre in diameter ranging from 9 to 17 μm. The filaments are then wound into larger threads and spun onto bobbins for transportation and further processing. In the process of roving filaments are spun into larger diameter threads. These threads are then commonly used for woven reinforcing glass fabrics and mats.

E-glass (lime aluminium borosilicate) is the most common glass reinforcement used in marine laminates because of its good strength properties and resistance to water degradation. **S-glass** (silicon dioxide, aluminium and magnesium oxides) exhibits about one third better tensile strength, and in general, demonstrates better fatigue resistance than E-glass. The cost of S-glass fibre is about three to four times that of E-glass fibre. GFRP use glass fibre textile as reinforcement. Fibre fabrics are web-form fabric reinforcing material which has both warp and weft directions. Fibre mats are web-form non-woven mats of glass fibres. Mats are manufactured in cut dimensions with chopped fibres or in continuous mats using continuous fibres. Chopped fibre glass is used in those processes where lengths of glass threads are cut between 3-26 mm. Glass fibre of short strands (0.2–0.3 mm) are used to reinforce thermoplastics made by injection moulding. Glass fibres account for over 90% of the fibres used in reinforced plastics because they are inexpensive to produce and have relatively good strength to weight characteristics. Glass fibres exhibit good chemical resistance, excellent tensile strength and processability.

Carbon fibres are created when Poly Acrylo Nitrile (PAN) fibres, pitch resins, or rayon are carbonized (through oxidation and thermal pyrolysis) at high temperatures. Carbon fibres are manufactured in diameters analogous to glass fibres with diameters ranging from 9 to 17 μm. These fibres are wound into larger threads and are woven or braided into carbon fabrics, cloths and mats that can then be used as reinforcements. These fibres are extremely stiff, strong, and light. Carbon fibres offer the highest strength and stiffness of all commonly used reinforcement fibres. High temperature performance of these fibres is particularly outstanding. Carbon fibres are brittle. Under load carbon fibre bends but will not remain permanently deformed. Instead, carbon fibre will fail suddenly and catastrophically, once the ultimate strength of the material is exceeded, In the design process it is critical that the engineer understand and account for this behaviour, particularly in terms of design safety factors. Carbon fibre creates a unique and beautiful surface finish. The major drawback to the PAN-base fibres is their relative cost, which is a function of energy intensive manufacturing process.

Aramid fibres are most commonly known as Kevlar, Nomex and Technora. Aramids are generally prepared by the reaction between an amine group and a carboxylic acid halide group (aramid). Fibres are then spun into larger threads and are woven into large ropes or woven fabrics. Aramid fibres are manufactured with varying grades based on varying qualities for strength and rigidity, so that these fibres can be tailored to specific design needs concerns.

The predominant aramid fibre Kevlar® was developed by DuPont. The main features of aramid fibres are low weight, high tensile strength and modulus, better impact and fatigue resistance than other fibres and weaveability. Compressive strength performance of aramids is not as good as glass, as they show nonlinear ductile behaviour at low strain values. Two main varieties of aramid fibres are Kevlar® 49 and Kevlar® 149. Water absorption of un-impregnated Kevlar® 49 is greater than other reinforcements and Kevlar® 149 absorbs almost two thirds less than Kevlar® 49. The unique characteristics of aramids can best be exploited if appropriate weave style and handling techniques are used. When glass fibre and carbon fibre fail by brittle cracking, aramid fibres fail by a series of small fibril failures, where the fibrils are molecular strands that make up each aramid fibre and are oriented in the same direction as the fibre itself. These many small failures absorb much energy and, therefore, result in very high toughness. Although impact resistance of glass fibre is more than that of aramid fibre, time taken by aramid fibre for complete failure is more than that of glass fibre. Many aerospace structures use aramids today, for its toughness and impact resistance. In some of these applications, the aramid is used only as a surface layer, with the bulk of the part being made from carbon fibres or glass fibre. These hybrid fibre composites give the protection of aramids but the high specific strength and specific stiffness of carbon fibres or glass fibres. Major disadvantage of aramid fibres is its toughness which makes them extremely difficult to cut.

UHMWPE (Ultra High Molecular Weight Poly Ethylene) fibres have high molecular weight which results in physical properties that are competitive with glass fibres, carbon fibres, and aramids. Sails for world class competition boats now routinely are made from UHMWPE fibres. The resistance to water, light weight, high strength and toughness, and the good resistance to distortion make this material suitable for making sails and marine ropes. The properties of UHMWPE fibres like light weight, ability to float on water, abrasion resistance, and cyclic fatigue resistance give added value to rope applications.

The field of composites gives the designer the freedom to use various reinforcement materials to improve structural performance of the laminate. Fibreglass was the reinforcement commonly used in the early days of composite manufacture in marine industry. Carbon and aramid fibres have evolved as two high strength alternatives in the marine industry. Carbon and aramid fibres are significantly more expensive than glass fibres. (Eric Greene Associates 1999). Carbon has the highest strength and stiffness values; however, it also is the most brittle, with a strain to failure of 0.5 to 2.4%. Glass fibres have a lower strength and stiffness but have a higher strain to failure (~3.2%). The mechanical properties of aramid lie between those of carbon and glass.

Reinforcement Construction also defines the properties of composite laminates. Reinforcement materials are combined with resin systems in a variety of forms to create structural laminates of different strengths.

Woven composite reinforcements generally fall into the category of cloth or woven roving. The cloths are lighter in weight, typically from 202 to 336 grams per square metre and require about 40 to 50 plies to achieve 2.54 centimetre thickness. Their use in marine construction is limited to small components and repairs.

Woven roving reinforcements consist of flattened bundles of continuous strands in a plain weave pattern with slightly more material in the warp direction. This is the most common type of reinforcement used for large marine structures since it is available in fairly heavy weights, which enable a rapid build up of thickness. Directional strength characteristics are possible with a material that is fairly drapable. Impact resistance is enhanced because the fibres are continuously woven.

Knitted reinforcement fabrics provide greater strength and stiffness per unit thickness as compared to woven rovings. A knitted reinforcement is constructed using a combination of unidirectional reinforcements that are stitched together with a non-structural synthetic such as polyester. A layer of mat may also be incorporated into the construction. The process provides the advantage of having the reinforcing fibre lying flat versus the crimped orientation of woven roving fibre. Additionally, reinforcements can be oriented along any combination of axes. Superior glass to resin ratio are achieved when knits are used, which makes overall laminate costs competitive with traditional materials.

Omni directional reinforcements can be applied during hand lay-up as prefabricated mat or via the spray-up process as chopped strand mat. Chopped strand mat consists of randomly oriented glass fibre strands that are held together with a soluble resinous binder. Continuous strand mat is similar to chopped strand mat, except that the fibre is continuous and laid down in a swirl pattern. Both hand lay-up and spray-up methods produce plies with equal properties along the x and y axes and good interlaminar shear strength. This is a very economical way to build up thickness, especially with complex moulds. Mechanical properties of composites made up of this type of reinforcements are less than composites made up of other reinforcements.

Pure unidirectional construction implies no structural reinforcement in the fill direction. Ultra high strength/modulus material, such as carbon fibre, is sometimes used in this form due to its high cost and specificity of application. Material widths are generally limited due to the difficulty of handling. Entire hulls are fabricated from unidirectional reinforcements when an ultra high performance laminate is desired. Some commonly used reinforcement styles in marine industry are chopped strand mat, woven roving, cloth, knit and unidirectional ones.(Eric 1999)

Resins - A polymer matrix is obtained by converting liquid resins into hard and brittle solids by chemical cross-linking. Polymers can be classified as thermoplastic (capable of being softened and hardened repeatedly by increasing and decreasing temperatures) or thermoset (changing into a substantially infusible and insoluble material when cured by the application of heat or by chemical means). In marine structures, thermoset resins, including polyester, vinyl ester and epoxy are made use of. Availability of different type of resins provides flexibility for designers.

Polyester Resins are the simplest, the most economical and the easiest to use resin systems. They exhibit good chemical resistance and are the least toxic thermoset resin. They are classified into saturated polyester and unsaturated polyester. Unsaturated polyesters are usually used for marine construction. Polyester Resins are also classified into Orthophthalic polyesters and Isophthalic polyesters. The ortho resins are environmentally sensitive and have limited mechanical properties, limited thermal stability, chemical resistance and processability characteristics. Isophthalic polyesters have better mechanical properties and show better chemical resistance than ortho resins. Ortho resins have been replaced in some applications by isophthalic polyesters due to their excellent environmental resistance and improved mechanical properties. Iso resins are used as a gel coat or barrier coat in marine laminates. The properties of the polyester resin are affected by the type and amount of reactant, catalyst and monomers used for setting it as well as the curing temperature.

Vinyl Ester Resins possess lower ester content and lower vinyl functionality than polyesters, which result in a greater resistance to hydrolysis. Vinyl esters also have higher elongation to break than polyesters, which also makes them tougher. Some advantages of the vinyl esters, which justify their higher cost than polyester resins are superior corrosion resistance, hydrolytic stability, and excellent physical properties, such as impact and fatigue resistance. It has been shown that a composite of 20 to 60 mils layers of thickness with a vinyl ester resin matrix can provide an excellent permeation barrier to resist blistering in marine laminates.

Epoxy Resins show the best performance characteristics of all the resins used in the marine industry. The high cost of epoxies and handling difficulties have limited their use for large marine structures. Recently, rubber toughened epoxy resins have gained significant interest. Small rubber particles scattered in the epoxy resin are believed to improve the fracture toughness of the resin.

Thermoplastics have one or two-dimensional molecular structures, as opposed to the three-dimensional structures of thermosets. The thermoplastics generally come in the form of moulding compounds that soften at high temperatures. Polyethylene, polystyrene, polypropylene, polyamides and nylon are examples of thermoplastics. Their use in the marine industry has generally been limited to small boats and recreational items.

Reinforced thermoplastic materials have been investigated for the large scale production of structural components.

The marine industry has generally based its structures on polyester resin, with trends to vinyl ester and epoxy for structurally demanding projects and highly engineered products. A particular resin system is also affected by its formulation, additives used, catylization and its curing conditions.

1.5. Manufacturing of composites

Various manufacturing methods have been evolved over the years. Manufacturing methods also affect the strength properties of composite materials.

Hand lay – up is a contact mould method suitable for making boats, tanks, housings and building panels for prototypes and other large parts requiring high strength. Production volume is low to medium. This is the simplest method offering low-cost tooling, simple processing and a wide range of part sizes. Design changes can be readily made. There is a minimum investment in equipment. Resin systems used in this process are general-purpose, room-temperature curing polyesters which will not drain or sag on vertical surfaces. Epoxies and vinyl esters are also used as resins.

Spray up method is a low-to-medium volume, open mould method similar to hand lay-up in its suitability for making boats, tanks, tub/shower units and other simple medium to large size shapes. Greater shape complexity is possible with spray-up than with hand lay-up. Advantages of spray up method are that it requires low-cost tooling and allows simple processing. Use of portable equipment permits on-site fabrication also. Resin systems used in this method are general-purpose, room-temperature curing polyesters or low-heat-curing polyesters.

Compression moulding is a high-volume, high-pressure method suitable for moulding complex, high-strength fibreglass reinforced plastic parts. Fairly large parts can be moulded with excellent surface finish. Thermosetting resins are normally used. The process can be automated. Great part design flexibility, good mechanical and chemical properties are obtainable in this method. Inserts and attachments can be moulded in.

Superior colour and finish are obtainable, contributing to lower part finishing cost. Subsequent trimming and machining operations are minimized. Resin systems that can be used are polyesters (combined with glass reinforcement as bulk or sheet moulding compound, preform or mat), and certain epoxies.

Filament winding is a process resulting in a high degree of fibre orientation and high fibre loading to provide extremely high tensile strengths in the manufacture of hollow, generally cylindrical products such as chemical and fuel storage tanks and pipe, pressure vessels and rocket motor cases. The process affords the highest strength-to-weight ratio of any glass fibre reinforced plastic manufacturing practice and provides the highest degree of control over uniformity and fibre orientation. Filament wound structures can be accurately machined. The process may be automated when high volume makes this economically feasible. Integral vessel closures and fittings may be wound into the laminate. Resins used in this method are polyesters and epoxies.

Pultrusion is a continuous process for the manufacture of products having a constant cross section, such as rod stock, structural shapes, beams, channels, pipes, tubing and fishing rods. The process is a continuous operation that can be readily automated. It is adaptable to shapes with small cross-sectional areas and uses low cost reinforcement. Very high strengths are possible due to the length of the stock being drawn. There is no practical limit to the length of stock produced by continuous pultrusion. Resins used are general-purpose polyesters and epoxies.

Vacuum bag moulding can improve mechanical properties of open-mould laminates with a vacuum-assist technique. Entrapped air and excess resin are removed to produce a product with a higher percentage of fibre reinforcement. Vacuum bag processing can produce laminates with a uniform degree of consolidation, while at the same time removing entrapped air, thus reducing the finished void content. Structures fabricated with traditional hand lay-up techniques can become resin rich, especially in areas where puddles can collect. Vacuum bagging can eliminate the problem of resin rich laminates. Additionally, complete fibre wet-out can be accomplished if the process is done correctly. Improved core-bonding is also possible with vacuum bag processing. Resins used are polyesters, vinyl esters and epoxies.

Autoclave moulding is used for curing high-quality aircraft components at elevated temperatures under very controlled conditions. A greater laminate density and faster cure can be accomplished with the use of an autoclave. Very precise quality control over the curing cycle can be accomplished with an autoclave. This is especially important for high temperature cure aerospace resin systems that produce superior mechanical properties. The performance of these epoxy systems is very much dependent on the time and temperature variables of the cure cycle, which is closely controlled during autoclave cure. Using this method mostly epoxies are incorporated into prepreg systems.

Resin transfer moulding is an intermediate-volume moulding process for producing reinforced plastic parts, and a viable alternative to hand lay-up, spray-up and compression moulding. The close-mould process produces parts with two finished surfaces. By laying up reinforcement material dry inside the mould, any combination of materials and orientation can be used, including 3-D reinforcements. Part thickness is also not a problem as exothermal can be controlled. Carbon/epoxy structures up to four inches thick have been fabricated using this technique. Resins that can be used are polyesters, vinyl esters, polyurethane, epoxies and nylons.

All the above composite manufacturing methods are being used for different parts as suitable in marine constructions.

1.6. Composite laminates for ship structures

Glass Fibre Reinforced Polymers (GFRP) and Carbon Fibre Reinforced Polymers (CFRP) are two common nonmetallic composite materials used for structural applications. Aramid Fibre Reinforced Polymers (AFRP) is another type of nonmetallic composite which alone or in combination with CFRP, GFRP or both can resist impact force more effectively. These FRP’s are used in laminate form in ship construction. Properties for laminates are given in table 1.2.

Table 1.2. Properties of laminates (Eric,1999)

Laminates	**Strength to weight ratio**	**Tensile strength (MPa)**	**Fibre content (% by weight)**	**Density (kg/m^3)**	**Elastic modulus (GPa)**	**Stiffness to weight ratio (E/wt)**
CFRP laminate-Carbon/epoxy	22.5 times that of steel	1200-2250	65-75	1600-1900	120-150	7.65-8.1
GFRP laminate – Glass /polyester	3.1 times that of steel	400-1800	50-80	1600-2000	20-55	1.28-2.8
AFRP laminate-Aramid/epoxy	22.3 times that of steel	1000-1800	60-70	1050-1250	40-125	3.9-10.2

Earlier fibreglass boats were built with single-skin or laminate structures. Stiffeners were used to obtain reasonable panel sizes. Chopped strand mats were laid-up manually or with a chopper gun in the beginning. Later on due to increased strength requirements, fibre glass cloth and woven roving were integrated into the laminate. An ortho-polyester resin is an universally accepted matrix material.

1.7. Strength of composites

The mechanical properties of an FRP laminate are highly dependent on manufacturing techniques, quality, fibre volume fraction, control of fibre direction and straightness etc. The reinforcement style may also affect the resulting laminate properties. In racing sailboats which are high performance vessels, longitudinal stiffness is obtained by unidirectional reinforcements or by using high modulus fibres such as carbon fibre.

Damage and failure modes for composites are different from those of metals. When loaded, metal will go through a transition from elastic behaviour to plastic behaviour and collapse in its entirety. When composite panels are stressed, one ply will fail at a time, causing a change in strength and stiffness, leading ultimately to a catastrophic failure. This would be followed by warning cracks at ply failure points. Due to anisotropic characteristics in their strength and stiffness, composite materials exhibit very complex failure mechanisms under static and fatigue loading.

A fundamental problem concerning the engineering uses of FRP is the determination of their resistance to combined states of cyclic stress. Fatigue causes extensive damage throughout the volume of the specimen, leading to a failure due to general degradation of the material instead of a predominant single crack. The four basic failure mechanisms in composite materials as a result of fatigue are matrix cracking, delamination, fibre breakage and interfacial debonding. The different failure modes combined with the inherent anisotropies, complex stress fields, and overall nonlinear behaviour of composites severely limits ability to understand the true nature of fatigue.

Mixed views exist to the effects of parameters like effect of heat, frequency, pre-stressing, initial flaws and moisture on composite laminates, due to the variation of materials used, fibre orientations, and stacking sequences, which make each composite, behave differently.

Low cycle fatigue is developed **w**hen high stress level is produced under very less number of cycles of load. The number cycles of load applied for failure in this loading will be less than 1000. Composites are very brittle and therefore low cycle fatigue which can cause serious damage in such structures is of great importance. When composites are subjected to low cycle fatigue load, its mechanical properties diminishes. Low cycle fatigue load is usually 50% - 90% of ultimate load. When these loads are applied, it will lead to large strains or plastic strains which will exceed the failure strain of fibres. Therefore when a composite fails due to low cycle fatigue, it will involve more failed fibres than when high cycle fatigue load is applied. The degradation rates are higher in LCF when compared to HCF. The strain and strain rates (0.05-10 s^{-1}) are finite in LCF and in HCF it is negligible. The extrapolation of S-N curves in LCF gives 0.5 times the quasi static strength of laminates, which is different from HCF extrapolations. Under low cycle fatigue, a damage accumulation happens in every cycle. This happens due to the failure of highly brittle fibres and fibres with flaws during each cycle. This results in an effective degradation of elastic modulus during the cycles. The breaking of fibres and debonding eventually lead to brooming failure of composites. This brooming failure is common to quasi static and cyclic loads. This is not because that the failure mechanism is same in both cases but because of the limited damage accumulation pattern present in composites between consequent damage stages. The fatigue life of composites under LCF is less than 10^4 cycles. Under LCF conditions, the cyclic damage growth starts from the non-cyclic pre-LCF damage state (the first dozen cycles, when damage accumulation patterns are characterized by random breakage of weaker fibres and short periods of damage growth around broken fibre) whereas HCF fatigue is affected only by the initial damage state. These differences result in higher and lower property degradation rates under LCF and HCF loads. The quasi-static strain-to-failure of fibres affects the strain-to-failure of composite specimens. At near- ultimate loads, LCF strains exceed the failure strain of many glass fibres and the LCF damage is dominated by the random fibre breakage and matrix cracks that grow around broken fibres.

In ship structures low cycle fatigue failure is caused due to concentrated out of plane loads acting on the structure. Stress concentrations from out-of-plane point loads occur for a variety of reasons. The largest loads on a boat often occur when the boat is in dry storage, transported over land, while launching the boat into the water and icebreaking loads. The weight of a boat is distributed over the hull while the boat is in the water, but is concentrated at support points of relatively small area when the boat is out of the water. Equipment mounting, such as rudders, struts, engines, mast and rigging, booms, cranes handling loads etc. can also introduce out-of-plane point loads into the structure through mechanical fasteners.

Impact strength is an important consideration that needs to be addressed when non metallic composites are used as hull materials. The introduction of composite materials into the shipping industry has led to lighter, stiffer and faster vessels. This requires increased impact performance, since higher speeds cause high energy impacts and stiffer structures usually absorb less impact energy before failure.

Primarily, the entire energy of the impact is absorbed by the structure in elastic deformation, and then released when the structure returns to its original position or shape. Higher energy levels exceed the ability of the structure to absorb the energy elastically. So they go to the next level i.e. plastic deformation, in which some of the energy is absorbed by elastic deformation, while the remainder of the energy is absorbed through permanent plastic deformation of the structure. Composite laminates absorb energy in elastic deformation. Since most composites are brittle in nature they can absorb energy in elastic deformation and damage mechanisms and not due to plastic deformation. Composites have limited ability for plastic deformation. Higher energy levels result in energy absorbed through damage to the structure. Finally, the impact energy absorption levels can exceed the capabilities of the structure, leading to catastrophic failure.

The response of hull bottom panels to wave impact can be attributed to several mechanisms. A low velocity impact on laminated composites can cause various types of damages including delamination, fiber breakage, matrix cracking and fiber-matrix interfacial de-bonding. These types of damage are very dangerous because some of them cannot be detected visually and lead to structural failure at loads well below design levels. The amount of energy which can be absorbed in laminate and structural damage depends on the resin properties, fibre types, fabric types, fibre orientation, core material, fabrication techniques and rate of impact. Under impact load, the specimen first deflects, then outer layer is first fractured by tensile stresses but the crack does not propagate clearly perpendicular to the fibres. These cracks branch to the sides and delaminations along the fibres occurs. As the specimen continues to bend another layer get fractured in tension and again the crack is stopped and delamination occurs. This process is continued until the remaining layer is thin enough to allow the specimen to bend excessively and fails.

E-glass can absorb approximately three times the elastic energy of carbon. Hybrid composites are often formed by adding glass or Kevlar to carbon composites to improve impact resistance, but mismatching of moduli between fibres increases the complexity of the design of hybrids. (Wisheart and Richardson 1996)

Most composite constructions are designed using a factor of safety 4 to 5 times more than that used for metal designs and when impact load is considered then the factor of safety may go up to 10 times. As a result the structure becomes heavy and bulky and advantage got over weight and strength and cost by using composite materials will be reduced enormously.

1.8. Sustainability of composite ships

The world of marine composite vessels is extremely concerned with the sustainability of the vessels which in turn is directly connected with the environmental impact of the composite laminate materials used for their construction. Composite materials have inherent benefits that make it a green material. These benefits are durability, high insulation, high strength to weight ratio, reuse capability, can incorporate recycle content and can offer material reduction. High durability increases the life span of vessels, high insulation makes the vessel a less energy consuming one and reuse capability, can incorporate recycle content and can offer material reduction makes the vessels more environmental friendly. In spite of these benefits environmental issues connected with the manufacturing of composite materials and disposal of the composite vessel is also of great concern. Disposal of huge composite vessels is not yet a planned process. Lack of rules in the area of breaking down of these vessels itself poses a difficult situation in its disposal. End-of-life issues associated large marine composite structures is still a matter of great concern. As composite vessels survive longer than their metal counterparts, seaworthiness of composite vessels is high and also have longer life than the machinery used in the vessels. This creates a great demand in the renovation of older designs. Thus composite vessels have high reuse value. But composite materials cannot be easily recycled for reuse with the existing technology. At present composite vessels end up in landfill sites due to their un-recyclability. Durability of composite materials makes it difficult to dispose off and remain un-decomposed for longer periods of time. Although composite materials do not pollute the environment, the problem of how to dispose of them is still unsolved. As composite hull construction has become an established construction practice, a huge number of vessels are expected to reach the end of their life cycle in future years. Often the vessels are abandoned in ports, boatyards or even disposed of illegally. In the early times GFRP was the favourite composite material for boat builders. Low cost of GFRP and huge capital intensive process of construction of marine vessels were the main reasons behind this. There was a lack of faith in accepting composite materials as an established marine vessel construction material due to lack of unified rules. This increased the uncertainties associated with trying out other FRP's than GFRP. This also increased the interest in GFRP as a hull construction material. At present, due to the confidence gained through experience in marine composite construction and composite construction in general and superior strength properties, CFRP and AFRP are also used extensively.

In this context there is the need to develop an index based on strength and sustainability, to assess the degree of acceptability of various composite materials as a hull construction material.

1.9. Design philosophy for composite laminate structures

Modulus of elasticity of CFRP is more than GFRP and that of AFRP lies between them. GFRP is the most preferred composite laminate for marine constructions. When toughness and impact strength is considered AFRP performs better than CFRP and GFRP. Design codes (DNV) discuss and describe clearly about use of GFRP as a composite laminate for ship hull construction.

Disposal of CFRP, GFRP and AFRP stands at the same level of importance and complications unless specific complete disposal method of composite material is assigned to either of them. Environmental friendliness of these composites varies with their respective CO2 emissions during the component manufacture, laminate manufacture and the matrices used.

Thus there is a need to develop a design philosophy which rests on the foundation of strength and sustainability, to assess the degree of acceptability of various composite materials as a hull construction material.

In the present study, development and use of new composite have been designed with sustainability and strength as the primary goals. Strength has been considered as the strength of structural components and sustainability has been studied in terms of reduced environmental impact. When material scientists and engineers work at macro-structural scale, in this study, sustainability goals have been incorporated into each level of material manufacturing and into each level of end-of-life material disposal.

1.10. Objectives

The definite objective of the investigation is to develop a new design philosophy for composite laminate ship hulls based on strength and sustainability. The objectives are set up as to construct strength index and sustainability index for the various laminates used for ship hull construction. Structural analysis using FEM has been proposed to arrive at the strength parameters and the sustainability parameters are derived based on the effect of composite material on environment. Strength and sustainability indices are calculated from these parameters using *composite indicator*. Acceptability criteria have to be developed for the selection of materials for ship hull construction based on the assessment built on strength and sustainability indices

1.11Scope of the research work

The scope of this research work is to develop a design philosophy 'Design for Strength and Sustainability' for the selection of nonmetallic composites for ship hull construction. This has to be achieved by conducting a two dimensional assessment of nonmetallic laminated composites used for ship hull structure. The two dimensional assessment has to be conducted using Strength Index and Sustainability Index of the nonmetallic composite materials. The study has been confined to the laminates used in ship/vessel construction. Accordingly the fibres selected are carbon, glass and aramid and resins used are epoxy, vinyl ester and polyester. To obtain the Strength Index of nonmetallic composites, the strength parameters selected are 1) bending strength, 2) buckling strength and 3) impact strength. Finite element analysis has to be conducted on laminates, used as per ASTM test standards to develop individual strength indices. Using the individual indices developed, based on the above three strength parameters a Strength Index has to be developed. Sustainability Index has to be developed based on the environmental sustainability of nonmetallic composites during the two phases of nonmetallic composite materials' lifecycle. The two phases selected are manufacturing phase of composite materials and disposal phase of the composite laminates. Individual Indices are to be constructed based on above two lifecycle phases and based on them a Sustainability Index has to be developed.

CHAPTER 2

LITERATURE REVIEW

2.1. General

Availability of literature on strength aspects of various composite laminates used in this study was nominal but similar strength aspects on specific composites under specific conditions could be used as a reference to continue with the studies. As described in the previous chapter, as there are various permutations and combinations possible and available for a combination of specific fibre and matrix, availability of literature on this aspect was limited. So availability of literature on different laminates posed a problem.

Availability of literature on sustainability aspects of various composite laminates or of any specific laminate was so limited that a necessity for compilation of such data is the need of the hour. Inspiration has been derived from literature on design philosophies and sustainability in other areas to complete the present investigation.

Taking care of above considerations and limitations, literature has been reviewed and presented under various subheadings such as materials of composites, strength of composites and sustainability of composites.

2.2. Materials of composite laminates

Norman (1975) has discussed that aramid fibre displays a linear tensile stress/strain curve to failure similar glass fibre and carbon fibre. Aramid fibre has the highest specific tensile strength followed by carbon fibre and then glass fibre. The carbon fibres have higher specific tensile moduli followed by aramid fibre and then glass fibre. On comparing mechanical properties of unidirectional lamina of aramid, glass, and carbon it has been found that aramid and carbon have significant advantages in density, tensile strength and stiffness over glass.

Wonderly et.al. (2005) have conducted various studies on two composite materials used for ship hull construction namely carbon/vinyl ester and glass/ vinyl ester. Both the laminates have been manufactured by vacuum infusion and biaxially knitted glass and carbon fibre fabrics have been used as fibres. The strengths of the glass and carbon fibre specimens in tension, compression, open hole tension, open hole compression, transverse tension, indentation and ballistic impact have been compared. It has been found that carbon/vinyl ester fibres were mechanically superior to glass/ vinyl ester where strength is a fibre dominated one. Under those tests where the strength of the laminates has been resin dominated i.e. compressive loading and ballistic impact glass/ vinyl ester performed better. In terms of specific properties the carbon fibre laminates have outperformed the glass fibre laminates in all respects except transverse tensile strength.

Tekalur et.al. (2008) have conducted various tests to compare strength of two composite materials used for ship hull construction namely carbon/vinyl ester and glass/ vinyl ester. Composites have been fabricated using VARTM (Vaccum Assisted Resin Transfer Moulding) process. It was found that carbon/vinyl ester composite showed higher tensile and compressive modulus. In-plane shear properties of both the composites were comparable and inter laminar shear properties of glass /vinyl ester composites were observed to be better than that of carbon/vinyl composite.

Zike et.al. (2011) have conducted studies on glass/polyester composite. Tensile modulus and Poisson ratio have been found out using ASTM Standard Test Method (D3039) and shear modulus has been found out using ASTM Standard Test Method (D3518).The dimensions of specimens have been 250 mm × 25 mm and gauge length has been 100mm.

2.3. Strength of composite laminates

2.3.1. Experimental and analytical studies of bending of composite laminates

Uleiwi (2007) has studied the effect of fiber volume on the flexural properties of the laminated composite test specimens constructed of two layers, one of them reinforced with glass fibre (bottom of the beam) and the other layer reinforced with Kevlar fibre (top of the beam) by conducting experiments. The test specimen has a length of (170 mm) and width of (13 mm) and a thickness of (3.5 mm). A three point load test was conducted to determine deflection, tension and compression stress of the test specimens. It was found that tension stress decreased with the increase in fibre volume fraction of glass fibre of the lower layer while it increased with the increase of kevlar volume fraction of the upper layer. The compression stress, increased with the increase in volume fraction of glass fibre of the lower layer and it decreases with the increase of volume fraction of Kevlar fibre of the upper layer.

Rathnakar and Shivanand (2013) have conducted flexural tests on graphite/epoxy and glass/epoxy laminated composite material. The 3-point bending tests were performed according to ASTM D790. It was found that laminates with fibre orientation $0/45^0$ exhibited more flexural strength than the laminates with $0/90^0$ orientation for the same type of the fibre reinforcement**.** For the same thickness graphite/epoxy laminates exhibited better flexural strength than glass/epoxy laminates.

Ahmed et.al.(2013) have conducted static and dynamic analysis of graphite/epoxy composite plates. Behaviour of laminated composite plates under transverse loading using an eight-node iso-parametric quadratic element based on First order Shear Deformation theory has been studied. Maximum deflection has been found out for different support conditions like simply supported and clamped boundary condition and for different parameters like aspect ratio, layer orientation, layer number, dimension of plate sizes and mesh size. Modelling has been done using ANSYS 12.0, using the element SHELL99, and the results have been compared with Finite Element Method code. In simply supported and clamped cross-ply laminates deflection has been less for symmetric case and in angle ply laminates deflection has been less for anti - symmetric arrangement with simply supported boundary condition and the deflection has been less for anti symmetric case with clamped boundary condition. The central deflection of composite laminated plate has been decreased by the increase of layer numbers for the same thickness, but this decrease in deflection can be neglected after increasing the layer number above ten for both simply supported and clamped composite plate. The deflection for simply supported composite plate depended on both short and long edge dimensions (width and length) of the plate, but in clamped plate it depended on the short edge dimension (width) only. The results from ANSYS program is in good agreement with results using FEM code.

BabuKiran and Harish (2014a) have conducted flexural tests on composite laminate specimens as per the ASTM D790 standards. The specimens used have been glass/epoxy and Carbon/epoxy of thicknesses 2mm and 4mm and prepared using the vacuum baggage technique. It has been found that the values of deflection and bending stress decreased as the thickness of laminated composite plate increased because of the increase in stiffness of the plate. It was found that for same thickness and orientation, carbon fiber provides better flexural properties as compared to glass under flexural loading conditions.

BabuKiran and Harish (2014b) have conducted flexural tests on carbon/epoxy, glass/epoxy and carbon/polyester, glass/polyester laminated composite materials. The bi woven glass/epoxy and bi woven graphite/epoxy laminated composites specimens of various thicknesses have been prepared using the hand layup, vacuum baggage technique. The 3-point bending tests have been performed according to ASTM D790. It has been found that the increase in thickness decreased the flexural properties such as flexural strength and flexural modulus and as the thickness increased the load carrying capacity of the specimen increased. Also for same thickness and orientation, carbon/epoxy laminates provided better flexural properties as compared to glass/epoxy, glass/polyester and graphite/epoxy, graphite/polyester laminates under flexural loading conditions.

2.3.2. Experimental and analytical studies of buckling of composite laminates

Gallagher (1971) has studied about different methods to calculate the buckling strength of different types of plates. Analytical methods and experimental methods can be used to find buckling strength. Analytical methods include classical methods and numerical methods. When adequate data on material properties are not available, these shall be obtained from standard material-property tests. For fibre reinforced polymers the material properties change as constituents, fibre orientations, stacking sequences etc. changes. Therefore dependence on experimental procedures at the ply level has been more in FRP’s.

Leissa (1985) has studied the buckling behaviour of orthotropic plates with different support conditions. Support conditions like simply supported, clamped, free edge on the same plate with various combinations have been applied and buckling strength of plates for these combinations have been studied. Other support conditions for orthotropic plates, such as elastic constraints, discontinuous boundary conditions and point supports were also applied in different combinations and buckling studies have been conducted. Cross-ply laminates, balanced and unbalanced laminates have been subjected to above buckling studies. It was found that theoretical values are same regardless of whether the load is applied to one set of parallel edges or to the other set, and irrespective of the ply thickness or stacking sequence, provided that the plate buckles in the mode having m = n = 1 for $\sigma_x = 0$ or $\sigma_y = 0$. However, the experimental loads for the two loading cases are seen to be approximately 5 per cent different. The specimens used were 25 cm x 25 cm x 0.14 cm. Akhbari et.al. (2008) have conducted buckling tests on a hybrid composite and it has been modelled using the commercial software ABACUS. The hybrid composite used has been glass-polyester fibres/polyester resin. The mechanical properties of the hybrid composites have been measured experimentally. In-plane Shear Properties have been found out using the test ASTM D 3410/D 3410M-95. Compressive Properties have been found out using the test ASTM D 4255/ D4255M-83 and for finding out tensile properties ASTM D 3039/D 3039-95a was used. The buckling behaviour of the hybrid composite plates has been studied experimentally. Using the mechanical properties of the hybrid composite as the input, the buckling behaviour of the hybrid composite has been modelled and studied. It has been found out that the hybrid composite exhibited more buckling strength than glass fibre/polyester resin. The results of finite element modelling have shown a good agreement with the experimental results.

Yang (2009) has developed methods based on CLPT(Classical Laminated Plate Theory) and FSDT(First order Shear Deformation Theory) to model buckling of composite plates and the developed methods have been validated using a commercial software ANSYS. Simply supported plates undergoing uniaxial compression, biaxial compression, in-plane shear loading and various combinations have been studied. It has been found that methods based on FSDT give a better estimation than CLPT and has been best suited for thin and moderately thick plates.

Mohan et.al.(2013) have studied the buckling behaviour of glass/epoxy laminated composite plates subjected to in-plane loads. The influence of the length-to-thickness ratio, the aspect ratio, the fibre orientation and the cut-out shapes on the buckling load for the glass epoxy laminated composite plate in clamped-free-clamped-free configuration have been studied. Finite Element analysis has been done using commercial software MSC.Patran/Nastran. It has been found that variation in buckling load decreases with increase in length to thickness ratio, increasing aspect ratio and with increase in the fibre orientation. The effects of circular, square and rectangular shaped cut-outs on buckling load were also studied. The plate with rectangular cut-out gave the least buckling load and the one with the circular cut-out gave the highest buckling load.

Reddy et.al.(2013) have studied the buckling behaviour of laminated composite plates under uniaxial compression load. Commercially available software ANSYS has been used for the study. Finite element analyses have been carried out to study the effect of side-to-thickness ratios, aspect ratios, modulus ratios, ply orientation, and boundary conditions on non dimenisonalized critical buckling load for three different materials like carbon/epoxy, graphite/epoxy and boron/epoxy. In this study, the shell91 structural shell element has been used. The numerical results have showed that, nondimensionalized critical buckling load decreased with the decrease of side to thickness ratio and modulus ratio under uniaxial compression due to the effect of shear deformation. As the aspect ratio has been increased, the effect of bending-extensional twisting stiffness has been to decrease the critical buckling load under uniaxial compression. The ANSYS results have been validated with the results predicted by third order shear deformation theory.

2.3.3. Experimental and analytical studies of impact of composite laminates

Norman (1975) has calculated the impact resistance of composites like aramid/epoxy, glass/epoxy, and carbon/epoxy. Tests like Charpy, Izod and ball drop impact tests have been conducted on these specimens. It has been found that aramid/epoxy showed the highest fracture resistance, followed by glass/epoxy and carbon/epoxy.

Sun and Yang (1980) have conducted static indentation tests on glass/epoxy and graphite/epoxy to determine the law of contact between an impactor and composite laminates. It has been found out that loading path followed the Hertzian power law. A high order beam finite element has been used to compute the dynamic contact force and response of the laminated composites subjected to impact.

Wisheart and Richardson (1996) have conducted a review on the impact properties of different composites. It has been found that although toughened resins or thermoplastics can reduce matrix-dominated damage that occur when epoxy resin is used, the fibres have the most bearing on impact response.

Faroop and Gregory(2009) have developed a computational model to simulate and predict failure response of composite panels subjected to drop-weight impact using finite element analysis. The mathematical formulation consisted of constitutive, equilibrium, and strain-displacement relations; finite element formulation with contact and external forces and failure criteria proposed by Hashin. Finite Element Method (FEM) has been chosen to model drop-weight test to predict the composites behaviour in a commercially available software ABAQUS. Results have been compared with the results from the available literature and have been found to be in good agreement.

Akin and Senel(2010) have studied the response of E-glass/epoxy laminated plates subjected to low velocity impact loading. Impact tests have been performed using a specially designed vertical drop-weight testing machine. Impact response on laminates of different stacking sequences has been studied. The specimens used have a dimension of 140mm x140mm.It has been observed that fibre orientation angle has little effect on impact experiments.

Zike et.al.(2011) have conducted impact studies on glass/polyester composite. The low velocity impact has been calculated by conducting drop tower tests. Specimens of dimensions 100 × 100 mm were used. Test has been conducted for an impact energy of 14 J. In the study, validation of experimental and numerical results of low-velocity impact tests of glass/ polyester composite laminate has been carried out. Impact specimens have been modelled using shell elements and ANSYS/DYNA has been used for analysis. On comparing impact characterizing parameters as load, energy and deflection a good agreement between experimental and simulation results has been achieved.

2.4. Sustainability of composite laminates

Lepech et.al.(2005) have studied about increasing sustainability in infrastructure development programmes. One approach they have discussed is the development and use of new materials, deliberately designed with sustainability as a primary goal, in terms of improved social well being, increasing economic prosperity, and reduced environmental impact. Their study encompassed the idea, that material sustainability cannot not be captured in the traditional two dimensional (2-D) Integrated Materials and Structural Design (ISMD) paradigm, which links material scientists and engineers working on the micro-structural scale with structural designers working on the macro-structural scale. In this study they have introduced a third dimension to ISMD i.e. sustainability within each apex of the 2-D ISMD scheme. Within this expanded paradigm, sustainability goals have been incorporated into each level of materials development. Knowing that without performing a complete analysis of the new system life cycle, sustainability cannot be attained, this study have exhibited a complete design methodology for developing sustainable infrastructure materials i.e. Engineered Cementitious Composites (ECC). While the solutions within this study has been unique to ECC, the sustainable material design methodology proposed has potential for widespread application in various areas.

Halliwell (2006) has discussed about the different issues concerned with end of life options of composites. Stress has been given to disposal of composites in a sustainable manner. The four classes of recycling techniques and their availability and issues concerned with it have been discussed in detail. The different classes of recycling techniques has been divided into primary recycling, secondary recycling, tertiary recycling and quaternary recycling. Primary recycling consists of converting waste into materials having equivalent properties, secondary recycling consists of converting waste into materials having inferior properties , tertiary recycling consists of converting waste into chemicals and fuels and quaternary recycling consists of converting waste into energy.

Gramman et.al. (2008) have discussed the IMO activities related to disposal of at the end of their life. End of life options of composite materials have been less and there is little experience in this field especially in the ship building industry. The following order of waste disposal hierarchy have been developed i.e. reuse, material recycle, chemical recycle, energy recovery and disposal. This paper identifies the existing solutions in the popular ship building composites like glass reinforced polymers and carbon reinforced polymers.

Song et.al.(2009) have conducted a Life Cycle Assessment (LCA) of fibre-reinforced composites manufactured using pultrusion process. All of the life cycle stages, i.e., material production, manufacturing, use, and end-of life phases, have been taken into account to estimate the total energy use. Three types of vehicles i.e. steel, composites, and aluminium vehicles were analyzed and compared in their entire life cycle. As energy consumption in the use stage dominates the life cycle energy use of automobiles, lighter materials have been more favourable for saving the life cycle energy. It has been found that use of pultruded composite, could save more energy in the application to trucks and buses than steel but not aluminium.

Kara and Manmek (2009) have conducted Life Cycle Assessment (LCA) analysis to assess the embodied energy of the cradle-to-factory and the cradle–to-grave analyses for composite materials from six companies. It has been found that composite products have significantly lower embodied energy during their material stage and higher embodied energy during the manufacturing process stage. Composite products have performed considerably better than the traditional products during their usage stage. In the end of life stage composite products have a great shortcoming. In this study the disposal option considered has been 100% landfill but the traditional products such as steel and aluminium is 65 to 70% recyclable.

Tabone et.al. (2010) have studied environmental impacts of 12 polymers, seven derived from petroleum, four derived from biological sources, and one derived from both, using life cycle assessment (LCA) methodology. Each polymer has also been assessed for its adherence to green design principles such as the “12 Principles of Green Chemistry,” and the “12 Principles of Green Engineering”. A decision matrix has been used to generate single value metrics for each polymer evaluated, either adherence to green design principles or life-cycle environmental impacts. It has been found that a positive correlation existed between adherence to green design principles and a reduction of the environmental impacts of production. While biopolymers ranked highly in terms of green design, it was Polyolefins which ranked highly in terms of LCA rankings. Complex polymers have been placed at the bottom of both ranking systems.

Witik et.al. (2011) have conducted Life cycle assessment (LCA) and manufacturing focused Life Cycle Cost (LCC) analyses to evaluate the potential advantages of composites in automotive applications. Lightweight vehicle components have been found to be more costly, however their use have lead to reduced costs over the life cycle through lower fuel consumption. Materials offering high weight savings such as carbon fibres and magnesium have been shown to give limited or negative environmental benefits over their life cycles due to increased environmental burdens associated with their production. Lower performance materials such as Sheet Moulding Compounds (SMC) have been found to perform better from a life cycle point of view. The requirement for automotive manufacturers has been to reduce use phase emissions and to increase recycling at the end of life. This study has identified that above two priorities may not be sufficient by themselves to build a strategy for more environmentally acceptable transportation and has highlighted that an overall vision of the whole life cycle is important to build up such a strategy.

2.5. Design philosophies

Jong and Brenda (1998) have discussed about developing and refining methods of analyzing the true cost of an economic activity over its entire life cycle. During a building's existence, it affects the local and global environments via a series of interconnected human activities and natural processes. The three principles of sustainable design have been economy of resources, life cycle design, and humane design. Economy of resources has been concerned with the reduction, reuse and recycling of the natural resources. Life cycle design provides a methodology for analyzing the building process and its impact on the environment. Humane design focuses on the interactions between humans and the natural world. These principles can provide a broad awareness of the environmental impact, both local and global, of architectural consumption.

Crul and Diehllft (2005) have discussed about Design for Sustainability as a more limited concept of Ecodesign. Ecodesign had evolved to encompass broader issues such as the social component of sustainability and the need to develop new ways to meet consumer needs in a less resource intensive way. Design for Sustainability has been a globally recognised way in which companies work to improve efficiencies, product quality and market opportunities (local and export) while simultaneously improving environmental performance. The concept embraces the idea of how best to meet consumer needs – social, economic and environmental - on a systematic level. The Design for Sustainability approach has been based on taking a life cycle view of a product. The product life cycle starts with the extraction, processing and supply of the raw materials and energy needed for the product. It then covers the production of the product, its distribution, use (and possibly reuse and recycling), and its ultimate disposal. Environmental impacts of all kinds occur in various phases of the product life cycle and have to be accounted for it in an integrated way.

Obla (2010) has discussed the importance of using performance-based specifications over prescriptive specifications in concrete mixes to achieve sustainability. Using a performance specification, the concrete producer was free to select the mixture proportions and was held responsible for meeting the performance criteria. It has been found that performance-based specifications helped to attain lower variability. Lower variability in concrete mixes promoted investment in better quality and improved technology practices. Optimized mixtures with a lower variability have resulted in mixtures that are more cost-effective and sustainable.

Perry et.al. (2012) have improved the design for recycling approach by applying it to carbon fibre reinforced composites (CFRC). The first focus was on the recycling of CFRCs, based on the current limitations and legislations in force and those to come. Next they have studied the possibilities of recovery and the improvement expected for the recycling of CFRC’s. They have discussed the necessity of improving the carbon fibre recycling processes and to integrate those possibilities in the composite product design phase. The knowledge gathered from these studies can be exchanged between recycler designers and material science experts. This approach can improve the environmental impact of these composites in a better way.

2.6. Critique

From review of literature it is clear that a comparative study of strength aspects of laminates which are used for ship hull construction has not been conducted yet. It has been seen that studies on sustainability aspects on any of the laminate or a comparative study of various laminates used for ship hull construction has not been conducted yet. Also a study on how strength parameters and sustainability parameters in combination can be incorporated to bring out a new design philosophy in the field of nonmetallic laminated ship structure which can bring a drastic change in shipping industry leading to a more environmentally sustainable one has not been looked into.

Whenever a new structural material has been developed it's response to different types of loads or strength is the only parameter based on which acceptability is decided upon. The material's environmental friendliness would be looked into only after the structure cease to be serviceable. In a structure like ship, a huge amount of waste pileup at the end of the service of the structure. If only strength is considered, as the acceptance criteria of ship hull materials, a huge problem of unsustainability crops up. The severity of the above issue can be reduced to an extent if environmental friendliness of the material is also looked into during the design phase of the structure.

Thus while designing a new material the main aspects that have to be looked upon are strength and sustainability. In composite laminates, a change in fibre or matrix or other aspects of laminate construction can drastically change the laminate's strength properties and testing each laminate variation is time and money consuming, FEM comes as a boon to navigate through the darkness of uncertainty. Sustainability of composite materials is an area that needs to be explored. Thus a new design approach where strength and sustainability plays a pivotal role needs to be developed.

CHAPTER 3

DESIGN FOR STRENGTH AND SUSTAINABILITY

3.1. Introduction

From review of literature it is clear that there is no design philosophy which has been developed for composite materials which can account for the strength variations and sustainability aspects due to change in fibre and matrix. In the case of composite materials an indecisiveness of strength properties arise due to changes in factors like matrix selection, reinforcement selection, fibre or matrix volume selection, angle of reinforcement selection, stacking sequence of different layers selection etc. In this study the design philosophy adopted is based on strength and sustainability of composite material.

3.2. Strength index for material

For any structural material, strength is the predominant selection criteria. In the present study an index value is prepared for every composite material selected, based on strength and ranked accordingly. The index thus prepared is called as 'Strength Index'. In the present study the parameters considered for constructing strength index are bending strength, buckling strength and impact strength. These are the major strength parameters which have applications in a ship structure. If strength is the only criteria for selection of a composite material for construction then the material having highest strength can be selected. This procedure can be applied to any industry or field when one has to choose composite materials of different strength properties although the constituents are same or different.

3.3. Sustainability index for material

When compared to already established construction materials like metals, there is a conception or misconception that composite materials are not sustainable, although composite materials possess better specific strength and specific stiffness than these conventional materials. With due consideration or thought given in use and disposal of composite materials and due to technological advancements that is taking place this misconception can be got rid of in the present future. As composite materials possess superior material properties it is the need of the hour to establish it’s superiority in the area of sustainability. Therefore it is important to conduct an evaluation of sustainability of composite materials. The evaluation can be conducted by developing an index and rank these materials accordingly. In this study the index thus developed is called as ‘Sustainability Index’.

3.4. Construction of index

In this study the indices, the ‘Strength Index’ and ‘Sustainability Index’ are constructed as a composite indicator. An indicator is a quantitative or a qualitative measure derived from a series of observed facts. It is a statistical measure of changes in a representative group. Composite indicators are a tool used for rating. They provide simple comparisons between complex and elusive issues like sustainability. A composite indicator consists of a single indicator, which is an aggregation or compilation of separate or individual indicators. Composite indicators help the material scientists and engineers to rate complex issues using one indicator than trying to find a common trend in many separate indicators. Composite indicators can be seen as a starting point for initiating discussions rather than using it to draw simple analytical or policy conclusions by them.(Nardo et.al. 2005)

3.4.1. Theoretical frame work for index

A multidimensional concept is usually rated using a composite indicator. Various dimensions of the concept are rated using individual indicators. These ratings are brought down to comparable scales. Then each ratings are assigned a weight depending upon their importance in the construction of rating. The ratings of individual indicators are aggregated or added to get a composite indicator.

Construction of composite indicators needs a clear theoretical framework. It should clearly define the multidimensional concept that is rated using composite indicators. The subcomponents or various dimensions of the concept that are rated using individual indicators should be clearly defined and the reason for their selection also should be clearly discussed. Further the weighting method and the aggregation method used to consolidate the individual indicators to a composite indicator also need to be clearly explained.

3.4.2. Selection of variables

Selection of variables is representative of the multidimensional concept selected, for which the index is created. The strength and weakness of the composite indicator depends upon the manner in which the variables are selected. Variables are to be selected based on the theoretical framework. Selection of variables can be subjective in nature as there are no single definite set of variables for creating a particular composite indicator and qualitative (soft) data can be used for the purpose.

Cradle to grave approach or cradle to factory approach can be used to create the sustainability index. Selection of variables can be based on either or one of these approaches. In cradle to grave approach sustainability index is assigned by assessing the impacts of all the stages of life cycle of a product/ process (i.e. from raw material extraction through material processing, manufacture, use, maintenance and disposal or recycling). In cradle to factory approach, impacts of those stages of life cycle like raw material extraction through material processing and manufacture alone, need to be considered.

3.4.3. Scaling of variables

Variables for the multidimensional concept are selected first. The various processes involved in the completion of the multidimensional concept can be considered as variables. Then data is collected under each variable. Their scaling is done to continue the process of indexing. Scaling techniques are applied to the measurements to transform the data of variables into a comparable format as available data set often have various measurement units. Normalisation of the data of each variable is done based on a base unit or a common unit. The most commonly used techniques are ranking, Z-score, the distance from the leader, the distance from the mean and the min – max. (Blanc et.al. 2008)

Ranking is the simplest normalisation technique. When less components are compared i.e. less than 10, then ranking can be effectively made use of. The technique Z-score gives the deviation of a data point from the mean divided by the average deviation from the mean of the variable. This method standardizes the variables so that their mean is zero and standard deviation is unity. In this method positive and negative values are possible. In the ‘distance from the leader’ method, the value which is the leading one, is assigned 100% and the other values are expressed as percentage points away from the leading value. In the ‘distance from the mean’ method, the mean value is assigned 100% and other values are scored according to their distance from the mean. In the ‘distance from min – max’ method the values are assigned points which reflect the distance between the extremes i.e. minimum and maximum values. All these four methods result in a unit less indicator. The Z – score and ‘distance from the mean’ are not too sensitive to extreme values, whereas ‘distance from the leader’ and ‘distance from min – max’ depend directly on extreme values.

3.4.4. Weighting of variables

In ‘weighting of variables’ step, two general approaches are made use of viz; Differential weight method and Equal weight method. In differential weight method, indicators are assigned different weights to establish a rank among the different indicators. Ideally the contribution of each indicator to the overall composite is to be reflected when differential weights are assigned. Such a ranking is a delicate and fragile task as various indicators address various issues which may or may not be related. There are various techniques to assign weight to indicators. They are based on scientific expertise, societal determination (policy makers or social surveys) and on statistical data treatment. The first technique of assigning weights is used when expert opinions reflecting theoretical factors need to be included while assigning a weight. Second technique is used when policy priorities need to be incorporated in weight assigning. This technique is more of subjective in nature. In the third technique weighting are derived from statistical models such as principal component analysis and factor analysis. When these three techniques not feasible, then equal weighting method is adopted. In equal weighting method, weights assigned to all variables are equal. In this method it is assumed that the preceding normalisation step incorporates the numerical counterpart of conceptual equivalence. Also a subjective analysis is done which culminates in the assigning of equal weights. In spite of its disadvantages, most composite indicators apply an equal weighting method. When there is no correlation between indicators, then weights cannot be estimated. In such cases or for such indicators equal weighting method can be made use of. (Nardo et.al. 2005)

3.4.5. Aggregation of variables

In the 'aggregation of variables' step, various individual indicators are aggregated or summated to get the composite indicator. The various aggregation methods used are linear/ additive aggregation method and geometric aggregation method. When all the indicators and sub-indicators have same measurement unit, linear aggregation method is useful. In linear aggregation method, simple additive method is used for aggregation of variables. According to this method, index values of all the indicators are linearly added to get the final index. Formula used in linear aggregation method is

$$CI = \sum_{q=1}^{n} Rank_q \qquad (3.1)$$

Where CI – composite indicator

$Rank_q$ - rank of qth variable

When weights are assigned to variables/ indicators, then the formula is improved to

$$CI = \sum_{q=1}^{n} w_q Rank_q \qquad (3.2)$$

Where w_q - weight of q^{th} variable

This method is more of a consensus based rating system. The main disadvantage of this method is that, sometimes absolute value of the information is lost as linear aggregation method provides full compensability. This means poor performance or low values in some indicators/ variables may be compensated by good performance or high values of other indicators. Linear aggregation will yield meaningful composite indicators, only if data is expressed in comparable scale.

For noncomparable or independent and all positive indicators, geometric aggregation method is suited. This provides less compensability between differently performing indicators. Formula used in geometric aggregation method is

$$CI = \prod_{q=1}^{n} {Rank_q}^{w_q} \qquad (3.3)$$

3.4.6 Ranking

Ranking of these values is done after the total index has been calculated using any of the aggregation method. Rank is assigned to each index value in the descending order. Therefore the highest index value is assigned the highest rank and lowest index value is assigned the lowest rank. Lowest value of rank must be one. If two index values are same then two methods can be adopted to assign the rank. In both the methods same rank is assigned to same index values. According to first method the two index value can be assigned the next immediate higher value, if the ranking is assigned from one to above or lower value, if the ranking is assigned from top rank to one. By the second method, average of the next two ranks is assigned as the rank for both the same index value.

3.5. Strength index versus Sustainability index plot

Composite materials have superior specific strength and specific stiffness. As a constructional material it is superior to already established materials. When sustainability is considered composite materials are given a second thought as there is not much study materials available in this area. Therefore it's very important to relate strength and sustainability and use this as a criterion for selection. This can be done by plotting the different materials against strength and sustainability and make a wise choice with the help of it. A strength index versus sustainability index plot has been constructed and the composite material which lies on the top right hand section of the plot or bottom left hand section, depending upon how the ranks have been assigned can be selected. This is a general procedure that can be adopted for an array of composite materials.

CHAPTER 4

STRENGTH OF SHIP BUILDING LAMINATES

4.1 Introduction

Use of composites in structural applications are increasing exponentially, as the anisotropic nature of composites can be exploited to produce materials which behave in a superlative manner or whose material properties are farfetched than its component properties or existing counterparts. As it is an engineered material structural engineers can design the composite for the desired design strength. This can be done primarily by changing the reinforcements or fibres and resins. Strength properties can also be changed by altering the volume of fibres used, laying angle of fibres, stacking sequence of various angle plies, combination of various fibres and by using various manufacturing methods.

In the present study various strength parameters of ship building laminates have been compared. The strength index has been developed based on the basic modes of failures in ship structures like tensile yield due to bending stress developed, buckling and brittle fracture due to impact load. Accordingly the strength parameters identified are bending, buckling and impact response of individual components constituting the hull. Even with all the details of construction like resins used, reinforcement used and reinforcement pattern being same, it is difficult to manufacture similar laminates of same strength. Analytical verification using finite element method has a great application in the field of composites, where attainment of homogeneity between samples is difficult when compared to metals. When various laminates are to be studied it is prudent to utilize the available superior technology to make the study less cumbersome. Therefore in the present study finite element method is used to conduct studies on various strength parameters.

In the present study, the fibres selected from the nonmetallic composite materials used for hull construction are Carbon(C), Glass (G) and Aramid (A) and the matrices selected are Epoxy (E), Vinyl Ester (VE) and Polyester (P). In this study composites made of above three fibres and three matrices are considered. All the combinations of above fibres and matrices are selected. Accordingly nine types of nonmetallic hull materials are studied. They are Carbon fibre and Epoxy matrix (CFRP-E), Carbon fibre and Vinyl Ester matrix (CFRP-VE), Carbon fibre and Polyester matrix (CFRP-P), Glass fibre and Epoxy matrix(GFRP-E), Glass fibre and Vinyl Ester matrix (GFRP-VE), Glass fibre and Polyester matrix (GFRP-P), Aramid fibre and Epoxy matrix (AFRP-E), Aramid fibre and Vinyl Ester matrix (AFRP-VE), Aramid fibre and Polyester matrix (AFRP-P).

4.2 Strength estimation of laminates

According to DNV (Det Norske Veritas) the following rules are applicable to design structures made of FRP single skin laminates. The FRP vessels are designed such that the loads are carried mainly by the fibres. The basic assumptions used for laterally loaded single skin laminates are the following (i) the principal directions of reinforcement are parallel to the edges of the panel, (ii) the difference in the modulus of elasticity in the two principal direction of reinforcement should be not more than 20% and (iii) the load is assumed to be uniformly distributed on the surface of the laminates.

The structural calculations may be performed in one of the three different levels of calculations. The calculation level can be chosen in the best manner to suit the purpose. The first level of structural calculations is the ‘Simplified Calculation Method’ which is based on rule formulae. This level may be used for panels, stiffeners and girders. The second level is the ‘Laminate Calculation Method’ and it is based on the strain failure criteria. This method has application in the structural calculation of larger structural elements such as longitudinal girders using finite element method. The third level is the ‘Detailed Laminate Calculation Method’ and it is based on ply calculation theory and the ply failure criteria. This method is used where detailed information of stresses in a local area is needed (DNV 2010).

The main components of ship structures are bottom structures, side structures, deck structures, bulkhead structures and super structures and deck houses. Bottom structures include longitudinal stiffeners supported by bulkheads or web frames, web frames which are continuous around the cross section of the craft, longitudinal girders carried continuously through bulkheads and engine girders. The bow should be protected from impact loadings acting at or below the waterline. Side structures consist of stiffeners used for vertical and longitudinal stiffening. Deck structures consist of longitudinal stiffeners and bulwarks. The thickness of the laminates should be such that necessary transverse buckling strength is achieved. Bulkhead structures used in ship structures are watertight bulkheads and supporting bulkheads. Bulkheads supporting decks are considered as pillars and they have to be designed for appropriate buckling strength. For superstructures and deckhouses, sufficient transverse strength is to be provided by means of transverse bulkheads or girder structures.

The basic ship structural components are commonly divided into two general types as plating and stiffeners. Stiffeners include frames, longitudinals, stringers, deck beams, deck girders, bulkhead stiffeners, and stanchions. Plating includes bulkhead plating, bottom plating, side shell plating, deck plating etc. Ship structures are made of combinations of plating and stiffeners. Analytically stiffeners are treated as beams and plating as plates. Beams are subjected to bending loads and plates are subjected to in-plane loads and lateral pressure. In a ship structure, the portion of the decks abreast the line of openings, the side shell plating, inner and outer bottom shell plating will contribute to the longitudinal strength and resist the longitudinal bending. The lateral loads acting on the side plating and deck plating are mainly loads due to cargo and water pressure.

Based on the above discussion, the ship structural component considered for various analyses in the present study is a plate section with various support condition. The weakest support condition and therefore the most commonly studied support condition is simply supported condition on all four sides of a plate.

The following minimum mechanical properties are required for structural composite laminates:
Tensile strength, σ_u = 80MPa
Tensile modulus, E_n = 7000MPa
Bending strength, σ_b = 130MPa
Bending modulus, E_b = 6000MPa (DNV 2003)

4.3. Analytical determination of material properties of laminate

Material properties of the composites constitute the various input parameters for the finite element studies on strength parameters. Material properties can be found out by conducting experimental studies or by using analytical methods. The inherent difficulties in manufacturing and testing various laminates forces experimental studies to take a backseat and makes finite element studies a relatively easier and more feasible option. In the present study material properties are found out using analytical method.

Material properties like E_1, E_2, E_3, ν_{12}, ν_{23}, ν_{13}, G_{12}, G_{23}, G_{13} of the lamina can be calculated, when the material properties of constituents are available using analytical formulae. Analytical methods like rule of mixtures (Eric Greene Associates, 1999) and classical lamination theory can be used to predict material properties and strength/ mechanical properties of composites. Rule of mixtures can be easily adopted and the latter is rather difficult as it involves large amount of calculations. Strength of a lamina is the basic element considered where strength of the laminate needs to be analysed. Material properties thus calculated can be used to predict structural properties. Once the strength characteristics are established guidelines for design based on strength considerations can be established.

Actual nature of fibre reinforced composite lamina is extremely complex and in order to produce micromechanical solutions some basic assumptions are to be made of. The following assumptions are made to calculate the material properties of composite materials using analytical methods.

i) Both the fibre and the matrix are homogeneous and isotropic.

ii) The fibre, the matrix and the resulting composite exhibit linear elastic behaviour.

iii) Perfect bond exists between fibres and matrices so that no slippage occurs at the interface.

iv) Fibres are uniform, regularly spaced and perfectly aligned.

v) The matrix is free of voids.

vi) The lamina is in a stress free state (i.e. no residual stresses are present).

vii) For structural applications, fibre reinforced composite materials are used in the form of thin plates.

viii) For the analysis of a specially orthotropic material the engineering constants required are E_1, E_2, E_3, ν_{12}, ν_{21}, ν_{23}, G_{12}, G_{23} and G_{13}. Material properties like E_1, E_2, ν_{12}, and G_{12} are found out using rule of mixtures and other material properties are made available by assuming $E_2 = E_3$, $\nu_{12} = \nu_{23} = \nu_{13}$, and $G_{12} = G_{23} = G_{13}$(Eric, 1999).

4.3.1. Rule of mixtures

Rule of mixtures can be used to find the material properties of composite laminates. The analytical formulae, *rule of mixtures* that can be used to find the material properties are:

To find E_1

$$E_1 = E_f V_f + E_m V_m \quad (4.1)$$

$$V_f = A_f / A \quad (4.2)$$

$$V_m = A_m / A \text{ or } (1 - V_f) \quad (4.3)$$

To find E_2

$$E_2 = E_f E_m / (E_f V_m + E_m V_f) \quad (4.4)$$

To find ν_{12}

$$\nu_{12} = V_m \nu_m + V_f \nu_f \quad (4.5)$$

$$\nu_{21} = \nu_{12} \text{ x } E_2/E_1 \quad (4.6)$$

To find G_{12}

$$G_{12} = G_f G_m / (G_f V_m + G_m V_f) \quad (4.7)$$

The values of E_f, E_m, G_f, G_m, ν_m and ν_f are available in literature. V_f is taken as 60%. From literature it has been found that use of 60% as percentage volume of fibres is a good value to produce a strong laminate encompassing the virtues of both fibre and matrix. (Eric,1999)

4.3.2. Material properties of constituents and laminates

Elastic modulus, poisson's ratio and shear modulus of the three fibres selected are given in Table 4.1. (Springer and Kollar 2003)

Table 4.1. Material properties of fibres

Fibre	E_f (GPa)	ν_f	G_f(GPa)
Glass	72	0.09	33
Carbon	234	0.26	93
Aramid	124	0.45	43

Elastic modulus, poisson's ratio and shear modulus of the three matrices selected are given in Table 4.2. (Springer and Kollar 2003)

Table 4.2. Material properties of matrices

Matrix	E_m(GPa)	ν_m	G_m(GPa)
Epoxy	3.4	0.35	1.25
Vinyl Ester	3.2	0.3	1.23
Polyester	3.3	0.25	1.32

Elastic modulus of laminate in the longitudinal direction, Elastic modulus of laminate in transverse direction, Inplane shear modulus and Poisson's ratio when inplane load is applied parallel to longitudinal direction of laminates are calculated using the above equations. The material properties of the FRP's under study are evaluated and are given in Table 4.3

Table 4.3 Material properties of laminates

FRP	V_f	E_1(GPa)	E_2(GPa)	G_{12}(GPa)	ν_{12}
CFRP(E)	0.6	141.76	8.32	3.06	0.3
CFRP(VE)	0.6	141.68	7.84	3.02	0.28
CFRP(P)	0.6	141.72	8.08	3.23	0.26
GFRP(E)	0.6	44.56	7.94	2.97	0.19
GFRP(VE)	0.6	44.48	7.5	2.91	0.17
GFRP(P)	0.6	44.52	7.72	3.11	0.15
AFRP(E)	0.6	75.76	8.16	2.99	0.41
AFRP(VE)	0.6	75.68	7.70	2.95	0.39
AFRP(P)	0.6	75.72	7.93	3.15	0.26

4.4. Bending strength of laminates

The smallest structural element of ship structure is the plate element. The inter stiffener plating and it bending response under loads are of great importance in analysis of ship structure. Bending strength of laminates has been assessed in terms of maximum deflection ($w_{\max}$), maximum stresses developed in the longitudinal direction ($\sigma_{x(max)}$) and transverse direction ($\sigma_{y(max)}$), stress developed at matrix failure(σ_{matf}), longitudinal strain developed at matrix failure (ε_x) and lateral strain (ε_y) developed at matrix failure.

Maximum deflection ($w_{\max}$), maximum stresses developed in the longitudinal direction ($\sigma_{x(max)}$) and transverse direction ($\sigma_{y(max)}$) are estimated using linear analysis.Stress developed at matrix failure(σ_{matf}), longitudinal strain developed at matrix failure (ε_x) and lateral strain (ε_y) developed at matrix failure are estimated using geometric nonlinear analysis.

4.4.1. Description of specimen

Laminates of same thickness and with same number of plies and same stacking sequence are considered for each material. Specimen selected for the study is a thin plate between two consecutive stiffeners and two consecutive transverse frames of an FRP ship hull and is shown in figure 4.1.

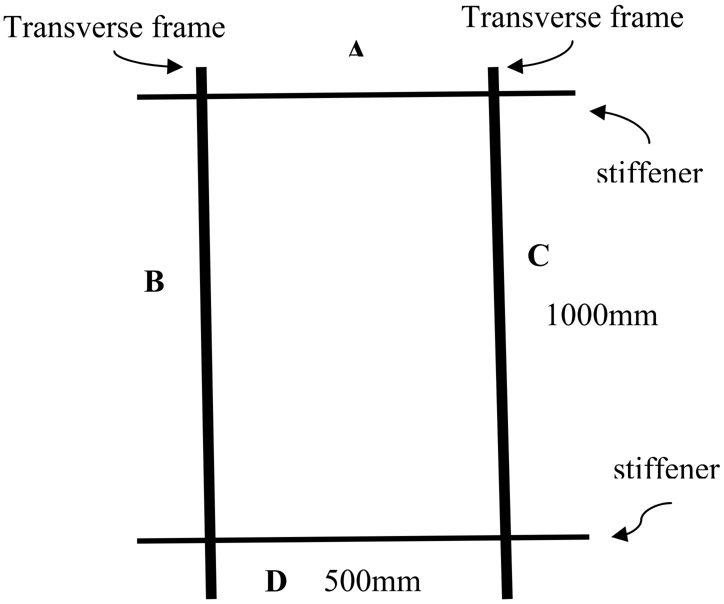


Figure 4.1. FRP plate used for ship hull construction

Accordingly a rectangular plate 500mm x 1000mm (b x a) is considered for the present study. Size of the specimen has been selected from an existing GFRP vessel. Number of plies, thickness of each ply and stacking sequence of the plies have been adopted from the ASTM standard specimen used for impact testing. Accordingly the plate consists of 8 plies of 0.5mm thick each. The stacking sequence of the plies is $[45/0/-45/90]_s$. The total thickness (t) of the plate is 4mm.

The study has been conducted using ANSYS. The element used to model the plate is SHELL 281, which is suitable for analyzing thin shell structures. The element has eight nodes with six degrees of freedom at each node namely, translations in the x, y, and z directions, and rotations about the x, y, and z axes. Geometry of SHELL281 is given in Figure 4.2.

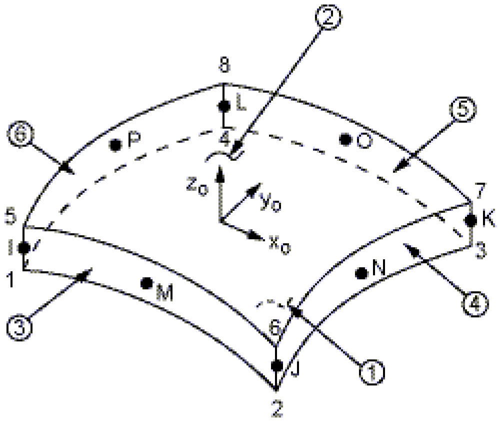


Figure 4.2. Geometry of SHELL281 of ANSYS Element Family

4.4.2. Linear Analysis of composite laminate

Load has been applied as a transverse pressure (q) of intensity $1 N/m^2$. All edges of the laminate are assumed to be simply supported in this analysis. Maximum deflection (w_{max}) has been calculated using classic lamination theory and FEA.

Classical Laminated Plate Theory (CLPT)

According to CLPT, the maximum deflection(w_{max}) in a composite laminate, simply supported at all the edges is given in Appendix A. Using the formulae given in A-2, the maximum deflection has been calculated for all the plates and are given in Table 4.4.

Finite Element Analysis (FEA)

Maximum deflection (w_{max}) has been calculated using FEA. To analyse the laminate using FEM, the plates are modelled using the material properties given in Table 4.3. Model used for bending analysis of a laminate with all the edges simply supported in ANSYS is given in Figure 4.1. The aspect ratio of the mesh has been maintained as 2. In the FEA model the number of divisions on 'x' axis has been taken as 50 and on 'y' axis is 50. Number of elements used in each model are 2500. For fixed support conditions all translations and rotations are arrested. For simply supported conditions translations along 'y' direction was arrested along all axes and rotation about 'x' axis was arrested along 'y' axis and rotation about 'y' axis was arrested along 'x' axis.

Although studies have been conducted on laminates of all nine materials and reported, models of CFRP-VE only have been shown in the report. Linear static analysis of all the laminates has been carried out. $w_{max,}$ have been found out and have been nondimensionalised as ($w_{max}E_2t^3/qa^4$) and are given in Table 4.4.

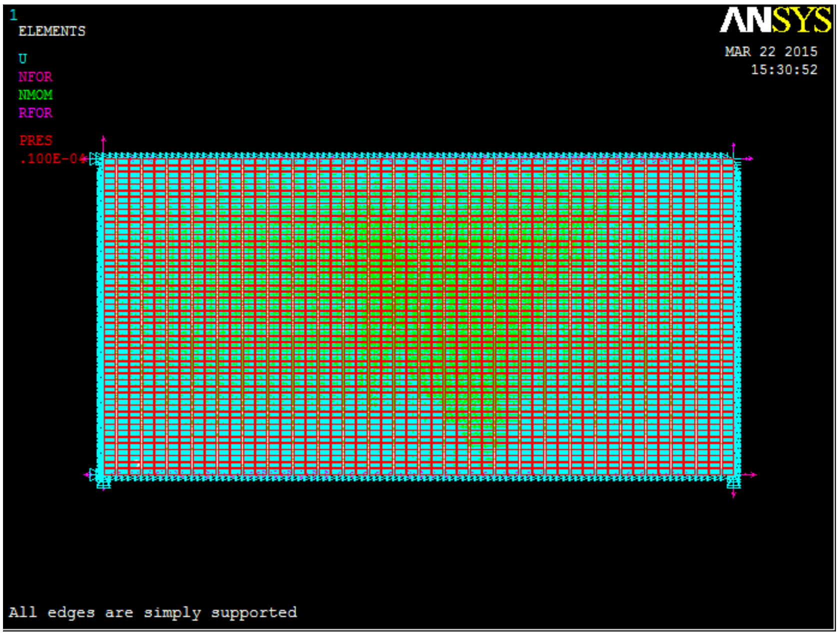


Figure 4.3. Model of plate used for laminate bending (CFRP-VE) in which all the edges are simply supported(AE-SS)

Figure 4.4 shows contour plot of displacements of the model shown in figure 4.3. The maximum displacement happen in the central node and the value is 0.00218 mm.

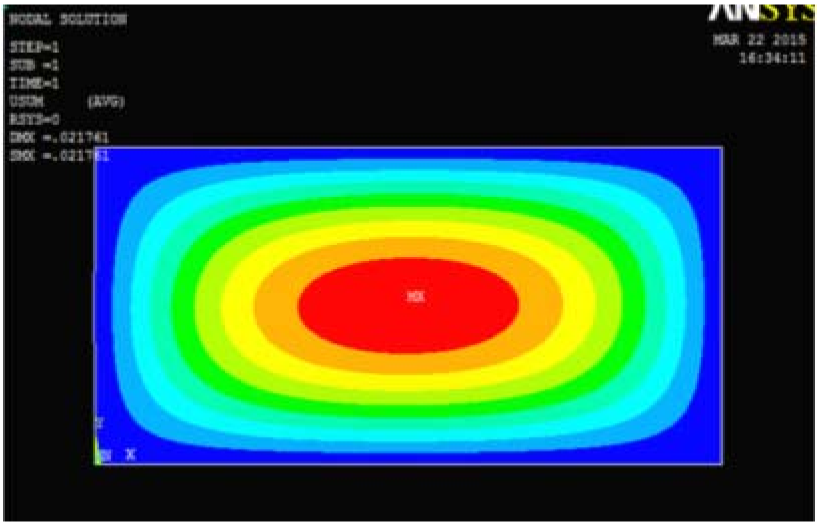


Figure 4.4. Contour plot of displacements of (CFRP-VE) for (AE-SS)

For nine composite structural laminates the above procedure has been repeated and maximum nondimensionalised deflections ($w_{max}E_2t^3/qa^4$) has been evaluated and tabulated and given in Table4.4. Based on the nondimensionalised deflection value, index value has been assigned from ‘1’ to’9’. Laminate with least deflection has been assigned a value of '1' and the laminate with maximum deflection has been assigned a value of '9'. Index value based on maximum deflection has been given in the same table 4.4.

Table 4.4. Maximum Deflection of Laminates

Specimen	$w_{\max}$ (CLPT) (mm)	$w_{\max}$ (FEM) (mm)	% Variation	$\frac{w_{max}E_2t^3}{qa^4}$	Index Value
CFRP(E)	0.001962	0.00216	10.10	0.019597	1
CFRP(VE)	0.001973	0.00218	10.49	0.019767	3
CFRP(P)	0.001967	0.00217	10.30	0.019682	2
GFRP(E)	0.005261	0.0056	6.44	0.015970	7
GFRP(VE)	0.005331	0.00568	6.54	0.016169	9
GFRP(P)	0.005292	0.00564	6.58	0.016070	8
AFRP(E)	0.003339	0.0036	7.81	0.017455	4
AFRP(VE)	0.003376	0.00365	8.13	0.017679	5
AFRP(P)	0.003403	0.00368	8.13	0.017834	6

Maximum stresses developed in longitudinal direction ($\sigma_{x(max)}$) and transverse direction ($\sigma_{y(\max)}$) have been found out and nondimensionalised as ($\sigma_{x(\max)}/E_1$) and ($\sigma_{y(\max)}/E_2$). Four types of plate arrangements as given Table 4.5 are considered for the study of maximum stresses developed in the laminates.

Figure 4.3, 4.5, 4.7 and 4.9 show the models used for bending analysis using ANSYS. Linear static analysis of all the laminates has been carried out.

Table 4.5. Four types of plate arrangements

Arrangement	Support along side A	Support along side B	Support along side C	Support along side D
AE-SS	Simply Supported	Simply Supported	Simply Supported	Simply Supported
AE-F	Fixed	Fixed	Fixed	Fixed
LE-F and SE-SS	Simply Supported	Fixed	Fixed	Simply Supported
LE-SS and SE-F	Fixed	Simply Supported	Simply Supported	Fixed

Maximum longitudinal stresses $\sigma_{x(max)}$ and transverse stresses $\sigma_{y(max)}$ developed in the plates with all the edges simply supported (AE-SS) has been given in Table 4.6. The nondimensional parameters such as ($\sigma_{x(max)}/E_1$) and ($\sigma_{y(max)}/E_2$) has also been given in the same table. The index values based on both the nondimensional parameters are also given in the same table.

Table 4.6. Maximum Stresses (AE-SS)

Specimen	$\sigma_{x(max)}$ (N/mm^2)	$\sigma_{y(max)}$ (N/mm^2)	($\sigma_{x(max)}/E_1$) x10^6	Index Value	($\sigma_{y(max)}/E_2$) x10^6	Index Value
CFRP(E)	0.1859	0.1859	1.3114	1	22.3473	6
CFRP(VE)	0.1866	0.1866	1.3171	3	23.8035	9
CFRP(P)	0.1861	0.1861	1.3131	2	23.0335	8
GFRP(E)	0.1633	0.1633	3.6656	7	20.5776	1
GFRP(VE)	0.1647	0.1647	3.7017	9	21.9533	4
GFRP(P)	0.1637	0.1637	3.6772	8	21.2079	2
AFRP(E)	0.1746	0.1746	2.3047	4	21.3860	3
AFRP(VE)	0.1757	0.1757	2.3210	6	22.8062	7
AFRP(P)	0.1755	0.1755	2.3180	5	22.1244	5

Figure 4.5. shows the model of the plate(CFRP-VE), whose all edges are fixed(AE-F).

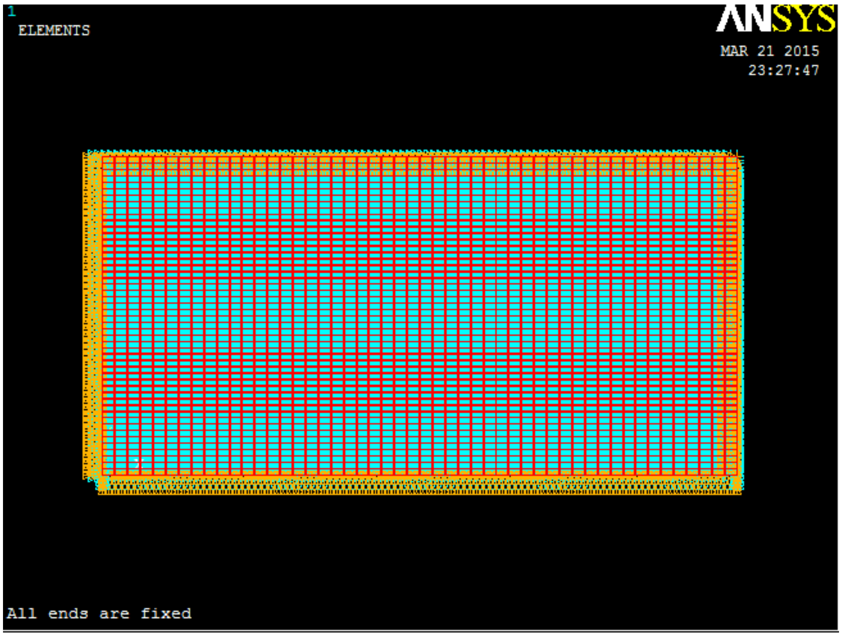
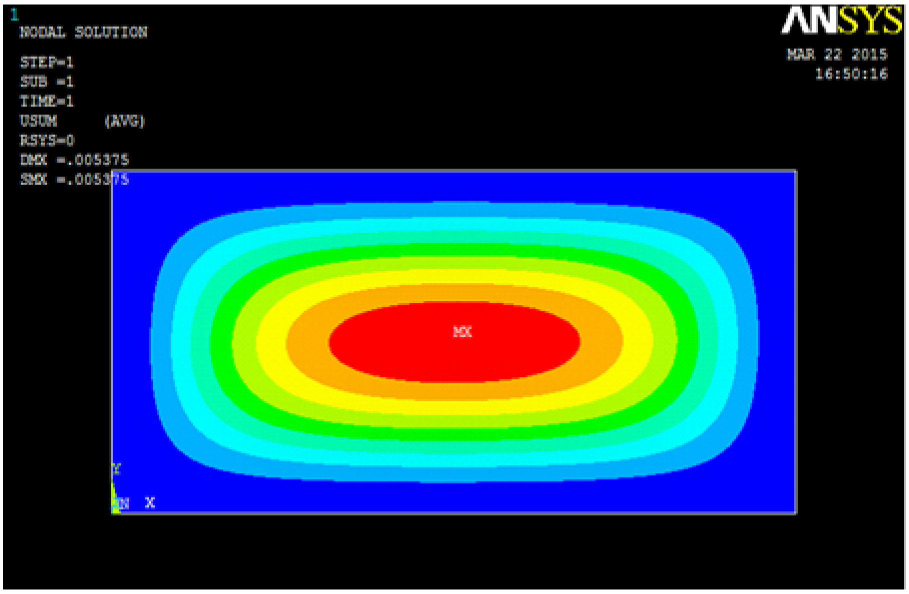


Figure 4.5. Model of plate used for laminate bending (CFRP-VE) in which all the edges are fixed (AE-F)

Figure 4.6. shows contour plot of displacements of the model shown in figure 4.5.


```
NODAL SOLUTION

STEP=1
SUB =1
TIME=1
USUM      (AVG)
RSYS=0
DMX =.005375
SMX =.005375
```

Figure 4.6. Contour plot of displacements of (CFRP-VE) for (AE-F)

Table 4.7 gives the maximum longitudinal stresses $\sigma_{x(max)}$ and transverse stresses $\sigma_{y(max)}$ developed in the plates with all the edges fixed. The nondimensional parameters ($\sigma_{x(max)}$ /E$_1$) and ($\sigma_{y(max)}$ /E$_2$) has been given in the same table. The index values based on both the nondimensional parameters are also given in the same table.

Table 4.7. Maximum Stresses (AE-F)

Specimen	$\sigma_{x(max)}$ (N/mm^2)	$\sigma_{y(max)}$ (N/mm^2)	($\sigma_{x(max)}$/E$_1$) x10^6	Index Value	($\sigma_{y(max)}$/E$_2$) x10^6	Index Value
CFRP(E)	0.07813	0.07813	0.5511	1	9.3921	6
CFRP(VE)	0.07845	0.07845	0.5537	3	10.0074	9
CFRP(P)	0.07821	0.07821	0.5519	2	9.6805	8
GFRP(E)	0.06783	0.06783	1.5222	7	8.5453	1
GFRP(VE)	0.06841	0.06841	1.5380	9	9.1213	4
GFRP(P)	0.06798	0.06798	1.5270	8	8.8065	2
AFRP(E)	0.07297	0.07297	0.9632	4	8.9378	3
AFRP(VE)	0.07344	0.07344	0.9704	6	9.5354	7
AFRP(P)	0.07336	0.07336	0.9688	5	9.2471	5

Figure 4.7. shows the model of the plate(CFRP-VE), whose long edges are fixed and short edges are simply supported(LE-F and SE-SS).

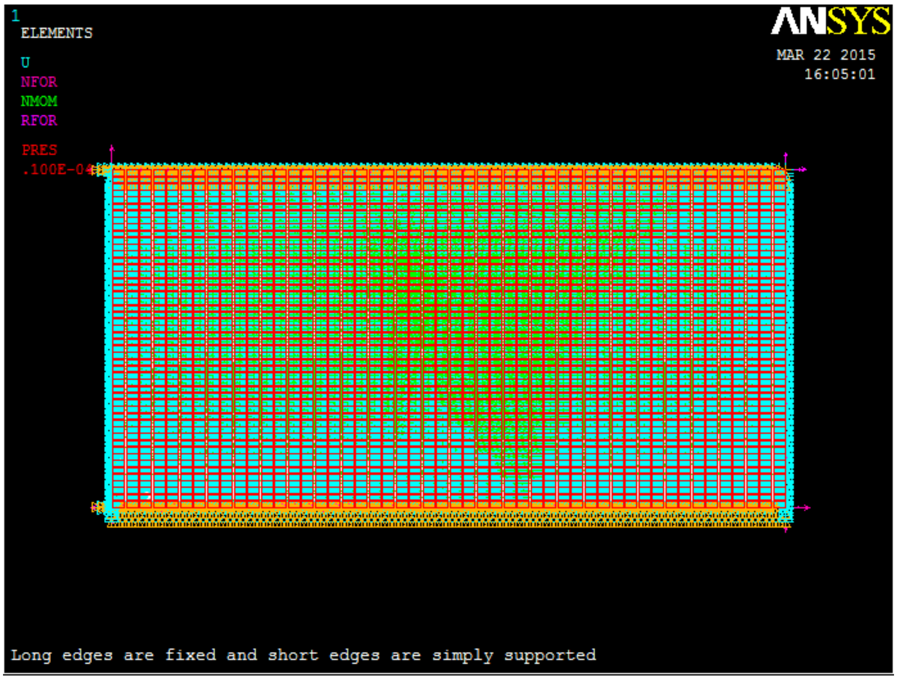


Figure 4.7. Model of plate used for laminate bending(CFRP-VE) in which long edges are fixed and short edges are simply supported(LE-F and SE-SS).

Figure 4.8. shows contour plot of displacements of the model shown in Figure 4.7.

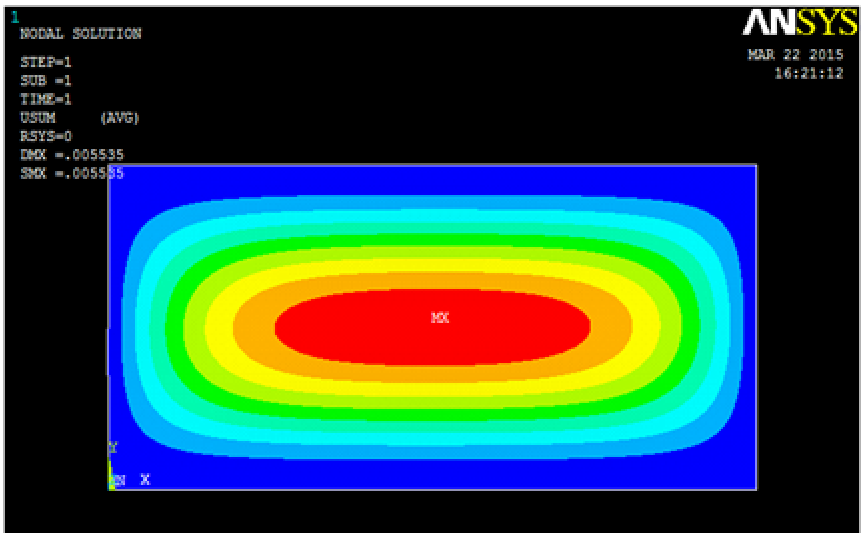


Figure 4.8. Contour plot of displacements of (CFRP-VE) for (LE-F and SE-SS)

Maximum longitudinal stresses $\sigma_{x(max)}$ and transverse stresses $\sigma_{y(max)}$ developed in the plates with all the long edges fixed and short edges simply supported has been given in Table 4.8. The nondimensional parameters (σ_x/E_1) and (σ_y/E_2) also has been given in Table 4.8. Based on the nondimensionalised stress value, index value has been assigned from '1' to '9'. Accordingly the composite laminate having the lowest ($\sigma_{x(max)}/E_1$) or ($\sigma_{y(max)}/E_2$) value has been assigned a value of '1' and the composite laminate having the highest ($\sigma_{x(max)}/E_1$) or ($\sigma_{y(max)}/E_2$) value has been assigned a value of '9'.The index values based on both the nondimensional parameters are also given in Table 4.8.

Table 4.8. Maximum Stresses (LE-F and SE-SS)

Specimen	$\sigma_{x(max)}$ (N/mm^2)	$\sigma_{y(max)}$ (N/mm^2)	($\sigma_{x(max)}/E_1$) x10^6	Index Value	($\sigma_{y(max)}/E_2$) x10^6	Index Value
CFRP(E)	0.2085	0.2085	1.4708	1	25.0640	6
CFRP(VE)	0.2094	0.2094	1.4780	3	26.7119	9
CFRP(P)	0.2087	0.2087	1.4726	2	25.8321	8
GFRP(E)	0.1786	0.1786	4.0081	7	22.5001	1
GFRP(VE)	0.1802	0.1802	4.0513	9	24.0267	4
GFRP(P)	0.1789	0.1789	4.0184	8	23.1757	2
AFRP(E)	0.1936	0.1936	2.5554	4	23.7132	3
AFRP(VE)	0.195	0.195	2.5766	6	25.3185	7
AFRP(P)	0.1947	0.1947	2.5713	5	24.5421	5

Figure 4.9. shows the model of the plate (CFRP-VE), whose short edges are fixed and long edges are simply supported.

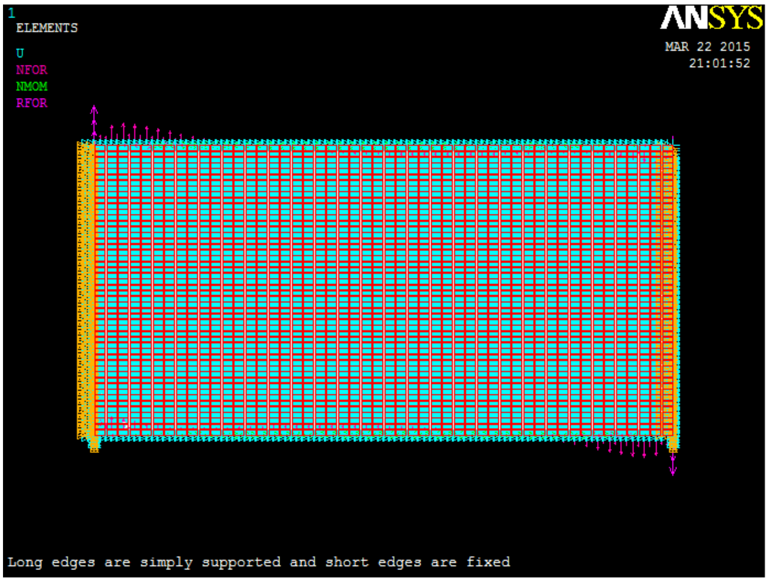


Figure 4.9. Model of plate used for laminate bending in(CFRP-VE) which long edges are simply supported and short edges are fixed (LE-SS and SE-F).

Figure 4.10. shows contour plot of displacements of the model shown in Figure 4.9.

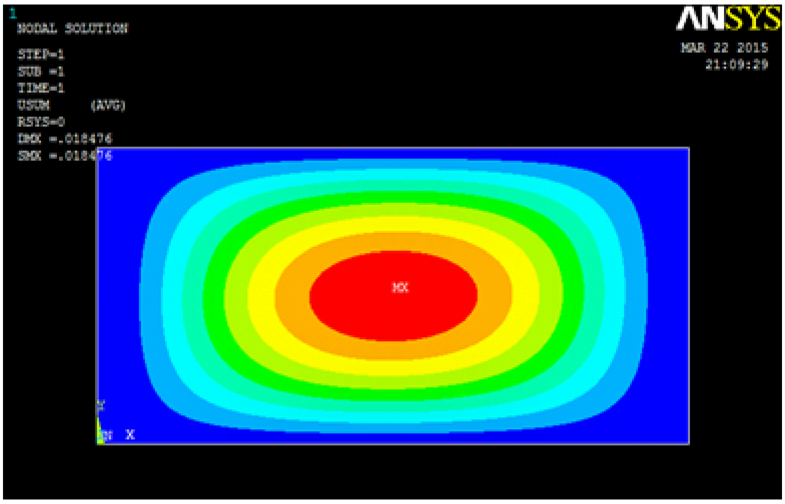


Figure 4.10. Contour plot of displacements of (CFRP-VE) for (LE-SS and SE-F)

Maximum longitudinal stresses (σ_x(max) and transverse stresses σ_y(max) developed in the plates with all the long edges simply supported and short edges fixed has been given in Table 4.9. The nondimensional parameters (σ_x/E_1) and (σ_y/E_2) also has been given in the same table. The index values based on both the nondimensional parameters are also given in the same table.

Table 4.9. Maximum Stresses (LE-SS and SE-F)

Specimen	$\sigma_{x(max)}$ (N/mm^2)	$\sigma_{y(max)}$ (N/mm^2)	($\sigma_{x(max)}/E_1$) x10^6	Index Value	($\sigma_{y(max)}/E_2$) x10^6	Index Value
CFRP(E)	0.1877	0.1877	1.3241	1	22.5636	6
CFRP(VE)	0.1884	0.1884	1.3298	3	24.0331	9
CFRP(P)	0.1879	0.1879	1.3259	2	23.2576	8
GFRP(E)	0.1649	0.1649	3.7006	4	20.7742	1
GFRP(VE)	0.1663	0.1663	3.7388	6	22.1733	4
GFRP(P)	0.1653	0.1653	3.7129	5	21.4139	2
AFRP(E)	0.1765	0.1765	2.3297	7	21.6187	3
AFRP(VE)	0.1775	0.1775	2.3454	9	23.0464	7
AFRP(P)	0.1773	0.1773	2.3415	8	22.3488	5

4.4.3. Geometrical nonlinear analysis of composite laminate

Geometrical NonLinear Analysis(GNLA) of the laminate has been conducted to find the stress and strain developed at matrix failure. Nonlinear behaviour of the laminates has been determined using GNLA. Figure 4.3 shows the model used for geometric nonlinear analysis of a laminate with all the edges simply supported. CFRP-VE has been the material used for the shown model.

Stress and strain developed at the point of matrix failure has been calculated as described below. In nonlinear analysis incremental load has been applied. Load – deflection curve (P-δ curve) has been drawn for central node (node having maximum deflection) as shown in Fig. 4.11.

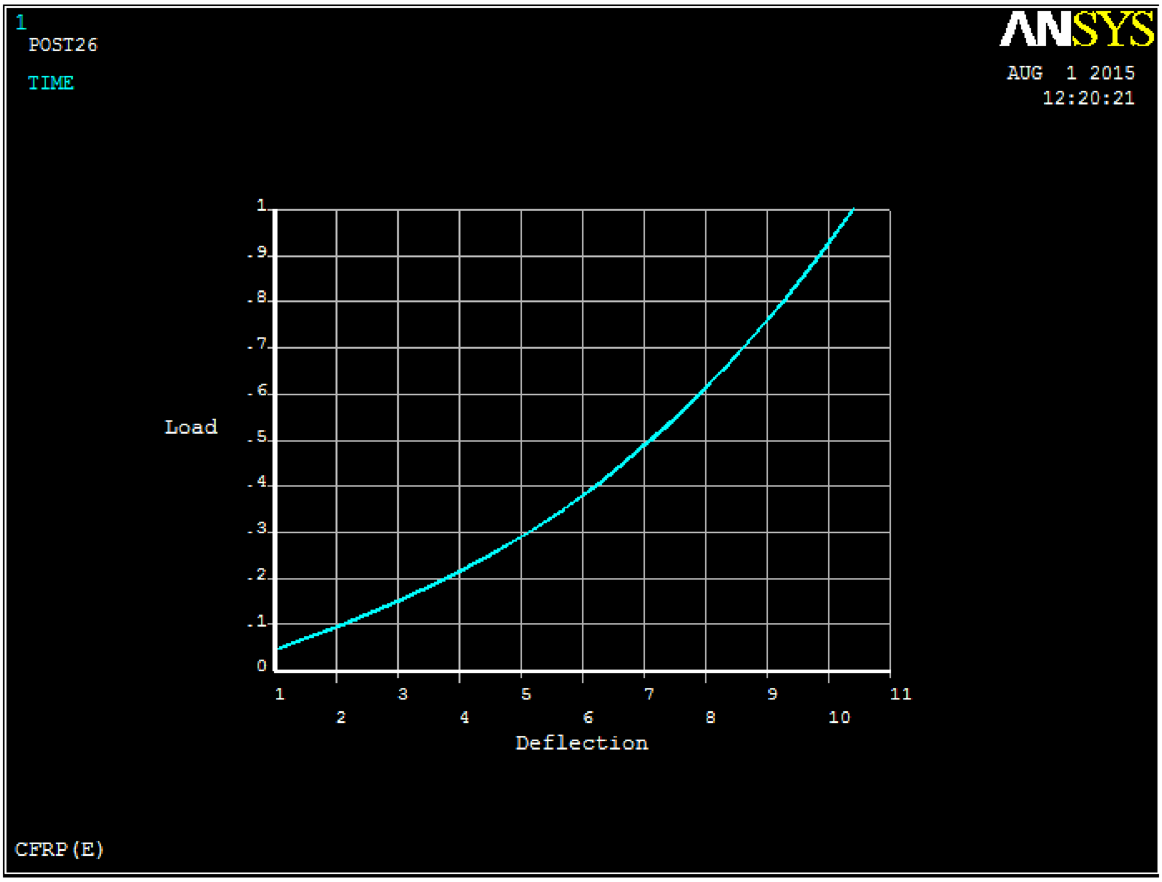


Figure 4.11. Load Deflection curve

Tangents have been drawn from upper and lower end of the P-δ curve. Deflection at the point of intersection of tangents drawn from upper and lower end of P-δ curve gives the deflection at the time of matrix failure (Fig. 4.12). Stress and strain corresponding to this deflection gives the stress and strain developed at matrix failure.

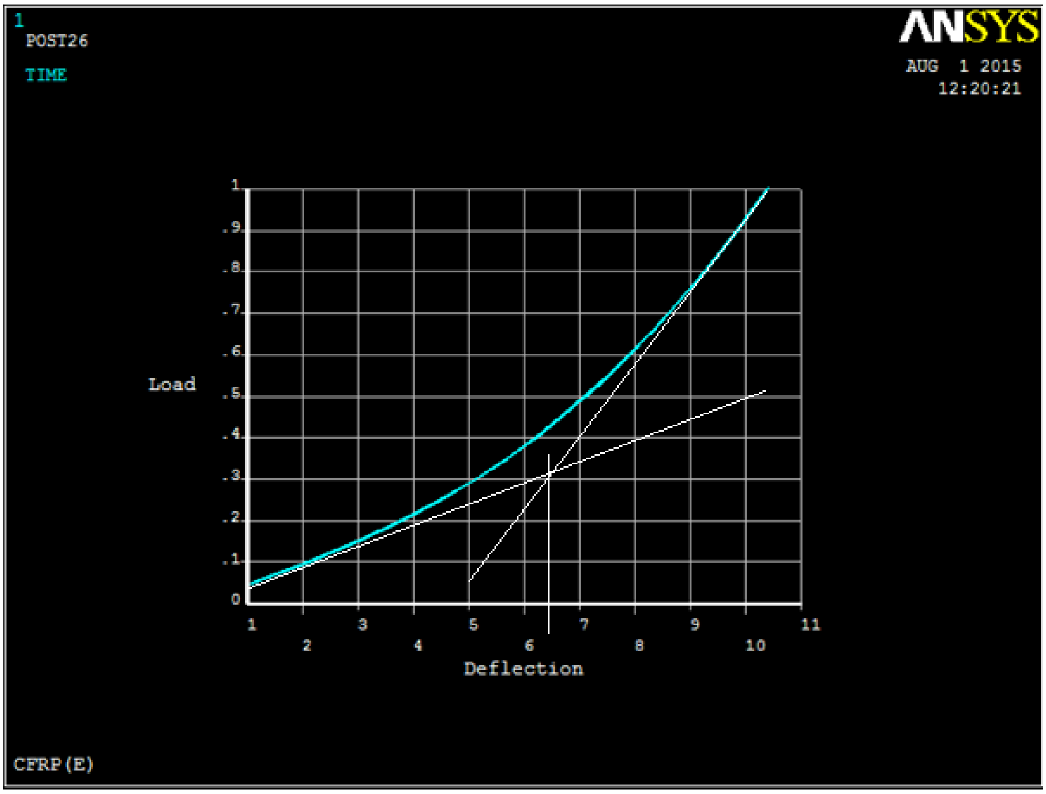


Figure 4.12. Deflection at the point of intersection of tangents drawn from upper and lower end of P-δ curve.

Stress at matrix failure has been nondimensionalised as σ_{matf}/E_1. Accordingly the nondimensionalised value of stress developed at matrix failure, strain developed at matrix failure along ‘x’ direction and ‘y’ directions are given in Table 4.10.

Table 4.10. Stress and strain developed in the laminate at matrix failure

FRP	Stress at matrix failure (σ_{matf}) (N/mm^2)	(σ_{matf}/E_1) x10^3	Index Value	Strain at matrix failure in 'x' direction(ε_x) x 10^3	Index Value	Strain at matrix failure in 'y' direction(ε_y) x 10^3	Index Value
CFRP(E)	52.91	0.373	3	0.366	9	0.274	4
CFRP(VE)	52.91	0.373	3	0.368	7	0.278	2
CFRP(P)	52.9	0.373	3	0.368	7	0.274	4
GFRP(E)	18.57	0.417	8	0.405	3	0.265	9
GFRP(VE)	18.58	0.418	8	0.408	2	0.269	7
GFRP(P)	18.57	0.417	9	0.409	1	0.265	9
AFRP(E)	30.1	0.397	6	0.378	6	0.290	1
AFRP(VE)	30.08	0.397	6	0.381	5	0.273	5
AFRP(P)	29.93	0.395	4	0.385	4	0.271	6

4.4.4. Results and discussions of bending analysis

Maximum nondimensionalised deflections developed in the laminates of all materials whose all edges has been simply supported have been given in Table 4.4. It has been seen that the variation of deflection is directly related to the E_l of the fibres and E_l of the laminate except for laminates where the fibre used is aramid. Accordingly maximum deflection is developed in GFRP (VE) and minimum in CFRP (E). Maximum longitudinal stresses $\sigma_{x(max)}$ and transverse stresses $\sigma_{y(max)}$ developed in the plates and the nondimensional parameters $(\sigma_{x(max)}/E_1)$ and $(\sigma_{y(max)}/E_2)$ for all four type of support conditions have been given in Table 4.6, Table 4.7, Table 4.8 and Table 4.9. It has been seen that the pattern of the variation of the nondimensional parameters $(\sigma_{x(max)}/E_1)$ and $(\sigma_{y(max)}/E_2)$ has been same for all the four support conditions. $(\sigma_{x(max)}/E_1)$value is maximum in the plates made of GFRP(VE) and in those made of CFRP(E) the value of $(\sigma_{x(max)}/E_1)$ is minimum. Except for AFRP (VE), $(\sigma_{x(max)}/E_1)$ value developed in all composite plates has a direct relation with the E_l of the material. In comparison with longitudinal modulus of elasticity, in AFRP (VE) plates, the $(\sigma_{x(max)}/E_1)$ value is more than expected. The values of $(\sigma_{y(max)}/E_2)$ do not show a direct relation with E_2 or any other material properties of the laminates. But it exhibits a proportional relation with the E of the matrices. It has been seen that least value has been exhibited by GFRP (E) and highest value by CFRP (VE). Based on $(\sigma_{x\ (max)}/E_1)$ and $(\sigma_{y(max)}/E_2)$, index values has been assigned to the composites as given in Table 4.9. From the above results it can be concluded that in composite plates the longitudinal flexural strength is fibre dominated while the transverse flexural strength is more sensitive to matrix strength.

Bending stress is a major cause of concern in establishing the safety of ship structure. Bending moments are largest at the mid ship area of a ship. Bending loads are due to hull, machinery, cargo loads and wave loads. Among the different structural members of a ship, members where tensile yield due to bending stress is an important factor use of CFRP's is advisable. These members are longitudinal and transverse girders, plates between the stiffeners etc.

($\sigma_{matf/}E_1$) and strain developed at matrix failure in longitudinal ('x') direction(ε_x) and lateral ('y') direction(ε_y) and corresponding index values have been given in Table 4.10. It can be seen that the stress developed at the matrix failure is directly related to 'E' of the fibres used alone. Accordingly stress at matrix failure has a maximum value for laminates with carbon fibre and a minimum value for laminates with glass fibre. Strain developed in 'x' direction is directly dependent on the fibre used in the laminate. Maximum strain is associated with the fact that at the time of matrix failure, yielding is more prominent. Thus material gives a warning before failure. Accordingly maximum strain in 'x' direction is developed in laminates where the fibre used is glass and minimum strain developed is in laminates where the fibre used is carbon. Strain developed in 'y' direction does not exhibit a direct relation with the E of the fibres used in the laminates. Index values have been assigned to laminates based on stress developed at matrix failure and due to the strain developed in longitudinal and lateral directions. Based on stress developed at matrix failure, laminates with maximum stress value has been given a value of '1' and laminates with minimum stress value has been given a value of '9'. Accordingly laminates with carbon fibre have been assigned a value of '3' and GFRP (E) has been assigned a value of '9'. Based on the strain developed in longitudinal and lateral directions, the laminate with maximum strain value has been given a value of '1' and the laminate with minimum strain value has been given a value of '9'. Accordingly GFRP(P) has been assigned a value of '1' and CFRP(E) has been assigned a value of '9', when strain in longitudinal direction is considered and AFRP(E) has been assigned a value of '1' and GFRP(P) has been assigned a value of '9', when strain in lateral direction is considered.

The response of ship structures subjected to rapidly varying loads such as slamming, sloshing, green water and underwater explosion produces large inelastic deformations. When the magnitude of the maximum deflection reaches the order of the plate thickness, the membrane action becomes comparable to that of the bending action. Beyond this (maximum deflection greater than thickness), the membrane action predominates. Therefore, in plate sections of a ship structure where large deformations occur, large deflection analysis is mandatory. By conducting geometric nonlinear analysis a strain based design method can be adopted. Knowing the strain at failure for specific composites, design strain limit can be developed for different materilas. Accordingly allowable deflections can be calculated and serviceability limits can be framed for panels made of different laminated composites.

Based on $\frac{w_{max}E_2t^3}{qa^4}$, $(\sigma_{x(max)}/E_1)$ and $(\sigma_{y(max)}/E_2)$, (σ_{matf}/E_1), ε_x and ε_y; bending strength index has been assigned to the composites as given in Table 4.11. To assign the index value for bending strength, the index values based on above variables have been aggregated linearly and given in Table 4.11. Index value based on bending strength has been assigned a value of ‘1’ to value of ‘9’. Accordingly the composite laminate having the lowest aggregated value has been assigned a value of ‘1’ and the composite laminate having the highest aggregated value has been assigned a value of ‘9’. Above index values are tabulated and given in Table 4.11.

Table 4.11. Index value based on Bending of Laminates

Specimen	**CFRP (E)**	**CFRP (VE)**	**CFRP (P)**	**GFRP (E)**	**GFRP (VE)**	**GFRP (P)**	**AFRP (E)**	**AFRP (VE)**	**AFRP (P)**
Index value based on $w_{\max}$	1	3	2	7	9	8	4	5	6
Index value based on ($\sigma_{x(max)}/E_1$)	1	3	2	7	9	8	4	6	5
Index value based on ($\sigma_{y(max)}/E_2$)	6	9	8	1	4	2	3	7	5
Index value based on (σ_{matf}/E_1)	3	3	3	8	8	9	6	6	4
Index value based on(ε_x)	9	7	7	3	2	1	6	5	4
Index value based on(ε_y)	4	2	4	9	7	9	1	5	6
Total Index value	24	27	26	35	39	37	24	34	30
Index value based on bending of plates	2	4	3	7	9	8	2	6	5

When bending strength is considered , CFRP(E) and AFRP(E) have been rated as the best in an equal manner and GFRP(VE) has been rated as the last choice.

4.5. Buckling strength of laminates

Buckling strength of laminates has been defined in terms of the critical buckling pressure under transverse loading and inplane loading. These parameters have been estimated using linear buckling analysis.

Inplane critical buckling pressure has been calculated using FEA of the standard strength specimen and using classical lamination theory. For the various materials critical buckling pressure has been tabulated and compared.

4.5.1. Linear buckling analysis due to inplane compressive load

To attain uniformity between the nine laminates, laminates of same thickness and with same number of plies and same stacking sequence are considered for all materials. Specimen selected for the buckling analyses is the same as that selected for bending analyses as given in Figure 4.1.

Accordingly a rectangular plate 1000mm x 500mm is considered for the present study. The plate consists of 8 plies of 0.5mm thick each. The stacking sequence of the plies used is [45/0/-45/90]s. The total thickness of the plate (t) is 4mm. The study was conducted using ANSYS. The element used to model the plate is SHELL 281. The aspect ratio of the mesh has been maintained as 2.

Load has been applied as inplane compressive load (p) acting along the short edges of the laminate. All the edges of the laminates are assumed to simply supported. The plates are modelled using the material properties given in table 4.3.

Classical Laminated Plate Theory (CLPT)

Critical buckling pressure due to inplane compressive pressure $(\overline{N_x})$ has been calculated analytically using CLPT. According to classic lamination theory the equation for evaluating critical buckling pressure of the composite laminate simply supported at all the edges is given in Appendix A (A-9).

Finite Element Analysis (FEA)

Critical buckling pressure due to inplane compressive pressure $(\overline{N_x})$ has been carried out using FEA. Model used for bucking analysis in ANSYS is given in Figure 4.11. For the given model the material used is CFRP-VE. Linear buckling analysis of all the laminates has been carried out and critical buckling pressure due to inplane compressive pressure has been found out.

Critical buckling pressure has been found out using FEM and CLPT and has been tabulated in Table 4.12. The critical buckling pressure due to inplane compressive pressure $(\overline{N_x})$ has been nondimensionalised as $\left(\frac{\overline{N_x}b^2}{E_2t^3}\right)$. Index value of '1' to '9' has been assigned to each laminate based on the critical buckling pressure. Accordingly laminate with highest buckling pressure has been assigned an index value of '1' and the laminate with lowest buckling pressure has been assigned an index value of '9'. Index value thus assigned has been given in Table 4.12.

Table 4.12. Critical buckling pressure due to inplane compressive load

FRP	Buckling pressure$(\overline{N_x})$ (FEM) (N/mm)	Buckling pressure$(\overline{N_x})$ (CLPT) (N/mm)	% variation	$\left(\frac{\overline{N_x}b^2}{E_2t^3}\right)$	Index value
CFRP(E)	74.05	83.59	11.41	39.24	1
CFRP(VE)	73.50	83.12	11.57	41.41	3
CFRP(PE)	73.99	83.36	11.24	40.30	2
GFRP(E)	30.06	31.17	3.56	15.33	7
GFRP(VE)	29.60	30.76	3.76	16.02	9
GFRP(PE)	29.99	30.99	3.22	15.68	8
AFRP(E)	44.99	49.11	8.38	23.51	4
AFRP(VE)	44.43	48.58	8.55	24.65	6
AFRP(PE)	44.52	48.19	7.62	23.74	5

4.5.2. Linear buckling analysis due to transverse load

Buckling due to transverse load occurs mainly on floor deck plates and on side hull panels (due to hydrostatic pressure).Linear buckling analysis has been conducted to find critical transverse buckling pressure (λ). FEA has been conducted to find the critical transverse buckling pressure.

Load has been applied as transverse pressure (q). Four types of plate arrangements are considered for the study as given in Table 4.5. The plates are modelled using the material properties given in table 4.3 and critical transverse buckling pressure is found out. The aspect ratio of the mesh has been maintained as 2.

Model used for bucking analysis in ANSYS is given in Figure 4.13, 4.15, 4.17 and 4.19. For all the shown models the material used is CFRP-VE. Linear buckling analysis of all the laminates has been carried out.

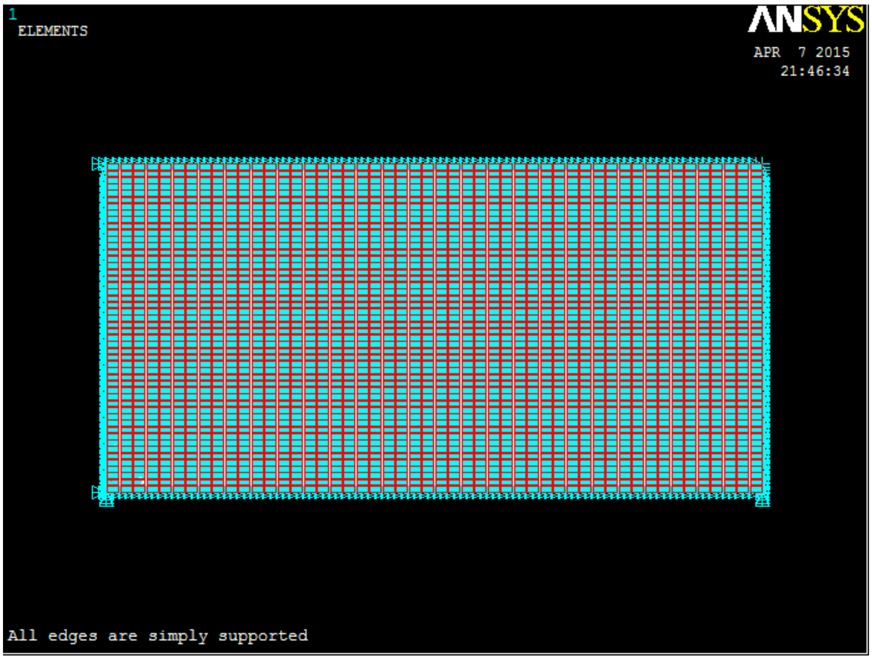


Figure 4.13. Model of plate used for buckling analysis (CFRP-VE) in which all the edges are simply supported (AE-SS)

Figure 4.14. shows contour plot of first mode of buckling of the model shown in Figure 4.13. The critical buckling pressure has been found out to be 32.497 x 10^3 N/mm^2.

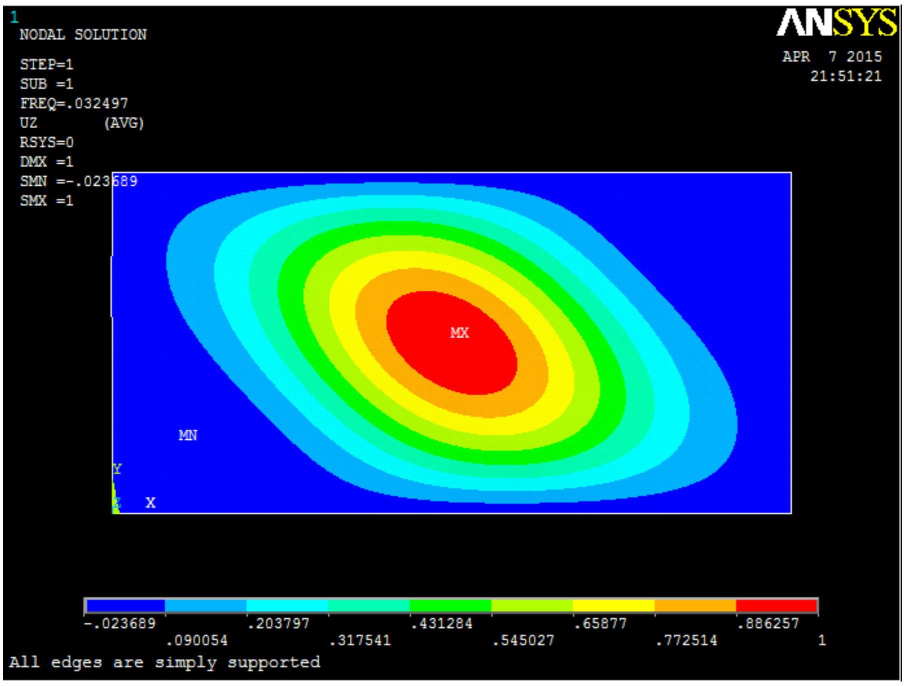


Figure 4.14. Contour plot of first mode of buckling of (CFRP-VE) for (AE-SS)

Figure 4.15. shows the model of the plate (CFRP-VE), whose all edges are fixed.

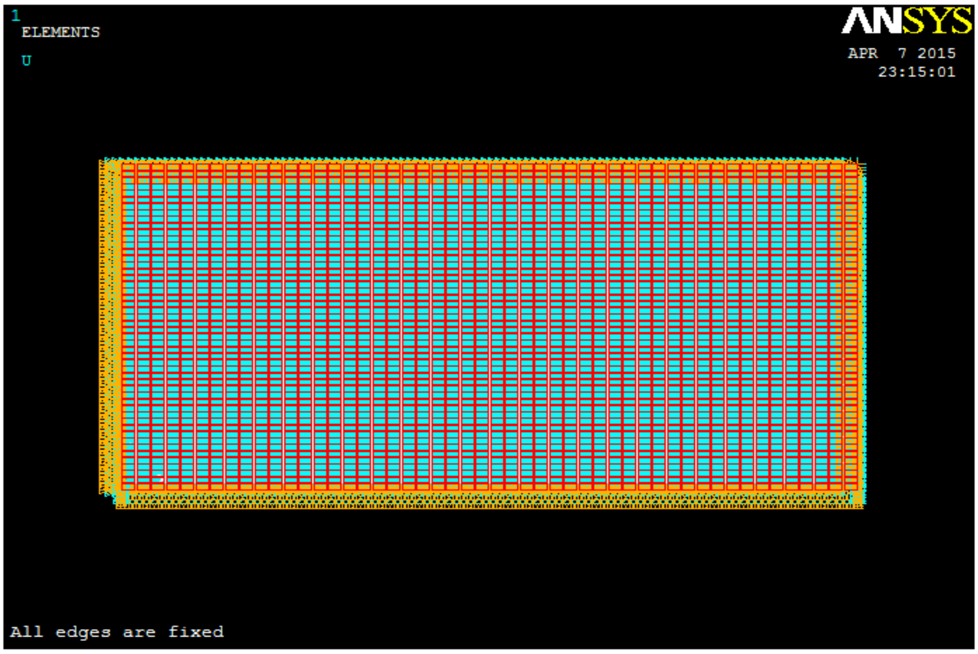


Figure 4.15. Model of plate used for buckling analysis (CFRP-VE) in which all the edges are fixed(AE-F)

Figure 4.16. shows contour plot of buckled mode of the model shown in Figure 4.15. The critical buckling pressure has been found out to be 126.12 x 10^3 N/mm^2.

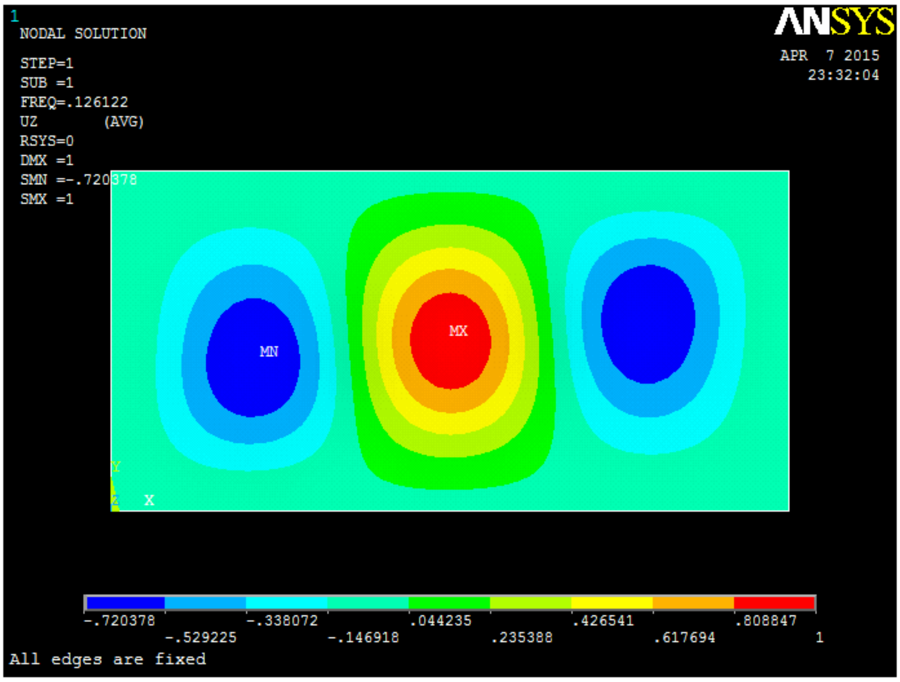


Figure 4.16. Contour plot of buckling mode of (CFRP-VE) for (AE-F)

Figure 4.17. shows the model of the plate (CFRP-VE), whose long edges are fixed and short edges are simply supported.

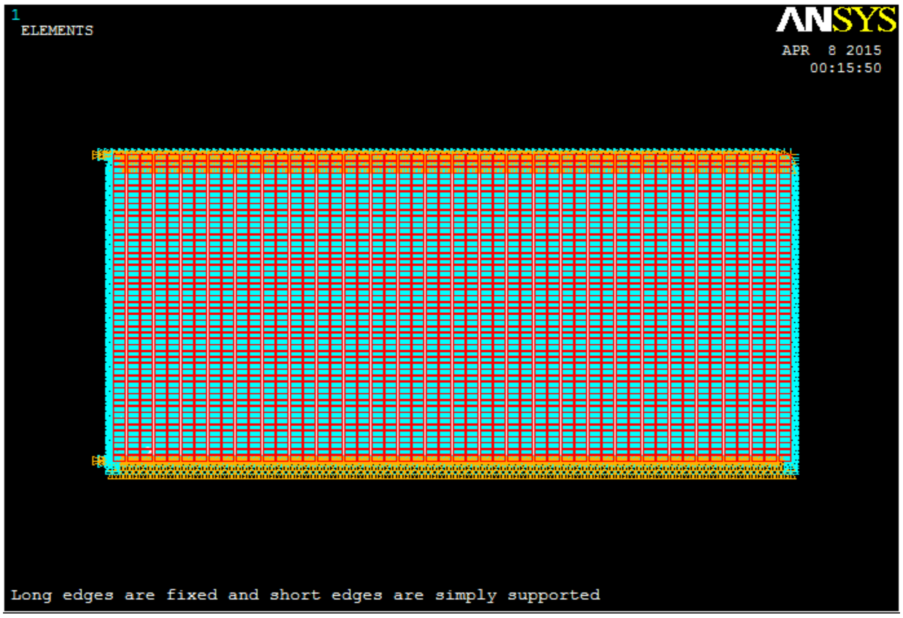


Figure 4.17. Model of plate used for buckling analysis (CFRP-VE) in which long edges are fixed and short edges are simply supported(LE-F and SE-SS)

Figure 4.18. shows contour plot of buckled mode of the model shown in Figure 4.17. The critical buckling pressure has been found out to be 189.38 x 10^3 N/mm^2.

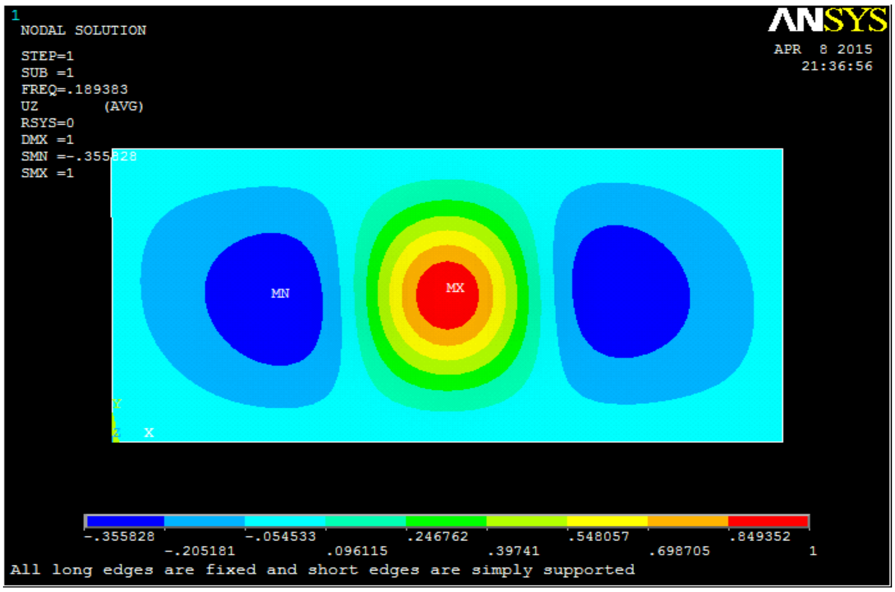


Figure 4.18. Contour plot of buckling mode of (CFRP-VE) for (LE-F and SE-SS)

Figure 4.19. shows the model of the plate(CFRP-VE), whose long edges are simply supported and short edges are fixed.

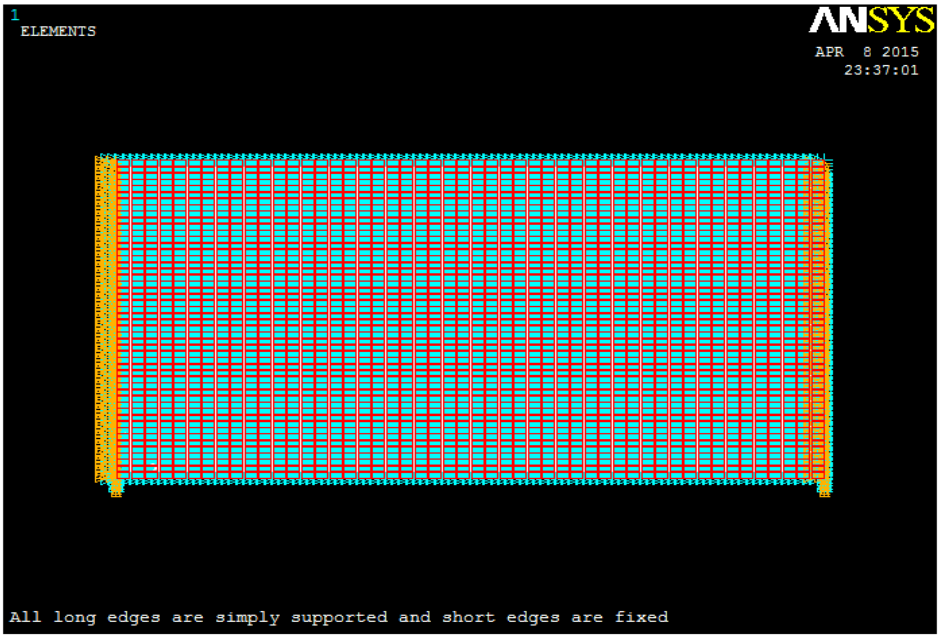


Figure 4.19. Model of plate used for buckling analysis (CFRP-VE) in which long edges are simply supported and short edges are fixed (LE-SS and SE-F)

Figure 4.20. shows contour plot of buckled mode of the model shown in figure 4.19. The critical buckling pressure has been found out to be 37.382 x 10^3 N/mm^2.

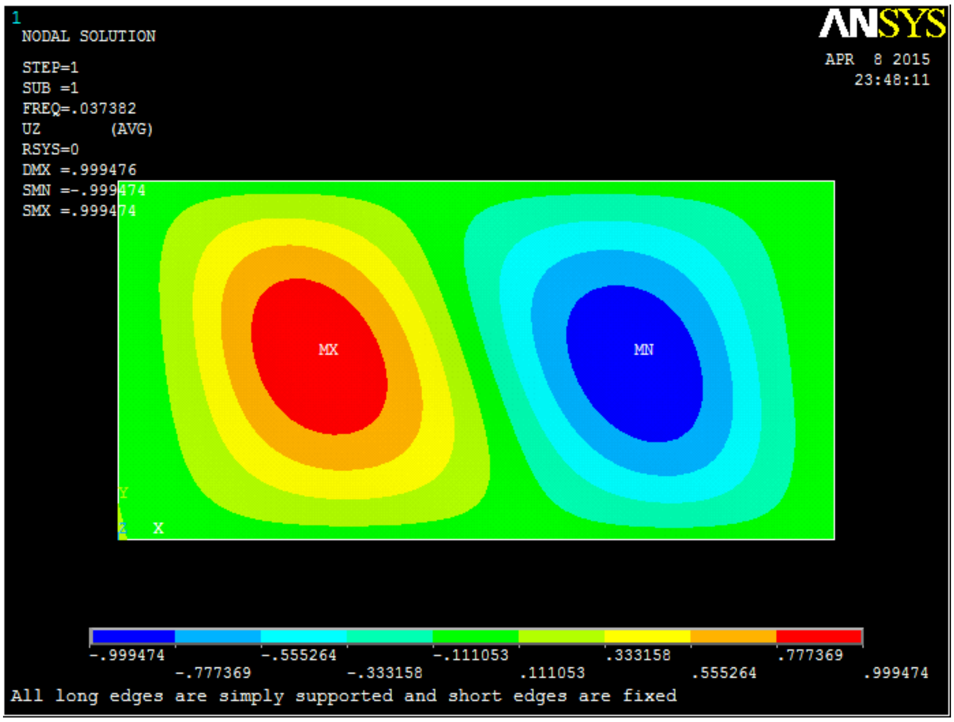


Figure 4.20. Contour plot of buckling mode of (CFRP- VE) for (LE-SS and SE-F)

The critical buckling pressure values developed in all the nine laminates for all the four support has been given in Table 4.13.

Table 4.13. Critical Buckling Pressure due to transverse load

Specimen	Buckling pressure(λ) x 10^3 (AE-SS) (N/mm^2)	Buckling pressure(λ) x 10^3 (AE-F) (N/mm^2)	Buckling pressure(λ) x 10^3 (LE-F and SE-SS) (N/mm^2)	Buckling pressure(λ) x 10^3 (LE-SS and SE-F) (N/mm^2)
CFRP(E)	32.916	127.46	191.60	37.826
CFRP(VE)	32.497	126.122	189.38	37.382
CFRP(P)	33.036	128.52	192.91	38.062
GFRP(E)	19.222	75.428	115.03	22.334
GFRP(VE)	18.636	73.768	112.24	21.737
GFRP(P)	19.337	77.245	117.53	22.639
AFRP(E)	22.619	88.296	132.87	26.267
AFRP(VE)	22.152	86.792	130.37	25.769
AFRP(P)	22.945	90.145	135.70	26.693

The transverse critical buckling pressure has been nondimensionalised as $\frac{\lambda b^2}{E_2 t^2}$. Based on the transverse critical buckling pressure, buckling strength index has been assigned to the composites as given in Table 4.14. It can be seen that the variation critical buckling pressure for different laminates follow the same pattern for all the support conditions. To assign the index value, the critical pressure values for the laminates with AE-SS has been used. Index value has been assigned from value ‘1’ to value ‘9’. Accordingly the composite laminate having the highest buckling pressure has been assigned a value of ‘1’ and the composite laminate having the least buckling pressure has been assigned a value of ‘9’.

Table 4.14. Transverse critical Buckling Pressure

Specimen	Buckling pressure (λ)x 10^3 (AE-SS) (N/mm^2)	$\left(\frac{\lambda b^2}{E_2 t^2}\right)$	Index Value
CFRP(E)	32.916	0.0618	2
CFRP(VE)	32.497	0.0648	3
CFRP(P)	33.036	0.0639	1
GFRP(E)	19.222	0.0378	8
GFRP(VE)	18.636	0.0388	9
GFRP(P)	19.337	0.0391	7
AFRP(E)	22.619	0.0433	5
AFRP(VE)	22.152	0.0450	6
AFRP(P)	22.945	0.0452	4

4.5.3. Results and discussions of linear buckling analysis

It has been found out that buckling pressure due to inplane compressive pressure is fibre dominated and has a direct relation with E_l of the composite laminates. Accordingly CFRP (E) buckles at the highest load and GFRP (VE) has the minimum resistance to buckling, when inplane compressive loads are considered. When transverse loads are considered buckling pressure has a direct relation with the E of the fibres used and E of the matrices dominates the transverse buckling behaviour of the plates. But, it can be seen that buckling load does not has a direct relation with the E_l of the composite laminates. This may be due to the orthotropic behaviour of composites. For all the four support conditions the same pattern has been found out.

The buckling strength of each panel of the ship structure is important for the overall strength of the structure. Buckling is likely to occur on panels on a ship due to large compressive stresses developed due to longitudinal stresses and where bulkheads act as supports i.e. the bulkheads supporting the decks. In composite ships where thin plates of high modulus of elasticity are used, buckling distortion of composite structures has emerged as a major obstacle to the cost-effective fabrication of composite ships.

Based on $\left(\frac{\overline{N_x}b^2}{E_2t^3}\right)$ and $\left(\frac{\lambda b^2}{E_2t^2}\right)$; buckling strength index has been assigned to the composites as given in Table 4.15. To assign the index value for bucking strength, the index values based on above variables have been aggregated linearly and then index value based on buckling strength has been assigned from value ‘1’ to value ‘9’. Accordingly the composite laminate having the lowest aggregated value has been assigned a value of ‘1’ and the composite laminate having the highest aggregated value has been assigned a value of ‘9’. Above index values are tabulated and given in Table 4.15.

Table 4.15. Index value based on Buckling of Laminates

Specimen	**CFRP (E)**	**CFRP (VE)**	**CFRP (P)**	**GFRP (E)**	**GFRP (VE)**	**GFRP (P)**	**AFRP (E)**	**AFRP (VE)**	**AFRP (P)**
Index value based on $\left(\frac{\overline{N_x}b^2}{E_2t^3}\right)$	1	3	2	7	9	8	4	6	5
Index value based on $\left(\frac{\lambda b^2}{E_2t^2}\right)$	2	3	1	8	9	7	5	6	4
Total Index value	3	6	3	15	18	15	9	12	9
Index value based on buckling of plates	2	3	2	8	9	8	5	6	5

When buckling pressure is considered CFRP(E) and CFRP(P) has been rated as the best options and GFRP(VE) has been rated as the last choice.

4.6. Impact strength of laminates

Impact loads that act on ships are wave impact load, loads due to weapon discharge, collisions, explosions, flight operations and bulk operations. For military ships, major load can be created by the impact of explosions both in the air, underwater and directly against a ship structure. Ships must be designed and manufactured with sufficient strength to resist these forces. When the rate of load is high it will lead to brittle fracture loads. The brittle fracture failure mode involves the rapid propagation of a small crack, often deep below the surface, into a large crack ultimately leading to fracture. The risk of brittle fracture occurring depends on the material, temperature, geometry, and rate of loading. Even if impact loads are loads are small, repeated impact loads lead to fatigue failure.

Impact strength, is the capability of the material to withstand a suddenly applied load and is expressed in terms of energy.Impact strength of laminates has been defined in terms of the energy the material can absorb while an impact load acts on the plates.

In the present study impact energy absorbed by the composites has been calculated using FEA of the standard strength specimen. For the various materials impact energy absorbed has been tabulated and compared.

4.6.1. Description of specimen

For attaining uniformity between the nine laminates, laminates of same thickness and with same number of plies and same stacking sequence are considered for all materials.

Specimen selected for the impact analyses is the same as that selected for bending analyses as given in Figure 4.1. Accordingly a rectangular plate 1000mm x 500mm is considered for the present study. The plate consists of 8 plies of 0.5mm thick each. The stacking sequence of the plies used is [45/0/-45/90]s. The total thickness of the plate is 4mm.

The study was conducted using commercially available softwares like LS-PrePost and LS-DYNA. Modelling of the plate and ball has been done in LS-PrePost and the solver LS-Dyna has been used for solution. **LS-PrePost** is an advanced pre- and post-processor and model editor from Livermoore Software Technology Corporation, preparing input data and processing the results from LS-DYNA analyses [www.lstc.com/products/ls-prepost]. **LS-DYNA** is a general-purpose finite element program capable of simulating highly nonlinear and transient dynamic problems. Finite element analysis using explicit time integration is used in this solver. Nonlinearity can be due to changing boundary conditions, large deformations and nonlinear materials that do not exhibit ideally elastic behaviour. Transient dynamic analyses deal with high speed, short duration events where inertial forces are important.

In impact study, a steel ball has been dropped from a known height and has been made to impact the plate. During impact analysis the ball is modelled as rigid body and plate is modelled as elastic material. On impact, the plate will absorb the kinetic energy possessed by the ball and total internal energy of the plate gives the impact energy. As the laminates studied are orthotropic and elastic, the plate has been modelled using the element '4N SHELL' having 'ORTHOTROPIC ELASTIC' properties. The ball has been modelled using the element 'SOLID SPHERE' having 'SOLID' properties. The material properties used as input is given in Table 4.3.

4.6.2. Load and support conditions

Impact load has been applied as a steel ball of 50 mm diameter falling from a height of 60 mm. The initial velocity of the steel ball was taken as 10mm/millisecond [www.lstc.com/products/ls-dyna].

Four types of plate arrangements are considered for the study as given in Table 4.5.The plates are modelled using the material properties given in table 4.3 and impact energy absorbed has been found out. The aspect ratio of the mesh has been maintained as 2.

The steel ball is modelled using the material properties given in Table 4.16.

Table 4.16. Material properties of steel ball

Specimen	Diameter(mm)	Density(kg/m^3)	Poisson's ratio
Steel	50	7800	0.3

The plate i.e. composite laminate and the impactor i.e. steel ball has been modelled in LS Pre Post as shown in Figure 4.21.

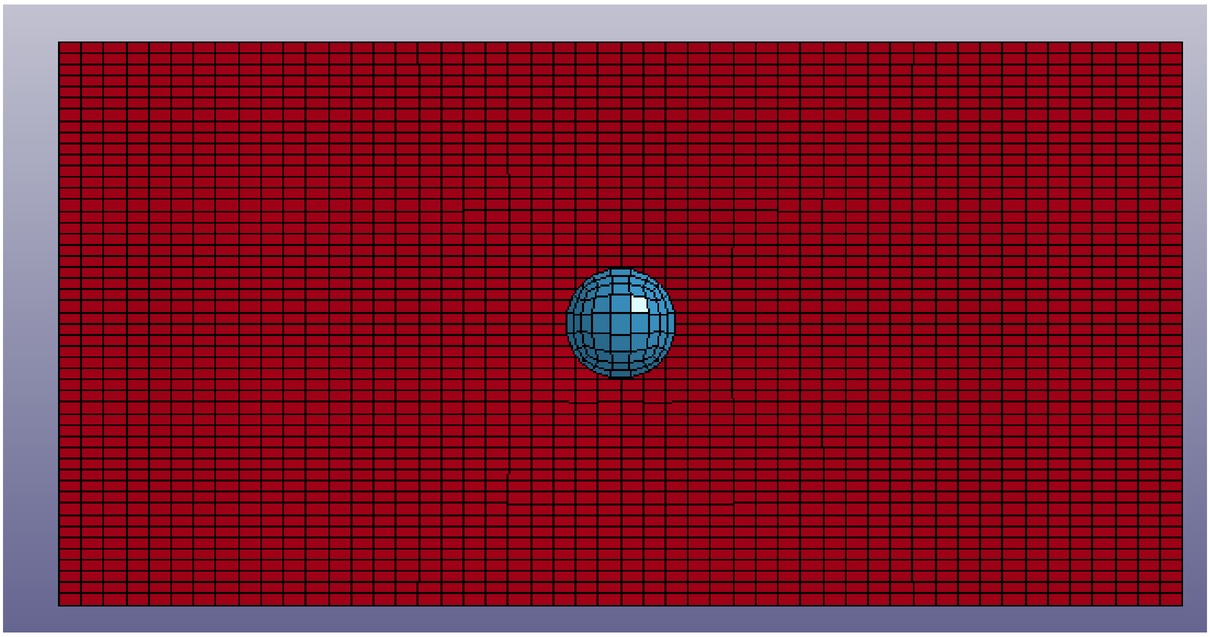


Figure 4.21. LS – Pre Post model of impactor and plate

The simulated model of the plate and impactor in LS DYNA has been shown in Figure 4.22. The front view of the model has been shown in the figure.

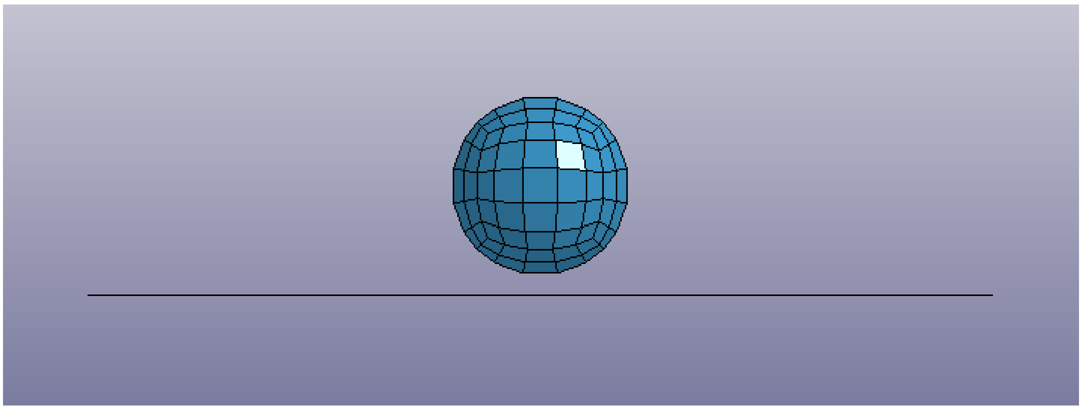


Figure 4.22. LS-DYNA simulated model (front view)

The front view of the deformed model in LS-DYNA has been shown in Figure 4.23.

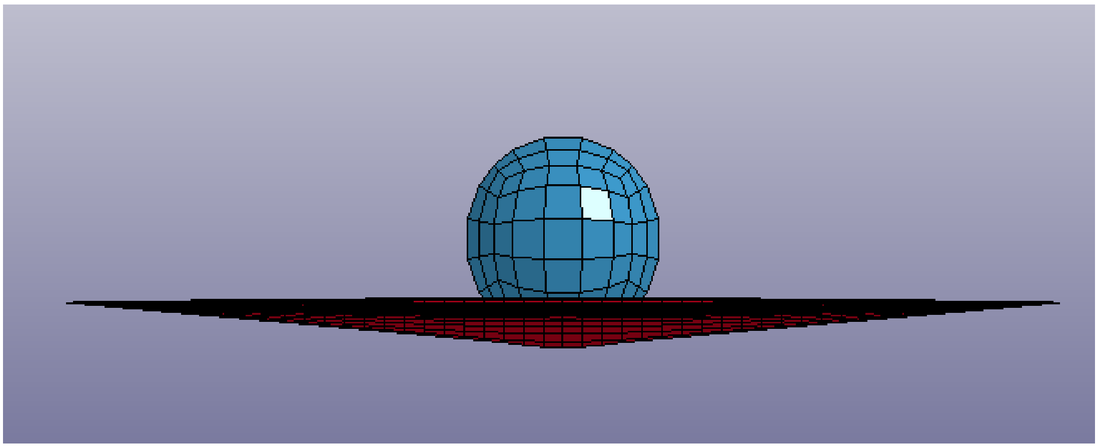


Figure 4.23. LS-DYNA deformed model (front view)

4.6.3. Results and discussions of impact analysis

The result of the impact tests will give the energy needed to fracture a material and can be used to measure the toughness of the material. This can be evaluated if the problem is modelled using a ‘damage model’. In the present study, damage model is excluded in the numerical simulation. Energy absorbing capacity of the material has evaluated. The quantitative results obtained can be used to compare the energy absorbing capacity of composites during impact. To assess the energy absorbing capacity of the plate, change in internal energy of the plate during the impact need to be found out.

Change in internal energy of composite plates during the impact with respect to time has been found out for all the nine composites and four types of support conditions. Maximum internal energy of the plate or the energy absorbed for all the specimens are given in Table 4.17.

Table 4.17. Maximum Internal Energy developed in the panel during impact

Specimen	Maximum Internal Energy (AE-SS) (kNmm)	Maximum Internal Energy (AE-F) (kNmm)	Maximum Internal Energy (LE-FF- SE-SS) (kNmm)	Maximum Internal Energy (LE-SS- SE-FF) (kNmm)
CFRP(E)	178.41	179.32	178.55	179.25
CFRP(VE)	176.77	179.23	177.22	179.18
CFRP(P)	176.46	179.13	177.1	178.89
GFRP(E)	170.24	172.37	173.62	168.65
GFRP(VE)	170.45	172.81	173.42	169.45
GFRP(P)	170.29	172.47	173.09	169.12
AFRP(E)	174.55	179.41	177.38	177.56
AFRP(VE)	175.89	177.13	178.41	174.89
AFRP(P)	175.71	176.31	178.37	173.62

The time taken by each specimen to reach the maximum internal energy for all support conditions has been tabulated in Table 4.18.

Table 4.18. Time taken for maximum absorption of impact energy

Specimen	Time (AE-SS) (millisec)	Time (AE-F) (millisec)	Time (LE-F and SE-SS) (millisec)	Time (LE-SS and SE-F) (millisec)
CFRP(E)	3.9	3.7	3.8	3.8
CFRP(VE)	3.9	3.8	3.7	3.9
CFRP(P)	3.9	3.8	3.8	3.9
GFRP(E)	4.5	4.4	4.5	4.5
GFRP(VE)	4.6	4.4	4.5	4.6
GFRP(P)	4.6	4.4	4.5	4.6
AFRP(E)	4.1	4.2	4	4.3
AFRP(VE)	4.1	4.1	4	4.2
AFRP(P)	4.1	4	4	4.1

‘Internal Energy’ vs ‘Time’ curve of CFRP(E), GFRP(E) and AFRP(E) has been superimposed and given in Figure 4.24.

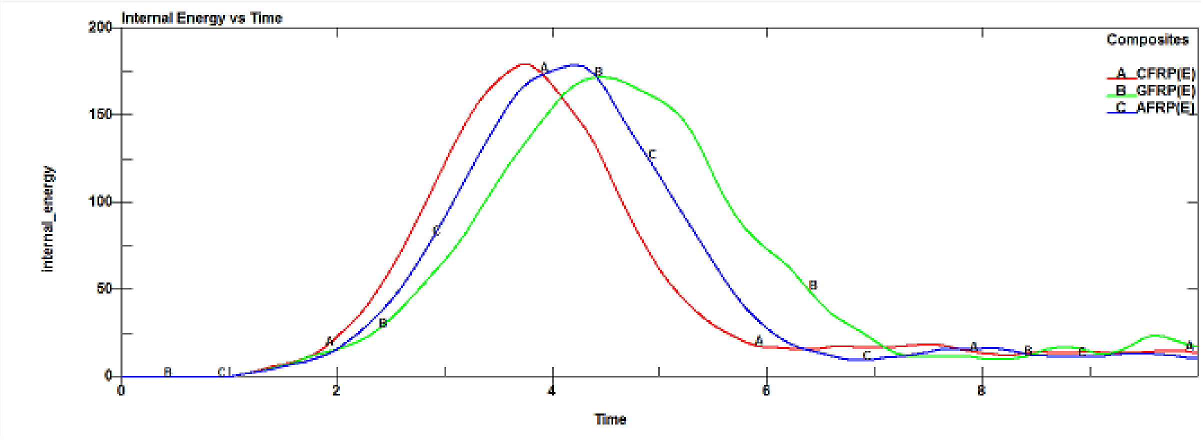


Figure 4.24. Internal Energy vs Time (All edges are Fixed)

In Figure 4.25. ‘Internal Energy’ vs ‘Time’ curves of CFRP(VE), GFRP(VE) and AFRP(VE) has been superimposed and in Figure 4.26. ‘Internal Energy’ vs ‘Time’ curves of CFRP(E), GFRP(E) and AFRP(E) has been superimposed. It has been seen that similar variations can be observed for all types of support conditions. In the study, analysis of laminates with all edges fixed has been considered.

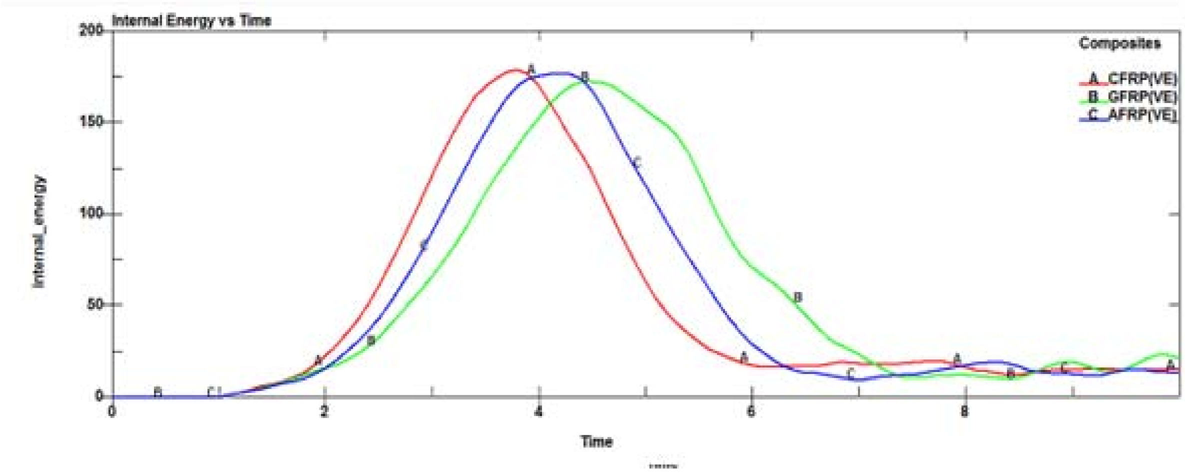


Figure 4.25. Internal Energy vs Time (All edges are Fixed)

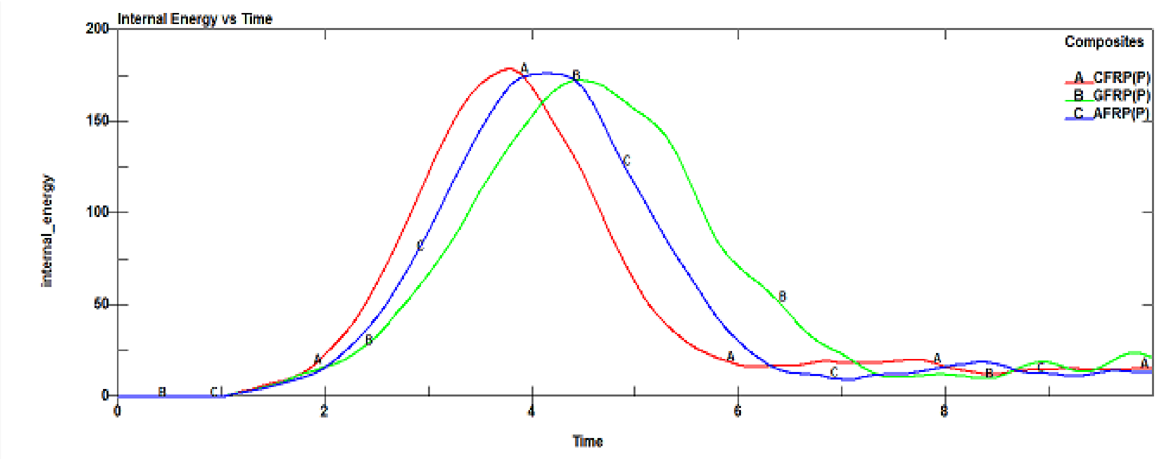


Figure 4.26. Internal Energy vs Time (All edges are Fixed)

‘Internal Energy’ vs ‘Time’ curves of CFRP(E), CFRP(VE) and CFRP(P) has been superimposed and given in Figure 4.27. In Figure 4.28, ‘Internal Energy’ vs ‘Time’ curves of GFRP(E), GFRP(VE) and GFRP(P) has been superimposed and in Figure 4.29, ‘Internal Energy’ vs ‘Time’ curves of AFRP(E), AFRP(VE) and AFRP(P) has been superimposed. In the analysis all edges are fixed.

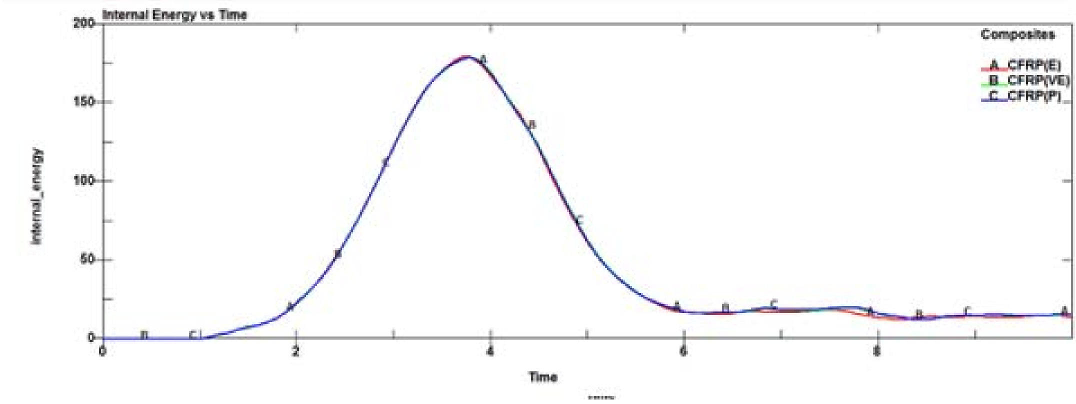


Figure 4.27. Internal Energy vs Time (All edges are Fixed)

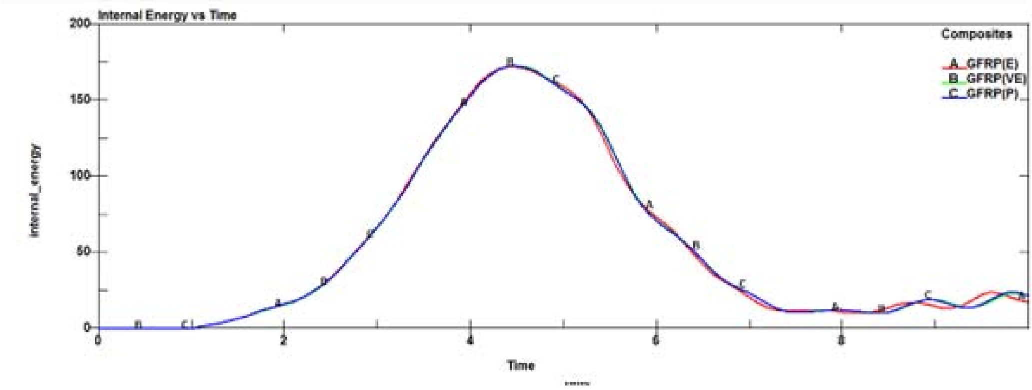


Figure 4.28. Internal Energy vs Time (All edges are Fixed)

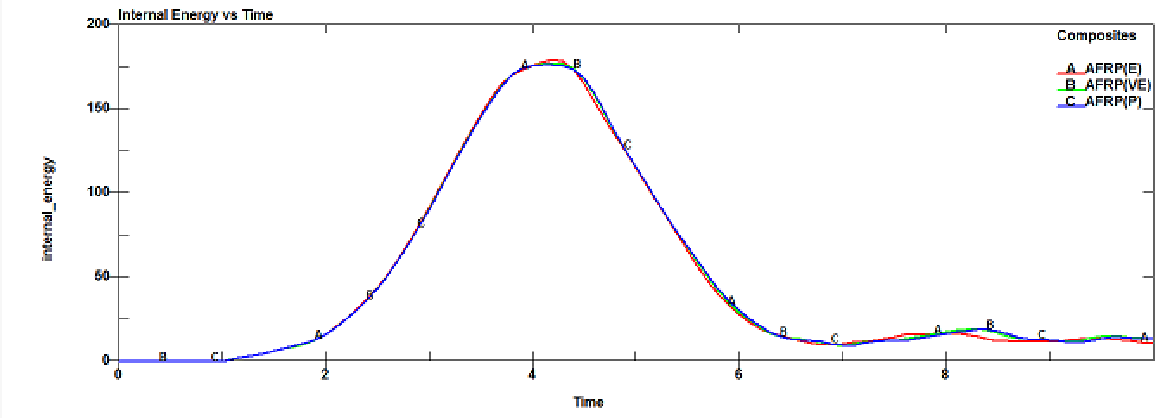


Figure 4.29. Internal Energy vs Time (All edges are Fixed)

'Internal Energy' vs 'Time' curves of CFRP (E) for all the four support conditions has been superimposed and given in Figure 4.30.

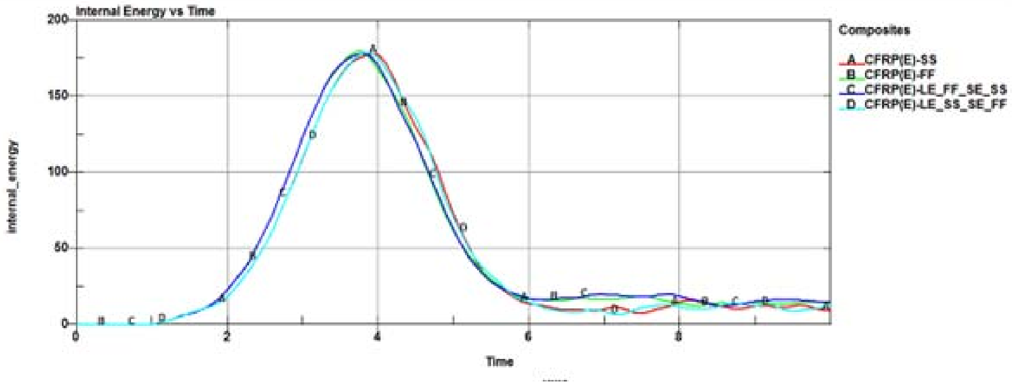


Figure 4.30. Internal Energy vs Time

The energy absorbing capacity of all specimens per unit mass for all support conditions has been calculated and tabulated in Table 4.19.

Table 4.19. Energy absorbed per unit mass

Specimen	**Energy absorbed per unit mass (J/kg) (AE-SS)**	**Energy absorbed per unit mass (J/kg) (AE-FF)**	**Energy absorbed per unit mass (J/kg) (LE-FF and SE-SS)**	**Energy absorbed per unit mass (J/kg) (LE-SS and SE-FF)**
CFRP(E)	56.89	57.18	56.94	57.16
CFRP(VE)	55.24	56.01	55.38	55.99
CFRP(P)	54.06	54.88	54.29	54.81
GFRP(E)	41.56	42.08	42.39	41.17
GFRP(VE)	40.97	41.54	41.69	40.73
GFRP(P)	40.31	40.83	40.98	40.04
AFRP(E)	64.55	66.35	65.60	65.67
AFRP(VE)	63.54	63.99	64.45	63.18
AFRP(P)	62.04	62.26	62.98	61.31

Energy absorbed per unit mass has been nondimensionalised as ‘Energy absorbed per unit weight per unit thickness and has been given in Table 4.20.

Table 4.20. Energy absorbed per unit weight per unit thickness

Specimen	Energy absorbed per unit weight per unit thickness (AE-SS)	Energy absorbed per unit weight per unit thickness (AE-FF)	Energy absorbed per unit weight per unit thickness (LE-FF and SE-SS)	Energy absorbed per unit weight per unit thickness (LE-SS and SE-FF)
CFRP(E)	1451.30	1458.70	1452.44	1458.13
CFRP(VE)	1409.20	1428.81	1412.79	1428.41
CFRP(P)	1379.15	1400.01	1384.15	1398.14
GFRP(E)	1060.27	1073.53	1081.32	1050.37
GFRP(VE)	1045.24	1059.72	1063.46	1039.11
GFRP(P)	1028.44	1041.61	1045.35	1021.37
AFRP(E)	1646.75	1692.60	1673.45	1675.14
AFRP(VE)	1621.02	1632.45	1644.25	1611.81
AFRP(P)	1582.77	1588.17	1606.73	1563.94

The energy absorption rate of all specimens per unit mass for all support conditions has been calculated and tabulated in Table 4.21.

Table 4.21. Energy absorbed rate per unit mass

Specimen	Energy absorption rate (AE-FF) J/kg/millisec	Energy absorption rate (AE-SS) J/kg/millisec	Energy absorption rate (LE-FF-SE-SS) J/kg/millisec	Energy absorption rate (LE-SS-SE-FF) J/kg/millisec	Average Energy absorption rate J/kg/millisec
CFRP(E)	45.75	48.46	46.99	47.17	47.09
CFRP(VE)	45.33	47.17	47.90	45.94	46.58
CFRP(P)	45.25	47.14	46.61	45.87	46.22
GFRP(E)	37.83	39.18	38.58	37.48	38.27
GFRP(VE)	37.05	36.00	38.54	36.84	37.11
GFRP(P)	37.02	39.20	38.46	36.77	37.86
AFRP(E)	42.57	42.72	44.35	41.30	42.73
AFRP(VE)	42.90	43.20	44.60	41.64	43.09
AFRP(P)	42.86	44.08	44.59	42.35	43.47

Values of different stresses developed in all specimens where all edges of the laminates are simply supported are given in Table 4.22.

Table 4.22. Stress Values (All edges Simply Supported)

Specimen	**σ_x (N/mm$^{2)}$**	**σ_y (N/mm$^{2)}$**	**σ_z (N/mm^2)**	**σ_{xy} (N/mm$^{2)}$**	**σ_{yz} (N/mm$^{2)}$**	**σ_{zx} (N/mm^2)**	**Von Mises stress (N/mm^2)**	**Principal stress (N/mm^2)**
CFRP(E)	286	1410	11.7	63.4	114	43.4	1290	1410
CFRP(VE)	273	1400	11.5	62.6	113	42.6	1280	1340
CFRP(P)	279	1340	11.4	65.3	114	43.2	1280	1390
GFRP(E)	259	726	9.76	49.3	75.4	37.6	637.2	726
GFRP(VE)	247	726	9.82	48.33	76.26	35.6	639	726
GFRP(P)	249	725	9.84	50.5	76.5	36.3	638	725
AFRP(E)	296	1080	12.59	59.6	105.9	45.4	960	1080
AFRP(VE)	283	1050	11.9	58.7	102	43.6	946	1050
AFRP(P)	280	1020	12.1	59.5	97.7	43.7	910	1020

Values of different stresses developed in CFRP (E) specimens supported in all four ways given in Table 4.23.

Table 4.23. Stress Values (CFRP(E))

Specimen	**σ_x (N/mm^2)**	**σ_y (N/mm^2)**	**σ_z (N/mm^2)**	**σ_{xy} (N/mm$^{2)}$**	**σ_{yz} (N/mm^2)**	**σ_{zx} (N/mm^2)**	**Von Mises (N/mm^2)**	**Principal stress (N/mm^2)**
CFRP(E) AE-SS	286	1410	11.7	63.4	114	43.4	1290	1410
CFRP(E) AE-FF	279	1410	12	65.9	116	42.5	1290	1420
CFRP(E) LE-FF-SE-SS	270	1410	11.8	66.1	116	41	1300	1420
CFRP(E) LE-SS-SE-FF	284	1410	11.7	63.4	114	43.6	1290	1410

Impact analyses had been conducted on the above nine composites for the four support conditions. Maximum internal energy developed in the plate during impact and the time taken to develop this internal energy has been found out for all the composites for all the four support conditions are given in Table 4.16 and Table 4.17. ‘Internal Energy’ vs ‘Time’ curves of CFRP(E), GFRP(E) and AFRP(E) has been superimposed and given in Figure 4.24. In Figure 4.25 ‘Internal Energy’ vs ‘Time’ curves of CFRP(VE), GFRP(VE) and AFRP(VE) has been superimposed and in Figure 4.26 ‘Internal Energy’ vs ‘Time’ curves of CFRP(P), GFRP(P) and AFRP(P) has been superimposed. In the present analysis all edges are taken as fixed. It has been found that time taken to reach the maximum internal energy is least for CFRP and highest for GFRP in all the specimens.

All the curves are bell shaped. It can be seen that the curve is more flat at top for GFRP and less flat for CFRP. A plateau of maximum internal energy exists at the top for AFRP, a sharp variation of internal energy exists at the top for CFRP and a stage between the two exists for GFRP. The time taken to reach the maximum internal energy value is highest for GFRP and least for CFRP. Under impact the structure fails when the material behaviour move from elastic range to plastic range or when the material behaves in a brittle manner. The time taken by steel to change from elastic behaviour to plastic behaviour to failure is more than the time taken by composite materials to failure. This is due to the fact that steel is ductile and composites are brittle. More time got before failure helps in detection of small fractures and they can be repaired. But in composites this does not happen and failure happens without giving any warning which is catastrophic for such structures. Therefore although CFRP can absorb maximum energy, GFRP is more advantageous in composite construction. The flatter top portion of AFRP shows the capacity of such composites to absorb high energies for a longer time than CFRP.

For all the edges fixed (the boundary condition that has been applied), ‘Internal energy vs Time’ curve has been drawn for all the three CFRP composites, three GFRP composites and three AFRP composites respectively in Figure 4.27., Figure 4.28. and Figure 4.29. All the three graphs show that change in fibres in the laminates affect their energy absorbing characteristics. Effect of change in matrices does not produce much change in the energy absorbing characteristics. Therefore it can be concluded that impact resistance is more of a fibre dominated property than a matrix dominated one.

‘Internal Energy’ vs ‘Time’ curve of CFRP(E) for all the four support conditions has been superimposed and given in Figure 4.30. All the four superimposed graphs almost follow the same pattern showing that effect of boundary conditions does not affect the energy absorbing characteristics much. When ‘AE-FF’ and ‘LE-FF-SE-SS’ follows the same pattern, ‘AE-SS’ and LE-SS-SE-FF’ follows the same pattern.

Energy absorption capacity of composites is studied as ‘Energy absorbed per unit mass’. AFRP composites show high ‘energy absorbed per unit mass’ value and then comes CFRP composites and GFRP composites. Therefore impact resistance capacity of composites varies from highest to least as from AFRP composites to CFRP composites to GFRP composites. Also the impact resistance capacity of composites varies from highest to least as from use of Epoxy matrix to Vinyl Ester matrix to Polyester matrix. It can be seen that there is no direct relation of impact resistance to modulus of elasticity of fibres used or that of the matrices used. This clearly shows that impact behaviour of anisotropic materials is complex or do not follow a pattern.

Energy absorption rate has been calculated and tabulated in Table 4.21. for all the composites studied and for all four support conditions. Higher the ‘Energy absorption rate’ of the material, faster will be the failure of the structure. Faster the failure of the structure lesser the time got for taking precautions for the safety of the structure. Therefore according to the study conducted GFRP composites are the most suitable composites to resist impact safely and CFRP composites rate as the last choice.

Various stresses calculated in the composite laminate panels with all the edges simply supported have been tabulated in Table 4.22. The principal stresses calculated are proportional to the modulus of elasticity of the fibres i.e. CFRP’s have the maximum stress developed values and GFRP’s have the minimum stress developed values. Within the CFRP’s the stress developed values are proportional to the modulus of elasticity of the matrices. But in GFRP’s and AFRP’s maximum principal stress values have been developed for laminates where the matrix used was epoxy and least value has been developed for laminates where the matrix used was Polyester. This shows that the stress values are not proportional to the modulus of elasticity of the matrices. With the change in support conditions specimens with AE-SS and LE-SS-SE-FF have similar stress developing patterns and specimens with AE-FF and LE-FF-SE-SS have similar stress developing patterns. These values are given in Table 4.23.

Considering the secondary variables under Impact strength as ‘Energy absorbed per unit weight per unit thickness’ and ‘Energy absorption rate’ index values has been calculated and tabulated as in Table 4.24. Index values have been assigned as, higher the values; lower the acceptability of those composites on the basis of impact resistance. Based on that it has been found that AFRP’s are the most accepted and CFRP’s are the least accepted ones.

The index value based on impact energy absorbed per unit weight per unit thickness and energy absorption rate per unit mass of composites is given in Table 4.24. Index value based on impact strength of composite laminates has been arrived at, based on two parameters energy absorbed per unit mass and their energy absorption rate per unit mass. The composite laminate exhibiting highest energy absorption per unit mass has been assigned a value of ‘1’ and the composite laminate having lowest energy absorption per unit mass has been assigned a value of ‘9’. Similarly, for the highest energy absorption rate per unit mass, the index value has been assigned as ‘1’ and for the lowest energy absorption rate per unit mass, the index value has been assigned as ‘9’. Then both the index values has been added linearly and total index value has been obtained.

Table 4.24. Index value based on Impact strength

Specimen	CFRP (E)	CFRP (VE)	CFRP (P)	GFRP (E)	GFRP (VE)	GFRP (P)	AFRP (E)	AFRP (VE)	AFRP (P)
Index value based on energy absorbed per unit weight per unit thickness	4	5	6	7	8	9	1	2	3
Index value based on energy absorption rate per unit mass	9	8	7	3	1	2	4	5	6
Total Index value	13	13	13	10	9	11	5	7	9
Index value based on impact	9	9	9	5	4	6	1	2	4

When impact value is considered AFRP(E) is the best choice among the nine laminates and CFRP(E),CFRP(VE) and CFRP(P) rates as the last choice.

4.7. Strength Index

Strength Index that has been calculated based on the indices prepared based on the variables bending strength, buckling strength and impact strength has been given in Table. 4.25. To arrive at the strength index, the index values of each strength parameter have been added linearly to get the total index value. Equal weighting method or equal importance has been assigned to individual strength parameters. Lowest total index value has been assigned a strength index of '1' and highest total index value has been assigned a strength index of '9'. Ranks have been assigned in such a manner that, lower the rank, higher the acceptability of the composite as a structural material for ship hull construction.

Table 4.25. Strength Index

Specimen	CFRP (E)	CFRP (VE)	CFRP (P)	GFRP (E)	GFRP (VE)	GFRP (P)	AFRP (E)	AFRP (VE)	AFRP (P)
Index value based on bending	2	4	3	7	9	8	2	6	5
Index value based on buckling	2	3	2	8	9	8	5	6	5
Index value based on impact	9	9	9	5	6	4	1	2	4
Total Index value	13	16	14	20	24	20	8	14	14
Strength Index	2	6	5	8	9	8	1	5	5

Comparison of index values between the bending strength, buckling strength and impact resistance indices are given in Figure 4.31.

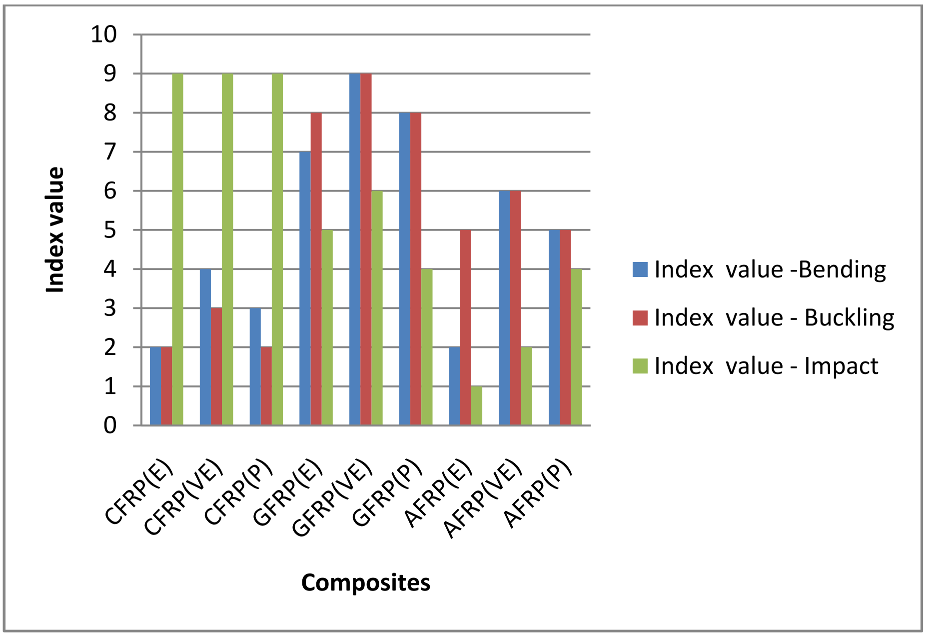


Figure 4.31. Comparison between bending strength, buckling strength and impact strength indices.

Accordingly AFRP(E) is the most acceptable composite and GFRP(VE) is the least acceptable composite when strength of the laminate is the criteria for selection.

CHAPTER 5

SUSTAINABILITY OF SHIP HULL MATERIALS

5.1 Introduction

With all the advantages, nonmetallic composite materials are highly criticized for its negative environmental impact. In the future, along with technological advancements, a proper knowledge about the material and its environmental impact during its lifetime can surely improve its environmental friendliness and thus a paradigm shift can be brought forward in the area of hull materials. Thus a comparative study of the environmental impact of already available non metallic composite material is necessary.

Any material will create an impact on the environment during its lifetime. The intensity of the impact varies from product to product and also along the various phases of the product. The various phases of a product are manufacturing phase, usage phase or operational phase, disposal phase etc. Based on the intensity of the environmental impact an index can be constructed to compare various materials used for the same purpose. In this context construction of a 'sustainability index for hull materials' is quite relevant.

5.2 Construction of Sustainability Index

In the present study, the environmental impact of nonmetallic composite laminate hull materials has been studied in the form of constructing a 'Sustainability Index'. In this study the 'Sustainability Index' is constructed as a *composite* indicator.

The fibres used in the nonmetallic composite materials used for hull construction are Carbon(C), Glass (G) and Aramid (A) and the matrices used are Epoxy (E), Vinyl Ester (VE) and Polyester (P). In this study, composites made of above fibres and matrices are considered. All the combinations of above fibres and matrices selected. Accordingly nine types of non metallic hull materials are studied. The combinations studied are Carbon Fibre and Epoxy matrix (CFRP-E), Carbon Fibre and Vinyl Ester matrix (CFRP-VE), Carbon Fibre and Polyester matrix (CFRP-P), Glass Fibre and Epoxy matrix(GFRP-E), Glass Fibre and Vinyl Ester matrix (GFRP-VE), Glass Fibre and Polyester matrix (GFRP-P), Aramid Fibre and Epoxy matrix (AFRP-E), Aramid Fibre and Vinyl Ester matrix (AFRP-VE), Aramid Fibre and Polyester matrix (AFRP-P).

5.2.1. Theoretical frame work for index

The theoretical frame work to construct 'Sustainability Index' is based on the concept that this index has been constructed based on the environmental sustainability of non metallic composite hull materials. Nine commonly used composite hull materials have been selected as discussed in the previous chapters. In this study a cradle to grave approach is used to select the variables. A ship's lifecycle has been decided upon using cradle to grave approach. According to cradle to grave approach, the different phases of a ship's life cycle considered are manufacturing (design and manufacture) phase, operation (operation and maintenance) phase and decommissioning (disposal and recycling) phase.

To study the environmental impact of a non metallic hull ship, life cycle analysis (LCA) studies should be considered. When LCA for metallic hull ships and non metallic hull ships were compared, it has been found that, there is a substantial decrease in the environmental impact of non metallic hull ships than metallic hull ships during the operation phase. (Dominic and Nandakumar 2012) This is due to the reduced fuel consumption of non metallic hull ships due to its low weight when compared to metallic hull ships. Therefore the primary variables selected for creating green index are manufacturing phase and disposal phase of a ship's life cycle. As comparative studies between different composites have been considered common aspects have been assumed to be same and not considered in the present study.

5.2.2. Selection of variables

Selection of variables is representative of the multidimensional concept for which the index is created. In the present study selection of variables have been done in a subjective manner. The primary variables selected for creating sustainability index are manufacturing phase and disposal or decommissioning phase of a ship's life cycle.

The variable selected under manufacturing phase is the impact of manufacturing of non metallic hull on the environment. Embodied energy, emissions during manufacturing of constituent materials (both matrix and fibre), gel coat application, material selection, matrix preparation, matrix application, curing, mould cleaning, equipment cleaning and disposal and hazardous practices involved due to speciality of the material or manufacturing practices used are the various factors included in this phase (Anderson, 2004).

The variables included under disposal or decommissioning phase are disposal of composite hulls and recycling of composite materials. Recycling of composite material has been studied based on the waste disposal hierarchy. The assumption made use of here is that the structure has completed the safe life span of intended purpose for which it has been constructed for. According to waste disposal hierarchy, the best option is reduce, and then reuse, recycle, incineration, landfill and the worst option is leaving the material in to the environment in the laminate form itself. (Halliwell 2006)

5.2.3 Scaling of variables

Among the various normalisation or scaling techniques discussed before, ranking method is made use of in this study. The other methods discussed need at least more than ten numbers of data for comparison. As there is no fixed minimum and maximum of values under the impact data values the application of the method 'distance from min – max' will not be appropriate. Other methods like 'distance from mean' Z-score, the distance from the leader etc. will not be an appropriate method as in this study maximum number of materials compared are only nine. If ranking method is used, then even two materials can be compared and a green index can be assigned for both. According to ranking method normalized values has been assigned a rank varying from '1' to '9', as nine laminates has been considered in this study.

5.2.4 Weighting of variables

In the present study both approaches of weighting; differential weighting method and equal weighting method of variables have been done. In equal weighting method no weights have been assigned to variables or an equal weight of one is assigned to all variables. In differential weighting method a mix of the different approaches of assigning weights has been used to assign weights to different variables. In this study weights are mainly assigned based on scientific expertise or based on data available. Wherever there is no correlation between variables, unit weight has been assigned.

5.2.5 Aggregation of variables

In this study, the effect of linear aggregation method and geometric aggregation method has been studied. Sustainability index has been assigned using both the methods.

5.2.6 Ranking of variables

Once the total index value is calculated, ranking of these values has been carried out. Rank is assigned to each index value in the descending order. Therefore the highest index value is assigned the highest rank and lowest index value is assigned the lowest rank. Rank assigned has to be interpreted as lower the rank, lower the environmental impact. Lowest value of rank has to be one and highest rank has to be the total number of specimens used for the study.

5.3. Software development

A program has been coded to calculate the index value for evaluating the Sustainability Index in the form of interactive software. It is a comprehensive, simple yet effective program to segregate different composite laminates based on their characteristics. The input for the program has been arranged under two categories. The two categories are based on the two phases considered to measure the environmental impact. The phases are manufacturing phase and decommissioning/disposal phase. To calculate Sustainability Index of nonmetallic composite hull materials, primary variables selected are manufacturing phase i.e. manufacturing of composite laminate hulls and disposal phase i.e. disposal of composite laminate hulls. The input for the program implementation is the variables which are selected under both the phases. The inputs used under the manufacturing phase are: the type of fibre used, type of matrix selected, type of gel coat application and type of manufacturing methods. Under the disposal phase, the input is the disposal method being adopted. Inputs are chosen based on the waste disposal hierarchy. Accordingly, type of fibre, reuse of composite laminates in different forms, different recycling methods, incineration, landfill and disposal in raw form are the input being taken into consideration. Hazardous practices or emissions during the respective phases have also been considered. Based on these input, the program developed in Visual Basic calculates the index values for each composite laminate. Using the index values of input a cumulative index value has been generated for each composite laminate. The output of the program is the index value of each composite laminate material.

The schematic diagram showing the calculation a *composite indicator* is given in Figure 5.1.

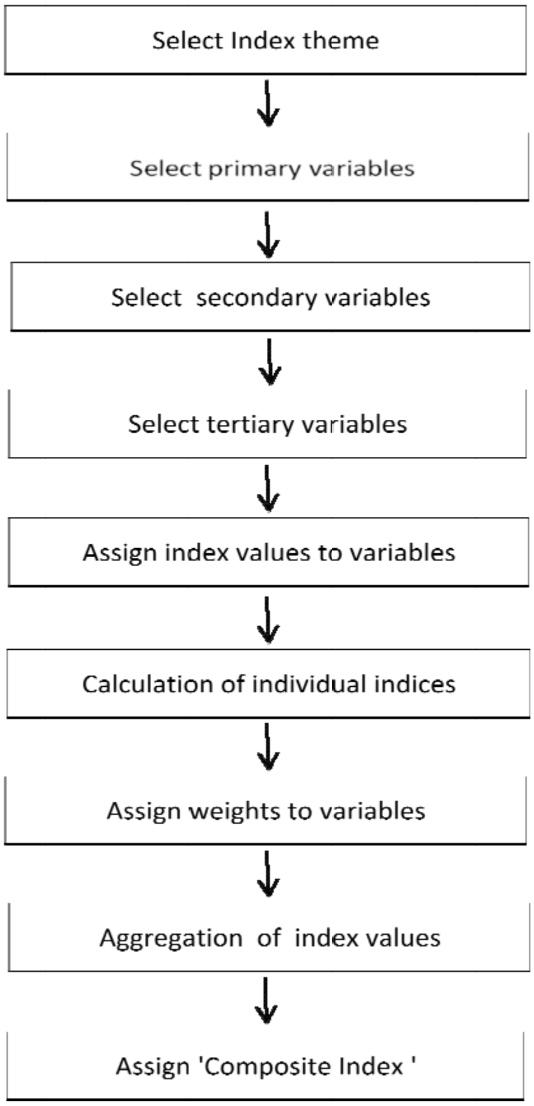


Figure 5.1. Schematic diagram to calculate '*composite indicator*'

The schematic diagram showing the steps involved in the interactive software to calculate Sustainability Index for nonmetallic composites is given in Figure 5.2.

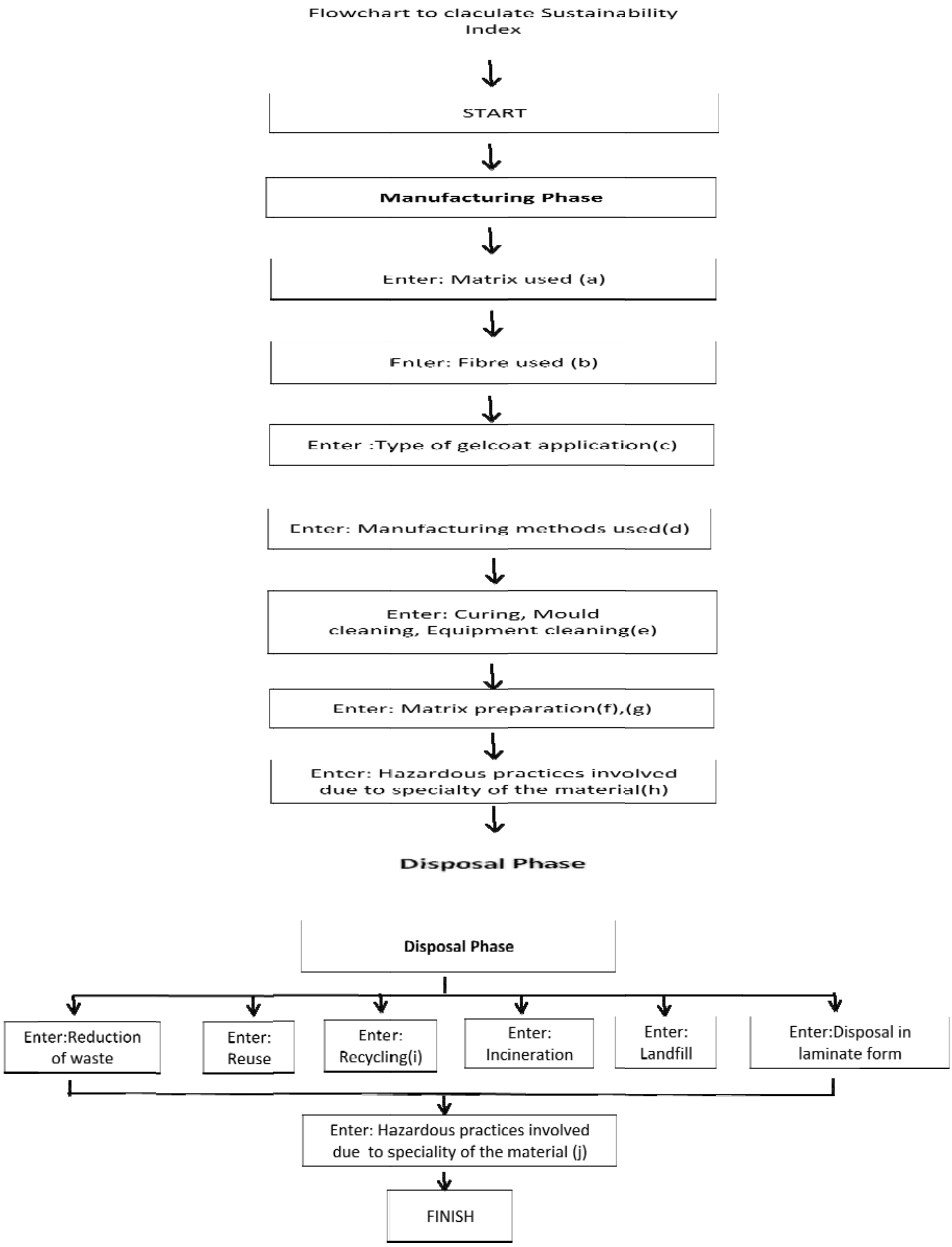


Figure 5.2. Schematic diagram to calculate Sustainability Index

‘Manufacturing phase’ calculate the individual index values based on different processes involved in manufacturing of the laminates

(a) Calculates individual index value based on CO2 emission and embodied energy of matrix used during it’s manufacture.
(b) Calculates individual index value based on CO2 emission and embodied energy of fibre used during it’s manufacture
(c) Calculates individual index value based on the type of gelcoat application.
(d) Calculates individual index value based on the manufacturing methods used.
(e) Calculates individual index value based on environmental impact during curing, mould cleaning and equipment cleaning.
(f) , **(g)** Calculates individual index value based on exposure of matrix preparation and styrene emissions during matrix preparation.

(h) Calculates individual index value based on hazardous practices involved due to specialty of the material.

Disposal phase calculates individual value based on the disposal method chosen.

(i) Calculates individual index values based on the type of recycling method used.
(j) Calculates individual index values based on hazardous practices involved due to disposal because of the specialty of the material.

The code of the interactive software to calculate sustainability index in Visual Basic has been given in Appendix E.

5.4. Estimation of Sustainability Index for ship hull materials

After the variables have been selected index values are assigned using the scientific data available. Accordingly index values are being assigned to the variables as shown below.

5.4.1. Index value for manufacturing phase

Following secondary variables have been considered in the manufacturing phase.

a) Environmental impact of manufacturing of constituent materials

The embodied energy of carbon is 400MJ/kg, glass is 80MJ/kg and aramid is 300MJ/kg. The CO2 emission of carbon is 28kg/kg, glass is 6kg/kg and aramid is 19kg/kg (Meo, 2013). Therefore the index values are assigned as shown in Table5.1.The embodied energy of epoxy is 76-80MJ/kg, poly ester is 63-78MJ/kg and vinyl ester has lesser value among the three matrices. The CO2 emissions of epoxy is 5.9kg/kg , vinyl ester - 4.15kg/kg and poly ester has the maximum CO2 emissions among the three matrices (Roos and Szpieg 2012). Therefore the index values for 'Environmental impact of manufacturing of constituent materials' are assigned as shown in Table 5.1.

Table 5.1. Index values for Environmental impact of manufacturing of constituent materials

Secondary variables	Environmental impact of manufacturing of constituent materials											
Tertiary variables	Fibre						Matrix					
	Embodied energy			CO2 emissions			Embodied energy			CO2 emissions		
	Carbon	Aramid	Glass	Carbon	Aramid	Glass	Epoxy	Poly ester	Vinyl Ester	Polyester	Epoxy	Vinyl Ester
Rank	3	2	1	3	2	1	3	2	1	3	2	1

Gel coat can be applied in many ways. Gelcoat can be brushed, rolled or sprayed. When the gelcoat is brushed the environmental impact is less and when it is sprayed the impact is the maximum. The impact of gelcoat being rolled lies in between. Therefore the index values for 'Gel coat application' are assigned as shown in Table 5.2 (Anderson, 2004).

Table 5.2. Index values for Gel coat application

Secondary variables	**Tertiary variables**	**Rank**
Gelcoat application	Gel coat brushed	1
	Gel coat rolled	2
	Gelcoat sprayed	3

b) Manufacturing methods

Use of prepegs has more environmental impact than the other in situ manufacturing methods, due to its high embodied energy during the production of prepegs. According to the environmental impact of other manufacturing methods are Autoclave moulding, Spray up, Resin Transfer Moulding (RTM), Vacuum Assisted Resin Infusion (VARI), Pultrusion, and Filament winding. They have been ranked as given in Table 5.3. Matrix preparation can be done either in closed or open manner. Environmental impact of other activities associated with manufacturing are same for all laminates. Depending upon the exposure of matrix preparation, index value has been assigned as given in Table 5.4. (Anderson, 2004). Hazardous emissions i.e. styrene emissions are more when polyester is used than vinyl ester and it is nil when epoxy is used. Therefore polyester and vinyl ester are given a value of 1 and epoxy, a value of 0.

Table 5.3. Index values for manufacturing methods and associated activities

Secondary variables	Manufacturing methods							Curing	Mould cleaning	Equipment cleaning and disposal	Hazardous practices involved due to speciality of the material used	
Tertiary variables	Use of prepegs	Autoclave moulding	Spray up	Resin Transfer Moulding (RTM)	Vacuum Assisted Resin Infusion (VARI)	Pultrusion	Filament winding	Common to all laminates	Common to all laminates	Common to all laminates	Yes	No
Rank	7	6	5	4	3	2	1	1	1	1	1	0

Table 5.4. Index values for matrix preparation

Matrix preparation	Exposure	Closed	0
		Open	1
	Styrene emission	Polyester	2
		Vinyl Ester	1
		Epoxy	0

5.4.2. Index value for disposal phase

Following secondary variables have been considered in the disposal phase.

a) Reduction of waste

When the strength or modulus of elasticity of the material is high, the quantity of material needed for structural construction will be less when compared to materials with low strength or modulus of elasticity. Therefore waste produced after the lifetime of a structure is inversely proportional to strength/modulus of elasticity of the material. Therefore waste produced is least when carbon fibre is used and maximum happens when glass fibre is used. Therefore carbon has been assigned a value of 1, aramid fibre, a value of 2 and glass fibre, a value of 3.

b) Reuse

As the lifespan of nonmetallic composite laminate materials are very high, reuse of the laminates in other structures or structural forms other than primarily intended for, is the best option for an environmentally safe disposal. When the composite vessel is reused in the form of a vessel of lesser importance than it was designed for (e.g. shallow sea vessels can be reused as coastal vessels or as floating houses or as a floating museum or as a floating restaurant), then the materials of the vessel need not be disposed. Thus material waste produced is nil. When components or parts are reused (e.g. large laminate panels are cut out from the parent vessel and used in other constructions of lesser importance i.e. in containers or in housings or where smaller panels are needed), a huge part of the material gets reused and a smaller part is to be disposed of. When material from the parent vessel is used as material (i.e. smaller sized pieces are used as fillers or for insulation), the waste produced after reuse is more than the other two reuse options. Therefore among the Reuse options, ‘Reuse as a vessel’ has been assigned a value of 0, ‘Reuse as component’ has been assigned a value of 1 and ‘Reuse as material, a value of 2.

c) Recycling

Recycling methods of disposal available for composite materials are thermal recycling, chemical recycling and mechanical recycling. In thermal recycling the composite material undergoes changes under high temperature. Pyrolysis is a thermal recycling process in which composites are heated in the absence of oxygen and a temperature below burning has been maintained. In this process the matrix will be converted to gases and fuels and the fibres can be retrieved. The fibres got by this method are clean.

Air pollution effects are less harmful in this case than compared to incineration (Meira et. al. 2014). Under thermal recycling, more research had been done in CFRP products (Bartholomew, 2004). In chemical recycling the fibres get separated from the matrices. Chemicals are used to dissolve the matrices and fibres can be retrieved. Hazardous solvents are used in chemical recycling. The fibres retrieved using chemical recycling retains the original strength than fibres retrieved using thermal recycling but have reduced adhesion properties. The fibres thus extracted from thermal and chemical recycling can be reused either where virgin fibres are to be used or in other applications. Thermal recycling like pyrolysis is a good option for recycling when fibres retrieved is of great value, compared to chemical recycling. Therefore for recycling CFRP and AFRP, where the fibres retrieved can be used economically again thermal recycling process is adopted than chemical recycling. When thermal recycling and chemical recycling are considered, GFRP has been assigned a value of 2 and CFRP and AFRP have been given a value of 1each.

In mechanical recycling, the composite materials are broken down into small pieces by shredding, crushing, milling or similar mechanical processes. The recyclates in the powder form is used as fillers in moulded composite parts or in concrete or reinforced polymer mortar (Ceclan et.al. 2013, Meira et.al. 2013). The recyclates in the fibrous form can be used as recycled reinforcements. Under mechanical recycling more research had been done for GFRP products and this process is more suitable for GFRP than CFRP as mechanical recycling does not recover individual fibres and fibre recovery is not an economical option for GFRP when compared to CFRP (Pimenta and Pinho 2011). Recycled carbon fibres can be used in a more economic way by replacing virgin carbon fibres than recycled glass fibres by replacing virgin glass fibres. Mechanical recycling is economically and environmentally advantageous than thermal recycling and chemical recycling for GFRP. Composite waste can be combusted in cement kilns and utilize its material and energy content can be recovered. Polymers in the composites meet the energy demand and the fibres add mineral value to the cement. This is a patented method and an accepted method for GFRP recycling according to European Waste Directive. This method guarantees 100% recycling of GFRP (www.compocycle.com 2010). AFRP can be ground and used as fillers or fibrous products can be reused. Therefore when recycling has been done in the form of powdered fillers, CFRP and AFRP have been assigned a value of 2 and GFRP, a value of 0. When recycling has been done by using them in fibrous form, then GFRP has been assigned a value of 2 and CFRP and AFRP a value of 1 each.

In landfill process, energy is not recovered from the composites and in incineration process; the option of recovery of energy is also possible. At present energy recovery from incineration is not an economic option for CFRP and AFRP waste treatment when compared to GFRP but it is surely a better environmental friendly waste treatment option than landfill. According to European Union (EU) directive, 1999/31/EC, landfilling of material with more than 10% organic content is prohibited. GFRP contains more than 10% organic material and therefore not allowed to be disposed as a landfill. A present due to ignorance of importance of sustainable disposal methods vessels are disposed off in the laminate form itself in open environment, which is worse than planned landfill. Therefore recycling methods like 'Landfill' and 'Disposal in laminate form' have been assigned a value of 1 each and 'Incineration' has been assigned values from 0 to 2 depending on energy and material recovery. While assigning index values, whenever the environmental impact is negligible, index value has been assigned as '0'. Applying the above data, index values are being assigned as given in Table 5.5.

d) Hazardous practices/ emissions involved due to the speciality of the new material

Composite wastes are classified as nonhazardous and inert. Since they are inert, problems of leachate and methane production does not exist in exercising landfilling option. The disadvantage of mechanical recyclates is that it will consist of all the scrap material including polymers, contaminations, paints etc. Also powdered GFRP is more flammable than GFRP scrap. Therefore recycling methods like 'Reduction of waste' and 'Reuse' has been assigned a value of 0 and other recycling methods are been given a value of 1 each.

Table 5.5. Index values for disposal methods

Secondary variables	Tertiary variables			Rank
Reduction of waste	Fibre	Carbon		1
		Aramid		2
		Glass		3
Reuse	Reuse as a vessel			0
	Reuse as component			1
	Reuse as material			2
Recycling	Thermal recycling	CFRP		1
		GFRP		2
		AFRP		1
	Chemical recycling	CFRP		1
		GFRP		2
		AFRP		1
	Mechanical recycling	Powdered fillers	CFRP	2
			GFRP	0
			AFRP	2
		Fibrous products	CFRP	1
			GFRP	2
			AFRP	1
Incineration	With energy recovery and material utilisation			0
	With energy and material recovery			1
	With or Without energy recovery			2
Landfill				1
Disposal in laminate form				1
Hazardous practices/ emissions involved due to the	Reduction of waste			0
	Reuse	Reuse as vessel		0
		Reuse as component		0
		Reuse as material		0
	Recycling	Thermal recycling		1

speciality of the new material		Chemical recycling	1
		Mechanical recycling	1
	Incineration		1
	Landfill		1
	Disposal in laminate form		1

5.4.3 Weights of variables

When differential weighting method is used weights are being assigned to variables. The weights assigned to each variable in the manufacturing phase and decommissioning / disposal phase have been given in Table 5.6.

Table 5.6. Weights of variables

Primary variables	**Secondary variables**	**Tertiary variables**		**weights**
Manufacturing phase	Toxic emissions of manufacturing of constituent materials	Fibre	Embodied energy	0.75
			CO2 emissions	0.75
		Matrix	Embodied energy	0.85
			CO2 emissions	0.85
	Gel coat application			1
	Manufacturing methods	Use of prepegs		1
	Matrix preparation	Exposure		1
		Styrene emission		0.125
	Manufacturing methods			1
	Curing	Common to all laminates		0.01
	Mould cleaning	Common to all laminates		0.01
	Equipment cleaning/ disposal	Common to all laminates		0.01
	Hazardous practices involved due to speciality of the material used			1
Decommissioning / disposal	Reduction of waste			1
	Reuse			2
	Recycling	Thermal recycling		3

phase		Chemical recycling		3
		Mechanical recycling	Powdered fillers	3
			Fibrous products	3
	Incineration			4
	Landfill			5
	Disposal in laminate form			6
	Hazardous practices/ emissions involved due to the speciality of the new material	Reduction of waste		0
		Reuse		0
		Recycling		1
		Incineration		2
		Landfill		3
		Disposal in laminate form		4

5.5. Sustainability index table for nonmetallic composite laminate hull materials

Index value has been calculated for all the nine materials considering the various phases of life cycle of a ship. For the present study sustainability has been ranked for combined manufacturing phase and disposal phase. Based on these index values an index ranking has been done by considering manufacturing phase and disposal phase together.

5.5.1 Sustainability Index based on equal weights and linear aggregation

The index values values based on equal weights and linear aggregation and corresponding Sustainability index ranking are given in Table 5.7. The calculations are given in Appendix B.

Table 5.7. Sustainability Index based on equal weights and linear aggregation

Composites	CFRP (E)	CFRP (VE)	CFRP (P)	GFRP (E)	GFRP (VE)	GFRP (P)	AFRP (E)	AFRP (VE)	AFRP (P)
Index Value	27	25	28	24	22	25	26	24	27
Index Rank	8	5	9	3	1	5	6	3	8

5.5.2. Sustainability Index based on differential weights and linear aggregation

The index values values based on differential weights and linear aggregation and corresponding Sustainability index ranking are given in Table 5.8. The calculations are given in Appendix C.

Table 5.8. Sustainability Index based on differential weights and linear aggregation

Composites	CFRP (E)	CFRP (VE)	CFRP (P)	GFRP (E)	GFRP (VE)	GFRP (P)	AFRP (E)	AFRP (VE)	AFRP (P)
Index Value	23.78	22.23	24.78	22.78	20.23	23.78	23.28	21.73	24.28
Index Rank	7	3	9	5	1	7	4	2	8

5.5.3. Sustainability Index based on geometric aggregation

The index values based on geometric aggregation and corresponding Sustainability index ranking are given in Table 5.9. The calculations are given in Appendix D.

Table 5.9. Sustainability Index based on geometric aggregation

Composite laminates	CFRP (E)	CFRP (VE)	CFRP (P)	GFRP (E)	GFRP (VE)	GFRP (P)	AFRP (E)	AFRP (VE)	AFRP (P)
Index Value	500.41	654.71	1000.83	288.91	126	577.83	544.78	237.59	1089.56
Index Rank	4	7	8	3	1	6	5	2	9

When equal weighting method and linear aggregation method is used it has been found that GFRP(VE) has least environmental impact and CFRP(P) has the maximum environmental impact. When differential weighting method and linear aggregation method is used it was found that GFRP(VE) has least environmental impact and CFRP(P) has the maximum environmental impact. When differential weighting method and geometric aggregation method is used it was found that GFRP(VE) has least environmental impact and AFRP(P) has the maximum environmental impact.

5.6. Selection of laminate based on strength index and sustainability index

According to the design philosophy developed in this study strength index and sustainability plays a key role in selecting the materials for ship hull construction. Degree of acceptability of various composite materials rests on the respective relation between these two indices. Thus, using Strength and Sustainability indices a two dimensional assessment of composites has been conducted, which forms the basis of ‘Design for Strength and Sustainability’.

Accordingly strength index has been plotted on ‘y’ axis and sustainability index has been plotted on ‘x’ axis. Based on strength index and sustainability index of each material, they have been plotted against both the axes. The position of each material in the ‘Strength Index versus Sustainability Index’ plot determines the acceptability of the material for an environmentally sustainable ship hull construction. The ‘Strength Index versus Sustainability Index’ plot has been shown in Figure 5.3

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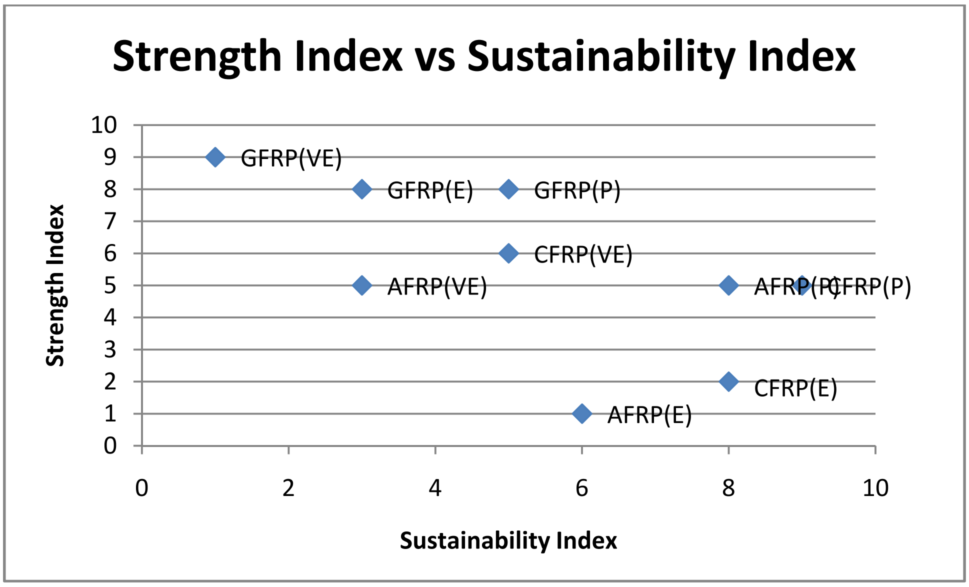

Figure 5.3. Strength Index versus Sustainability Index

It has been discussed earlier that for both strength index and sustainability index, lower the rank, higher is the acceptability of the material as a ship hull material. Accordingly the material lying on the coordinate (1,1) of the plot is the most acceptable one and the material lying on the coordinate (9,9) of the plot is the least acceptable material. The material with the coordinate (1,9) is highly acceptable if sustainability index alone is considered but highly unacceptable if strength index alone is considered. The material with the coordinate (9,1) is highly acceptable if strength index alone is considered but highly unacceptable if sustainability index alone is considered. Therefore a material with an ‘x’ coordinate ‘4’ or ‘5’ and ‘y’ coordinate ‘5’ or ‘4’ is more acceptable when both the indices are considered simultaneously. As the plot explains itself, any material which lies in the area of the plot with an ‘x’ and ‘y’ coordinate less than the above is the most acceptable material.

Accordingly the material that has been selected for ship hull construction is Aramid Fibre Reinforced Polymer - AFRP (VE). Strength and Sustainability indices of this composite have a coordinate of (5,3). The next choice is Carbon Fibre Reinforced Polymer - CFRP (VE) with a Strength and Sustainability index coordinate of (6, 5).

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1. Summary

Due to economic and environmental advantages over other transportation modes, the reliance on ocean shipping to transport raw materials and manufactured goods internationally is expected to rise. The U.N.'s International Maritime Organization (IMO) has estimated that without changes in current operating efficiencies and with increasing trade volumes, total ship emissions of CO2 will increase. However, introduction of new technology, changes to ship and engine design and improvements to operating procedures will ensure a much slower rate of growth for CO2 emissions.

In this study, use of composite materials i.e. lightweight materials over steel as hull construction material have been concentrated upon as a means to improve the environmental sustainability of shipping industry. The thesis addresses the sustainability of the shipping industry when composites are used as the major ship building material.

Till now the acceptability of a structural material has been based on the design philosophy i.e. Design for strength. Keeping environmental sustainability of materials in mind, a design philosophy based on strength and sustainability i.e. Design for strength and sustainability, of composite laminates has been proposed for selection of composites for ship hull construction.

For this purpose, an index based on strength of composite laminates and an index based on sustainability of composites has been tabulated and materials need to be selected based on these indices. Both the indices have been constructed as a *composite indicator*.

Index based on strength has been developed based on the index values of various strength parameters. Sustainability index has been developed based on the index values of the composites based on the environmental impact of various phases of a ship’s life cycle.

Nine non metallic composites have been considered in the present study. Index values based on strength parameters like bending strength, buckling strength and impact strength have been found out. Environmental impact during the manufacturing phase and disposal phase of composites has been found out. Based on these index values, indices based on strength and sustainability have been constructed respectively. Ranks have been assigned in such a way that, lower rank corresponds to higher strength and lower environmental impact. This also means lower the rank, higher the acceptability of the composite laminates. Using these two indices a two dimensional assessment of composites has been conducted. In this study both the indices have been superimposed to get strength index versus sustainability index plot. Analysis of this graph is the core of the design philosophy, 'Design for strength and sustainability'. According to this design philosophy, the composite which has the least strength index rank and least sustainability index rank should be selected for ship hull construction so that the structure will be strong and at the same time have a low environmental impact.

A format has been prepared to calculate the sustainability index. The same has been converted to an user friendly interactive software in Visual Basic.

6.2. Conclusions

Nine composite laminates had been studied for bending strength, buckling strength and impact strength. When bending strength is considered CFRP(E) and AFRP(E) rates as the best in an equal manner and GFRP(VE) has been rated as the last choice. When buckling pressure is considered CFRP(E) and CFRP(P) has been rated as the best options and GFRP(VE) has been rated as the last choice. When impact value is considered AFRP(E) is the best choice among the nine laminates and CFRP(E),CFRP(VE) and CFRP(P) rates as the last choice. It has been seen that AFRP(E) is the most acceptable composite and GFRP(VE) is the least acceptable composite when strength of the laminate is the criteria for selection.

When equal weighting method and linear aggregation method is used it has been found that GFRP(VE) has least environmental impact and CFRP(P) has the maximum environmental impact. When differential weighting method and linear aggregation method is used it has been found that GFRP(VE) has least environmental impact and

CFRP(P) has the maximum environmental impact. When differential weighting method and geometric aggregation method is used it has been found that GFRP(VE) has least environmental impact and AFRP(P) has the maximum environmental impact.

Using Strength and Sustainability indices a two dimensional assessment of composites has been conducted, which forms the basis of Design for Strength and Sustainability. Accordingly both the indices have been superimposed to get Strength Index versus Sustainability Index plot.

Among the composite laminates considered in this study, when Strength Index and Sustainability index has been considered together, the one that has been selected for ship hull construction is Aramid Fibre Reinforced Polymer - AFRP (VE). The next choice is Carbon Fibre Reinforced Polymer - CFRP (VE).

It has been found that none of the composite laminates/materials completely dominated the strength aspects and sustainability aspects. In the strength aspect CFRP’s dominated the bending and buckling properties and AFRP’s dominated the impact properties. In sustainability aspects GFRP’s dominated the rankings. It has been found that some strength properties are fibre dominated ones and other strength properties are more of matrix sensitive. To exploit the dominance of various laminates in certain strength aspects and sustainability aspects hybrid constructions can be considered as a useful choice. Arrangement of laminae made of various materials in the laminate can be decided depending upon the structures used and their dominating failure modes.

6.3. Scope for future work

This procedure can be extended to any number of composites in the marine area or to composites that has application in other areas. In the present study strength and sustainability indices are prepared by considering less number of parameters. More parameters can be included to attain a more reliable assessment. For that more research is needed in the various other strength properties. In the present study among the disposal methods the best options available has been assigned to each composite laminate, although they may not be economically feasible. The secondary variables selected under disposal phase have been studied only at the periphery. More in depth technological studies are needed for a more reliable assessment. For that more research is needed so that more practically feasible recycling methods of these laminates are available. Also more studies are required and thorough structural analysis of hybrid composites is needed to be conducted to make use of proposed design philosophy keeping in mind the strength and sustainability aspects.

REFERENCE

1. Ahmed, J. K., Agarwal, V. C., Pal, P., & Srivastav, V. "Static and Dynamic Analysis of Composite Laminated Plate." 2013: 6(3).

2. Akhbari, M., Shokrieh, M. M., & Nosraty, H. "A study on buckling behavior of composite sheets reinforced by hybrid woven fabrics." *Transactions-Canadian society for mechanical engineering*. 2008. 32(1), p81.

3. Akin, C., Şenel, M. "An experimental study of low velocity impact response for composite laminated plates." *Journal of the Institute of Science & Technology of Dumlupinar*, 2010: (21), p77.

4. Al-Mosawi, A. I., Rijab, M. A., Abdullah, N., and Mahdi, S. "Flexural strength of fiber reinforced composite." *International journal of enhanced research in science technology and engineering*, 2013: 2(1),1-3.

5. Anderson J. *Green Guide to Composites: An Environmental Profiling System for Composit Materials and Products.* Building Research Establishment and NetComposites (Firm), 2004.

6**.** ANSYS Mechanical APDL Verification Manual. 2013.

7. Arivalagan, P., Suresha, B., Chandramohan, G., Krishnaraj, V., and Palaniappan, N. "Mechanical and abrasive wear behavior of carbon fabric reinforced epoxy composite with and without fly ash cenospheres. Journal of Composite Materials", *Journal of Composite Materials*, 2012.

8. ASTM standard :D7136/D7136M – 12 - Standard test method for measuring the damage resistance of a fiber-reinforced polymer matrix composite to a drop-weight impact event.

9. BabuKiran, B. V., and Harish, G. "Effect of thickness on flexural properties of laminated composites." *International Journal of Research in Engineering & Advanced Technology*, 2014: (3),pp1-8.

10. BabuKiran, B. V., and Harish, G. "Influence of Resin and thickness of Laminate on Flexural Properties of Laminated Composites." *International Journal of Engineering Science and Innovative Technology*, 2014: 3(1), pp279-289.

11. Bartholomew, K. "Fiberglass Reinforced Plastics Recycling". Minnesota Technical Assistance Program. (2004).

12. Bhushan, S. T., Chandekar, G. S., Kelkar, A. D., & Chaphalkar, P. (2008). Studies on behavior of carbon and fiberglass epoxy composite laminates under low velocity impact loading using LS-DYNA. In *10th International LS- DYNA users conference* (Vol. 9, pp. 43–54).

13. Blanc, I., Damien F., Manuele M., and Olivier J. "Towards a New Index for Environmental Sustainability Based on a DALY Weighting Approach." *Sustainable Development*, 2008: 16 (4): 251–60.

14. Burman M., Lingg,B., Villiger,S., Enlund,H.,Hedlund-Astrom, A. and Hellbratt,S.E., "Cost and Energy Assessment of a High-Speed Ship", Transactions of the Royal Institution of Naval Architects Part B : International Journal of Small Craft Technology, 150(1): pp. 1-10, 2008.

15. Ceclan, Vasile A., Paul B., Marian B., Sorin G., and Cristina B. "Development of Environmental Technology for Carbon Fibre Reinforced Materials Recycling." *Materiale plastice*, 2013: 50 (2): 79–83.

16. Crul, M. R. M., and Diehllft, J. C. "*Design for sustainability",*UNEP and Delft,U.T.,. 2005.

17. DNV. "High Speed, Light Craft and Naval Surface Craft PART 3 CHAPTER 4,Hull structural design,fibre composite and sandwich constructions." DET NORSKE VERITAS, 2003.

18. DNV. " Standard for certification of Craft No.2.21 April 2010." DET NORSKE VERITAS, 2010.

18a. DNV. “Offshore standard, DNV-OS-C501, Composite components”, October 2010, DET NORSKE VERITAS, 2010.

19. Dominic, M., and Nandakumar C.G. "Environmental impact of Non Metallic Hull Ships." *Green Technologies (ICGT), 2012 International Conference on Green Technologies.* IEEE, 2012. 307–312.

20. Eric Greene Associates . "*Marine composites"*, Eric Greene Associates Inc. 1999.

21. Evegren F., Hertzberg T., Rahm M., LASS-C; Lightweight construction of a cruise vessel, SP Report 2011:12,2011.

22. Faroop, U., and Gregory, K. " Computational modeling and simulation of low velocity impact on fibrous composite panels drop weight unpartitioned mode." *Journal of Engineering and Applied Sciences*, 2009: 4(2), pp24-32.

23. Gallagher, R.H. *Buckling strength of structural plates.* Case copy file, NASA 8068, 1971.

24. Gramman, H., Krapp, R., & Bertram, V. "Disposal and recyclying of HSC materials.", Germanischer Lloyd, Hamburg, Germany, 2008.

25. Halliwell, S. "End of life options for composite waste." National Composite Network, 2006.

26. Hertzberg Tommy, LASS, Lightweight Construction Applications at Sea, SP Technical research institute of Sweden, SP Report 2009:13

27. HSC code," International Code of Safety for High-Speed Craft (2000) - 2008 edition", 2008.

28. Jones M Robert, “Mechanics of composite materials”, McGraw-Hill book company .

29.JongJin Kim and Brenda Rigdon. "Sustainable Architecture Module: Introduction to sustainable Design." 1998.

30. Kara, S., and Manmek, S. "Life cycle engineering of composites", Life cycle engineering and management research group, University of New South Wales, 2009.

31. Kevlar® Technical Guide. 1992.

32. Kukureka, S. N., Hooke, C. J., Rao, M., Liao, P., & Chen, Y. K. " The effect of fibre reinforcement on the friction and wear of polyamide 66 under dry rolling–sliding contact." *Tribology International*, 1999: 32(2), 107–116.

33. Leissa, Arthur W. *Buckling of composite plates and shells.* The Ohio state university, 1985.

34. Lepech, M. D., Li, V. C., & Keoleian, G. A." Sustainable infrastructure material design ." *Proceedings of The 4th International Workshop on Life-Cycle Cost Analysis and Design of Civil Infrastructures Systems.* Cocoa Beach, Florida, 2005. pp. 83–90.

35. Loidl, D., Peterlik, H., Paris, O., Müller, M., Burghammer, M., & Riekel, C. "Poisson ratio of carbon fibres at the microscopic and the nanoscopic scale."

36. Meira C., A.C., Ribeiro M.C.S., Santos J., Meixedo J., P., Silva F.J.G., Fiúza A., Dinis M.L., and Alvim M.R. " Sustainable Waste Recycling Solution for the Glass Fibre Reinforced Polymer Composite Materials Industry." *Construction and Building Materials*, 2013: 45 (August): 87–94.

37. Meira C., Ana C., Joao P. C., Maria C.S. R., João P. M., Francisco J.G. S., António F., and Maria L. Dinis. "An integrated recycling approach for GFRP pultrusion wastes: Recycling and reuse assessment into new composite materials using fuzzy boolean nets." *Journal of Cleaner Production*, 2014: 66 (March): 4,20–30.

38. Meo M. “Composite Science and Technology: 2020 - Scientific and Technical Challenges: Proceedings of the 9th International Conference on Composite Science

and Technology (ICCST-9)”. April 24-26, 2013, Sorrento, Italy (International Conference on Composite Science and Technology), DES tech Publications, Inc.

39. Mohan, K. M., Jacob, C. V., Lakshminarayana, N., Puneeth, B. M., & Nagabhushana, M. "Buckling analysis of woven glass epoxy laminated composite plate." *American Journal of Engineering Research*, 2013: 2(7), pp33–40.
40. Mohan, M. "The advantages of composite material in marine renewable energy structures." 2008.
41. Nardo, Michela, Michaela S., Andrea S., Stefano T., Anders H., and Enrico G. *Handbook on Constructing Composite Indicators: Methodology and User Guide.* OECD publishing, 2005.
42. Norman, J. C. *Damage resistance of high modulus aramid fiber composites in aircraft applications.* SAE Technical Paper., 1975.
43. Obla, K. H. *Performance-Based Specifications for Concrete to Advance Sustainable Development.* Farmington Hills, MI.: SP 269, American Concrete Institute, pp. 7-20, 2010.
44. Perry, N., Bernard, A., Laroche, F., and Pompidou, S. *Improving design for recycling – Application to composites.* CIRP Annals - Manufacturing Technology, 61(1), pp 151–154, 2012.
45. Pimenta, Soraia, and Silvestre T. Pinho. "Recycling Carbon Fibre Reinforced Polymers for Structural Applications: Technology Review and Market Outlook." *Waste Management*, 2011: 31 (2): 378–92.
46. Rathnakar, G., and Shivanand, H. K. "Fibre Orientation and Its Influence on the Flexural Strength of Glass fibre and Graphite fibre reinforced polymer composites." *International Journal of Innovative Research in Science, Engineering and Technology*, 2013: Vol. 2, Issue 3.

47. Reddy, K. M., Reddy, B. S., and Kumar, R. M. "Buckling Anlysis of Laminated Composite Plates Using Finite Element Method." *International Journal of Innovative Research in Science, Engineering and Technology*, 2013: 2 (1), pp 3281-3286.

48. Roos, S., and Szpieg, M." Life cycle assessment of Z-Bee". Swerea IVF Project report, 2012

49. Song, Y. S., Youn, J. R., and Gutowski, T. G. "Life cycle energy analysis of fiber-reinforced composites." *Composites Part A: Applied Science and Manufacturing*, 2009: 40(8), pp1257–1265.

50. Springer, S. G., and Kollar, P. L. Mechanics of composite structures. Cambridge University Press , 2003.

51. Sun, C. T., and Yang, S. H. *Contact law and impact responses of laminated composites.* Indiana: Purdue University, School of Aeronautics and Astronautics, 1980.

52. Tabone, M. D., Cregg, J. J., Beckman, E. J., and Landis, A. E. "Sustainability metrics: life cycle assessment and green design in polymers." *Environmental Science & Technology*, 2010: 44(21), pp 8264–8269.

53. Tekalur, S. A., Shivakumar, K., and Shukla, A. "Mechanical behavior and damage evolution in E-glass vinyl ester and carbon composites subjected to static and blast loads." *Composites Part B: Engineering*, 2008: 39(1), pp 57–65.

54. Tsai, S. W. *Strength Characteristics of Composite Materials.* DTIC Document, 1965.

55. Uleiwi, J. K. "Experimental Study of Flexural Strengthof laminate Composite." *Material. Eng. & Technology*, 2007: Vol.25, Suppl.of No.3,pp 454-466.

56. Valayil, T. P., & Issac, J. C. (2013). Crash Simulation in Ansys Ls-Dyna to Explore the Crash Performance of Composite and Metallic Materials. *International Journal of Scientific & Engineering Research*, *4*(8).

57. Vasconcelos, P. V., Lino, F. J., Baptista, A. M., & Neto, R. J. L. "Tribological behaviour of epoxy based composites for rapid tooling." *Wear*, 2004: 260(1-2), 30–39.

58. Wisheart, M. J., and Richardson M. 0. W. "Impact properties and finite element analysis of a pultruded composite system". *Composites Part A*, 1996: 27A, pp 1123-1131.

59. Witik, R. A., Payet, J., Michaud, V., Ludwig, C., and Månson, J.-A. E. "Assessing the life cycle costs and environmental performance of lightweight materials in automobile applications." *Composites Part A: Applied Science and Manufacturing*, 2011: 42(11),1694–1709. .

60. Wonderly, C., Grenestedt, J., Fernlund, G., and Cěpus, E. "Comparison of mechanical properties of glass fiber/vinyl ester and carbon fiber/vinyl ester composites." *Composites Part B: Engineering*, 2005: 36(5), pp 417–426.

61. *www.compocycle.com*. 2010. (accessed 2013).

62. www.lstc.com/products/ls-dyna(accessed 2015)

63. www.lstc.com/products/ls-prepost(accessed 2015)

64. Yamashita, Y., Kawabata, S., Okada, S., & Tanaka, A. "Mechanical characteristics of PBO single fiber." *Carbon (T-300, PAN)*, 2003: 234(6.03), 18–20.

65. Yang, Q. J., 'Simplified Approaches to Buckling of Composite Plates'. Faculty of Mathematics and Natural Science, University of Oslo, 2009.

66. Zike, S., Kalnins, K., Ozolins, O., and Knite, M. "An Experimental and Numerical Study of Low Velocity Impact of Unsaturated Polyester/Glass Fibre Composite." *Materials Science*, 2011: 17(4), pp 384-390

APPENDIX A

Formula for calculating composite laminate plate deflection (Jones)

According to classic lamination theory deflection in a composite laminate simply supported at all the edges is given by

$$w = \frac{16\mathrm{p} \sum_{\mathrm{m}=1,3,5,....}^{\infty} \sum_{\mathrm{n}=1,3,5,...}^{\infty} \frac{1}{\mathrm{mn}} \sin\frac{\mathrm{m}\pi \mathrm{x}}{\mathrm{a}} \sin\frac{\mathrm{n}\pi \mathrm{y}}{\mathrm{b}}}{\pi^6 \left[\mathrm{D}_{11}\left(\frac{\mathrm{m}}{\mathrm{a}}\right)^4 + 2(\mathrm{D}_{12} + 2\mathrm{D}_{66})\left(\frac{\mathrm{m}}{\mathrm{a}}\right)^2\left(\frac{\mathrm{n}}{\mathrm{b}}\right)^2 + \mathrm{D}_{22}\left(\frac{\mathrm{n}}{\mathrm{b}}\right)^4\right]} \qquad (\mathrm{A}.1)$$

w_{max} occurs at x = a/2 and y = b/2. For m =1 and n = 1,

$$w_{max} = \frac{16\mathrm{p}}{\pi^6 \left[\mathrm{D}_{11}\left(\frac{1}{\mathrm{a}}\right)^4 + 2(\mathrm{D}_{12} + 2\mathrm{D}_{66})\left(\frac{1}{\mathrm{a}}\right)^2\left(\frac{1}{\mathrm{b}}\right)^2 + \mathrm{D}_{22}\left(\frac{1}{\mathrm{b}}\right)^4\right]} \qquad (A.2)$$

Where $\mathrm{D}_{\mathrm{ij}} = \frac{1}{3}\sum_{\mathrm{k}=1}^{\mathrm{N}}(\overline{\mathrm{Q}_{\mathrm{ij}}})_{\mathrm{k}}\left(\mathrm{Z}_{\mathrm{k}}{}^{3}\text{-}\mathrm{Z}_{\mathrm{k-1}}{}^{3}\right)$ (A.3)

Where $\overline{Q_{11}} = Q_{11}\ (\cos\theta)^4 + 2(Q_{12} + 2Q_{66})(\sin\theta)^2(\cos\theta)^2 + Q_{22}(\sin\theta)^4$ (A.4)

$\overline{Q_{12}} = (Q_{11} + Q_{22} - 4Q_{66})(\sin\theta)^2\ (\cos\theta)^2 + Q_{12}\left((\sin\theta)^4 + (\cos\theta)^4\right)$ (A.5)

$\overline{Q_{22}} = Q_{11}\,(\sin\theta)^4 + 2(Q_{12} + 2Q_{66})(\sin\theta)^2(\cos\theta)^2 + Q_{22}(\cos\theta)^4$ (A.6)

$\overline{Q_{66}} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})(\sin\theta)^2(\cos\theta)^2 + Q_{66}\left((\sin\theta)^4 + (\cos\theta)^4\right)$

(A.7)

Where $Q_{11} = \frac{E_1}{1-\upsilon_{12}\upsilon_{21}},\quad Q_{12} = \frac{\upsilon_{12}E_2}{1-\upsilon_{12}\upsilon_{21}},\quad Q_{11} = \frac{E_2}{1-\upsilon_{12}\upsilon_{21}}, Q_{66} = G_{12}$ (A.8)

Z_{k} is the distance of kth lamina from the mid surface of the laminate

$\mathrm{Z}_{\mathrm{k-1}}$ is the distance of (k-1)th lamina from the mid surface of the laminate

Formula for calculating buckling pressure in a composite laminate and

According to classic lamination theory critical buckling pressure of the composite laminate simply supported at all the edges is given is by

$$\overline{N_x} = \pi^2\left[D_{11}\left(\frac{m}{a}\right)^2 + 2(D_{12} + 2D_{66})\left(\frac{n}{b}\right)^2 + D_{22}\left(\frac{n}{b}\right)^4\left(\frac{a}{m}\right)^2\right] \qquad (\mathrm{A}.9)$$

where D_{11}, D_{12}, D_{22} and D_{66} have been calculated as per equations (A.3) to (A.8)

By taking m=1 and n=1, $\overline{N_x}$ has been calculated.

Accordingly

$$\overline{N_x} = \pi^2\left[\frac{D_{11}}{a^2} + \frac{2(D_{12}+2D_{66})}{b^2} + \frac{D_{22}}{b^4}\,a^2\right] \qquad (\mathrm{A}.10)$$

APPENDIX – B

Sustainability index with no weight or equal weight and using linear aggregation

Serial no:	*Variables*	*Secondary variables*	*Tertiary variables*			*Ranking*	*Index points*								
							CFRP (E)	*CFRP(VE)*	*CFRP(PE)*	*GFRPE)*	*GFRP(VE)*	*GFRP(PE)*	*AFRP (E)*	*AFRP (VE)*	*AFRP(PE)*
1	Manufacturing phase	Toxic emissions of manufacturing of constituent materials	Fibre	Embodied energy	Carbon	3	3	3	3	1	1	1	2	2	2
					Aramid	2									
					Glass	1									
				CO2 emissions	Carbon	3	3	3	3	1	1	1	2	2	2
					Aramid	2									
					Glass	1									
			Matrix	Embodied energy	Epoxy	3	3	1	2	3	1	2	3	1	2
					Poly ester	2									
					Vinyl ester	1									
				CO2 emissions	Poly ester	3	2	1	3	2	1	3	2	1	3
					Epoxy	2									
					Vinyl ester	1									
2		Gel coat application	Gelcoat brushed			1	3	3	3	3	3	3	3	3	3
			Gelcoat rolled			2									
			Gelcoat sprayed			3									
3		Manufacturing methods	Use of prepegs			7	7	7	7	7	7	7	7	7	7
		If prepegs are not used, then include next three rows (i.e. 4 and 5)													
4		Matrix preparation	Exposure		Closed	0									
					Open	1									
			Styrene emission		Poly ester	2									

				Vinyl ester	1									
				Epoxy	0									
5		Manufacturing methods	Autoclave moulding		6									
			Spray up		5									
			Resin Transfer Moulding (RTM)		4									
			Vacuum Assisted Resin Infusion (VARI)		3									
			Pultrusion		2									
			Filament winding		1									
6		Curing	Common to all laminates		1	1	1	1	1	1	1	1	1	1
7		Mould cleaning	Common to all laminates		1	1	1	1	1	1	1	1	1	1
8		Equipment cleaning and disposal	Common to all laminates		1	1	1	1	1	1	1	1	1	1
9		Hazardous practices involved due to speciality of the material used	Yes		1	0	1	1	0	1	1	0	1	1
			No		0									
10	Disposal phase	Reduction of waste	Carbon		1	1	1	1	3	3	3	2	2	2
			Aramid		2									
			Glass		3									
		Reuse	Reuse as a vessel		0									
			Reuse as component		1									
			Reuse as material		2									
		Recycling	Thermal recycling	CFRP	1	1	1	1				1	1	1
				GFRP	2									
				AFRP	1									
			Chemical recycling	CFRP	1									
				GFRP	2									

						AFRP	1									
				Mechanical recycling	Powdered fillers	CFRP	2				0	0	0			
						GFRP	0									
						AFRP	1									
					Fibrous products	CFRP	1									
						GFRP	2									
						AFRP	1									
		Incineration		With energy recovery and material utilisation			0									
				With energy and material recovery			1									
				With energy recovery			2									
				Without recovery			3									
		Landfill					1									
		Disposal in laminate form					1									
11		Hazardous practices/ emissions involved due to the speciality of the new material	Reduction of waste				0									
			Reuse	Reuse as vessel			0									
				Reuse as component			0									
				Reuse as material			0									
			Recycling	Thermal recycling			1	1	1	1	1	1	1	1	1	1
				Chemical recycling			1									
				Mechanical recycling			1									
			Incineration				1									
			Landfill				1									
			Disposal in laminate form				1									
						Total index		27	25	28	24	22	25	26	24	27

							Index ranking	8	5	9	3	1	5	6	3	8

APPENDIX – C

Sustainability index based on differential weight and using linear aggregation

Serial no:	***Primary variables***	***Secondary variables***	***Tertiary variables***			***Ranking***	***weights***	***Index points***								
								CFRP (E)	***CFRP(VE)***	***CFRP(PE)***	***GFRPE)***	***GFRP(VE)***	***GFRP(PE)***	***AFRP (E)***	***AFRP (VE)***	***AFRP(PE)***
1	Manufacturing phase	Toxic emissions of manufacturing of constituent materials	Fibre	Embodied energy	Carbon	3	0.75	3	3	3	1	1	1	2	2	2
					Aramid	2										
					Glass	1										
				CO2 emissions	Carbon	3	0.75	3	3	3	1	1	1	2	2	2
					Aramid	2										
					Glass	1										
			Matrix	Embodied energy	Epoxy	3	0.85	3	1	2	3	1	2	3	1	2
					Poly ester	2										
					Vinyl ester	1										
				CO2 emissions	Poly ester	3	0.85	2	1	3	2	1	3	2	1	3
					Epoxy	2										
					Vinyl ester	1										
2		Gel coat application	Gelcoat brushed			1	1	3	3	3	3	3	3	3	3	3
			Gelcoat rolled			2										
			Gelcoat sprayed			3										
3		Manufacturing methods	Use of prepegs			7	1	7	7	7	7	7	7	7	7	7
		If prepegs are not used, then include next three rows (i.e. 4 and5)														
4		Matrix preparation	Exposure		Closed	0	1									
					Open	1										
			Styrene emission		Poly ester	2	0.125									
					Vinyl ester	1										
					Epoxy	0										
5		Manufacturing methods	Autoclave molding			6	1									
			Spray up			5										

			Resin Transfer Molding (RTM)			4										
			Vacuum Assisted Resin Infusion (VARI)			3										
			Pultrusion			2										
			Filament winding			1										
6		Curing	Common to all laminates			1	0.01	1	1	1	1	1	1	1	1	1
7		Mould cleaning	Common to all laminates			1	0.01	1	1	1	1	1	1	1	1	1
8		Equipment cleaning/ disposal	Common to all laminates			1	0.01	1	1	1	1	1	1	1	1	1
9		Hazardous practices involved due to speciality of the material used	Yes			1	1	0	1	1	0	1	1	0	1	1
			No			0										
10	Decommissioning / disposal phase	Reduction of waste	Carbon			1	1	1	1	1	3	3	3	2	2	2
			Aramid			2										
			Glass			3										
		Reuse	Reuse as a vessel			1	2									
			Reuse as component			2										
			Reuse as material			3										
		Recycling	Thermal recycling		CFRP	1	3	1	1	1				1	1	1
					GFRP	2										
					AFRP	1										
			Chemical recycling		CFRP	1	3									
					GFRP	2										
					AFRP	1										
			Mechanical recycling	Powdered fillers	CFRP	2	3				1	1	1			
					GFRP	1										
					AFRP	2										
				Fibrous products	CFRP	1	3									
					GFRP	2										
					AFRP	1										
		Incineration	With energy recovery and material utilisation			0	4									
			With energy and material recovery			1										
			With energy recovery			2										
			Without recovery			3										

		Landfill			1	5									
		Disposal in laminate form			1	6									
11		Hazardous practices/ emissions involved due to the speciality of the new material	Reduction of waste		0	0									
			Reuse	Reuse as vessel	0	0									
				Reuse as component	0										
				Reuse as material	0										
			Recycling	Thermal recycling	1	1	1	1	1	1	1	1	1	1	1
				Chemical recycling	1										
				Mechanical recycling	1										
			Incineration		1	2									
			Landfill		1	3									
			Disposal in laminate form		1	4									
Total Index							23.78	22.23	24.78	22.78	20.23	23.78	23.28	21.73	24.28
Index Ranking							7	3	9	4	1	7	5	2	8

APPENDIX – D

Sustainability Index ranking using geometric aggregation

Serial no:	*Primary variable*	*Secondary variables*	*Tertiary variables*			*Ranking*	*weights*	*Index points*								
								CFRP (E)	*CFRP(VE)*	*CFRP(PE)*	*GFRP E)*	*GFRP(VE)*	*GFRP(PE)*	*AFRP (E)*	*AFRP (VE)*	*AFRP(PE)*
1	Manufacturing phase	Toxic emissions of manufacturing of constituent materials	Fibre	Embodied energy	Carbon	3	0.75	3	3	3	1	1	1	2	2	2
					Aramid	2										
					Glass	1										
				CO2 emissions	Carbon	3	0.75	3	3	3	1	1	1	2	2	2
					Aramid	2										
					Glass	1										
			Matrix	Embodied energy	Epoxy	3	0.85	3	1	2	3	1	2	3	1	2
					Poly ester	2										
					Vinyl ester	1										
				CO2 emissions	Poly ester	3	0.85	2	1	3	2	1	3	2	1	3
					Epoxy	2										
					Vinyl ester	1										
2		Gel coat	Gelcoat brushed			1	1	3	3	3	3	3	3	3	3	3

		application	Gelcoat rolled		2										
			Gelcoat sprayed		3										
3		Manufacturing methods	Use of prepegs		7	1	7	7	7	7	7	7	7	7	7
		If prepegs are not used, then include next three rows (i.e. 4 and 5)													
4		Matrix preparation	Exposure	Closed	0	1									
				Open	1										
			Styrene emission	Poly ester	2	0.125									
				Vinyl ester	1										
				Epoxy	0										
5		Manufacturing methods	Autoclave moulding		6	1									
			Spray up		5										
			Resin Transfer Moulding (RTM)		4										
			Vacuum Assisted Resin Infusion (VARI)		3										
			Pultrusion		2										
			Filament winding		1										
6		Curing	Common to all laminates		1	0.01	1	1	1	1	1	1	1	1	1
7		Mould cleaning	Common to all laminates		1	0.01	1	1	1	1	1	1	1	1	1
8		Equipment cleaning/ disposal	Common to all laminates		1	0.01	1	1	1	1	1	1	1	1	1
9		Hazardous practices involved due to speciality of the material used	Yes		2	1	1	2	2	1	2	2	1	2	2
			No		1										
10	Decommissi	Reduction of	Carbon		1	1	1	1	1	3	3	3	2	2	2

	oning / disposal phase	waste	Aramid			2										
			Glass			3										
		Reuse	Reuse as a vessel			1	2									
			Reuse as component			2										
			Reuse as material			3										
		Recycling	Thermal recycling		CFRP	1	3	1	1	1				1	1	1
					GFRP	2										
					AFRP	1										
			Chemical recycling		CFRP	1	3									
					GFRP	2										
					AFRP	1										
			Mechanical recycling	Powdered fillers	CFRP	2	3				1	1	1			
					GFRP	1										
					AFRP	2										
				Fibrous products	CFRP	1	3									
					GFRP	2										
					AFRP	1										
		Incineration	With energy recovery and material utilisation			0	4									
			With energy and material recovery			1										
			With energy recovery			2										
			Without recovery			3										
		Landfill				1	5									
		Disposal in laminate form				1	6									
11		Hazardous	Reduction of waste			0	0									
			Reuse	Reuse as vessel		0	0									

		practices/ emissions involved due to the speciality of the new material		Reuse as component	0										
				Reuse as material	0										
			Recycling	Thermal recycling	1	1	1	1	1	1	1	1	1	1	1
				Chemical recycling	1										
				Mechanical recycling	1										
			Incineration		1	2									
			Landfill		1	3									
			Disposal in laminate form		1	4									
			Total Index				500.41	654.7	1000.83	288.91	126	577.83	544.78	237.59	1089.6
			Index Ranking				4	7	8	3	1	6	5	2	9

APPENDIX E

Visual Basic code for calculating sustainability index for ship hull materials using equal weights

FORM 1 CODE

```
Public Class Form1

    Public Sub Form1_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load

    End Sub

    Public Sub Button1_Click_1(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
        Form2.Show()
    End Sub


End Class
```

Form 2 Code

```
Public Class Form2
    Public Shared sum As Decimal

    Public Sub Form2_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load

        sum = 0

    End Sub


    Public Sub RadioButton1_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton1.CheckedChanged
        sum = 6

    End Sub

    Public Sub RadioButton2_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton2.CheckedChanged
        sum = 4

    End Sub

    Public Sub RadioButton3_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton3.CheckedChanged
        sum = 2


    End Sub
```

```
    Public Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click

        Form3.Show()

    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        MsgBox("The age is " & sum)


    End Sub
End Class
```

Form 3 CODE

```
Imports WindowsApplication1.Form2

Public Class Form3

    Public Shared sum1 As Decimal



    Public Sub Form3_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load

        sum1 = Form2.sum




    End Sub

    Private Sub RadioButton1_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton1.CheckedChanged
        sum1 = Form2.sum + 5
    End Sub

    Private Sub RadioButton2_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton2.CheckedChanged
        sum1 = Form2.sum + 5
    End Sub

    Private Sub RadioButton3_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton3.CheckedChanged
        sum1 = Form2.sum + 2
    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        MsgBox(sum1)
    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
```

```
        Form4.Show()
        Me.Hide()

    End Sub
End Class
```

FORM 4 CODE

```
Imports WindowsApplication1.Form3
Public Class Form4


    Public Shared sum2 As Decimal

    Public Sub Form4_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
        sum2 = Form3.sum1
    End Sub

    Private Sub RadioButton1_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton1.CheckedChanged
        sum2 = Form3.sum1 + 1
    End Sub


    Private Sub RadioButton2_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton2.CheckedChanged
        sum2 = Form3.sum1 + 2
    End Sub

    Private Sub RadioButton3_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton3.CheckedChanged
        sum2 = Form3.sum1 + 3
    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
        MsgBox(sum2)
    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        Form5.Show()
    End Sub
End Class
```

FORM 5 CODE

```
Imports WindowsApplication1.Form4

Public Class Form5


    Public Shared sum3 As Decimal
    Public Shared count As Integer
```

```
    Private Sub Form5_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load

        count = 0
        sum3 = Form4.sum2
    End Sub

    Private Sub RadioButton1_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton1.CheckedChanged
        sum3 = Form4.sum2 + 1
    End Sub

    Private Sub RadioButton2_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton2.CheckedChanged
        sum3 = Form4.sum2 + 2
    End Sub

    Private Sub RadioButton3_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton3.CheckedChanged
        sum3 = Form4.sum2 + 3
    End Sub

    Private Sub RadioButton4_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton4.CheckedChanged
        sum3 = Form4.sum2 + 4
    End Sub

    Private Sub RadioButton5_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton5.CheckedChanged
        sum3 = Form4.sum2 + 5
    End Sub

    Private Sub RadioButton6_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton6.CheckedChanged
        sum3 = Form4.sum2 + 6
    End Sub

    Private Sub RadioButton7_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton7.CheckedChanged
        sum3 = Form4.sum2 + 7
        count = 1
    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        MsgBox(sum3)
    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
        If count = 1 Then
            Form8.Show()
        Else
```

```
            Form6.Show()
        End If

    End Sub
End Class
```

FORM 6 CODE

```
Imports WindowsApplication1.Form5

Public Class Form6

    Public Shared sum4 As Decimal

    Private Sub Form6_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs)
        sum4 = Form5.sum3
    End Sub

    Private Sub RadioButton1_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton1.CheckedChanged
        sum4 = Form5.sum3 + (1 * 0)
    End Sub

    Private Sub RadioButton2_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton2.CheckedChanged
        sum4 = Form5.sum3 + (1 * 2)
    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
        MsgBox(sum4)
    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        Form7.Show()
    End Sub

    Private Sub Form6_Load_1(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load

    End Sub
End Class
```

FORM 7 CODE

```
Imports WindowsApplication1.Form6

Public Class Form7


    Public Shared sum5 As Decimal
    Private Sub Form7_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        sum5 = Form6.sum4
```

```
    End Sub

    Private Sub RadioButton1_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton1.CheckedChanged
        sum5 = Form6.sum4 + 2
    End Sub

    Private Sub RadioButton2_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton2.CheckedChanged
        sum5 = Form6.sum4 + 1
    End Sub

    Private Sub RadioButton3_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton3.CheckedChanged
        sum5 = Form6.sum4 + 0
    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
        MsgBox(sum5)
    End Sub



    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        Form8.Show()
    End Sub

    Private Sub Form7_Load_1(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load

    End Sub
End Class
```

FORM 8 CODE

```
Imports WindowsApplication1.Form5
Imports WindowsApplication1.Form7

Public Class Form8

    Public Shared sum6, sum7 As Decimal
    Private Sub Form8_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
        If Form5.count = 1 Then
            sum6 = Form5.sum3
        Else
            sum6 = Form7.sum5
        End If

    End Sub

    Private Sub RadioButton1_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton1.CheckedChanged
        sum7 = sum6 + 3
```

```
    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
        MsgBox(sum7)
    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        Form9.Show()
    End Sub
End Class
```

FORM 9 CODE

```
Imports WindowsApplication1.Form8

Public Class Form9



    Public Shared sum8 As Decimal

    Private Sub Form9_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
        sum8 = Form8.sum7
    End Sub

    Private Sub RadioButton1_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton1.CheckedChanged
        sum8 = Form8.sum7 + (1 * 1)
    End Sub

    Private Sub RadioButton2_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton2.CheckedChanged
        sum8 = Form8.sum7 + (0 * 1)
    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
        MsgBox(sum8)
    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        Form10.Show()
    End Sub
End Class
```

FORM 10 CODE

```
Imports WindowsApplication1.Form9

Public Class Form10


    Public Shared sum9, count1 As Decimal
```

```
    Private Sub Form10_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
        sum9 = Form9.sum8
        count1 = 0

    End Sub

    Private Sub RadioButton2_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton2.CheckedChanged

        sum9 = Form9.sum8 + (2 * 1)
    End Sub

    Private Sub RadioButton1_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton1.CheckedChanged

        sum9 = Form9.sum8 + (1 * 1)
    End Sub

    Private Sub RadioButton3_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton3.CheckedChanged

        sum9 = Form9.sum8 + (3 * 1)
    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
        MsgBox(sum9)
    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        Form11.Show()
    End Sub

    Private Sub Label3_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Label3.Click

    End Sub
End Class
```

FORM 11 CODE

```
Public Class Form11




    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
        Form12.Show()
    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
```

```
        Form13.Show()
    End Sub

    Private Sub Button3_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button3.Click
        Form14.Show()
    End Sub

    Private Sub Button4_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button4.Click
        Form15.Show()
    End Sub

    Private Sub Button5_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button5.Click
        Form16.Show()
    End Sub

    Private Sub Form11_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load

    End Sub
End Class
```

FORM 12 CODE

```
Imports WindowsApplication1.Form10

Public Class Form12

    Public Shared sum10 As Decimal

    Private Sub Form12_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
        sum10 = Form10.sum9
        Form10.count1 = 0
    End Sub

    Private Sub RadioButton1_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton1.CheckedChanged
        sum10 = Form10.sum9 + 1
    End Sub

    Private Sub RadioButton2_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton2.CheckedChanged
        sum10 = Form10.sum9 + 2
    End Sub

    Private Sub RadioButton3_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton3.CheckedChanged
        sum10 = Form10.sum9 + 3
    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
        MsgBox(sum10)
    End Sub
```

```
    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        Form20.Show()
    End Sub
End Class
```

FORM 13 CODE

```
Imports WindowsApplication1.Form10

Public Class Form14

    Public Shared sum10 As Decimal
    Private Sub Form14_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
        sum10 = Form10.sum9
        Form10.count1 = 5
    End Sub

    Private Sub RadioButton1_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton1.CheckedChanged
        sum10 = Form10.sum9 + 0
    End Sub

    Private Sub RadioButton2_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton2.CheckedChanged
        sum10 = Form10.sum9 + 1
    End Sub

    Private Sub RadioButton3_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton3.CheckedChanged
        sum10 = Form10.sum9 + 2
    End Sub

    Private Sub RadioButton4_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton4.CheckedChanged
        sum10 = Form10.sum9 + 3
    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
        MsgBox(sum10)
    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        Form20.Show()
    End Sub
End Class
```

FORM 14 CODE

```
Imports WindowsApplication1.Form10

Public Class Form14
```

```
    Public Shared sum10 As Decimal
    Private Sub Form14_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
        sum10 = Form10.sum9
        Form10.count1 = 5
    End Sub

    Private Sub RadioButton1_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton1.CheckedChanged
        sum10 = Form10.sum9 + 0
    End Sub

    Private Sub RadioButton2_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton2.CheckedChanged
        sum10 = Form10.sum9 + 1
    End Sub

    Private Sub RadioButton3_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton3.CheckedChanged
        sum10 = Form10.sum9 + 2
    End Sub

    Private Sub RadioButton4_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton4.CheckedChanged
        sum10 = Form10.sum9 + 3
    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
        MsgBox(sum10)
    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        Form20.Show()
    End Sub
End Class
```

FORM 15 CODE

```
Imports WindowsApplication1.Form10

Public Class Form15

    Public Shared sum10 As Decimal

    Private Sub Form15_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
        sum10 = Form10.sum9
        Form10.count1 = 6
        sum10 = Form10.sum9 + 1
    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
```

```
        MsgBox(sum10)
    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        Form20.Show()
    End Sub
End Class
```

FORM 16 CODE

```
Imports WindowsApplication1.Form10

Public Class Form16


    Public Shared sum10 As Decimal

    Private Sub Form16_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
        sum10 = Form10.sum9
        Form10.count1 = 7
        sum10 = Form10.sum9 + 1
    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
        MsgBox(sum10)
    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        Form20.Show()
    End Sub
End Class
```

FORM 17 CODE

```
Imports WindowsApplication1.Form10

Public Class Form17


    Public Shared sum10 As Decimal

    Private Sub Form17_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
        sum10 = Form10.sum9
        Form10.count1 = 1
    End Sub

    Private Sub RadioButton1_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton1.CheckedChanged
        sum10 = Form10.sum9 + 1
    End Sub

    Private Sub RadioButton2_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton2.CheckedChanged
```

```
        sum10 = Form10.sum9 + 2
    End Sub

    Private Sub RadioButton3_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton3.CheckedChanged
        sum10 = Form10.sum9 + 1
    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
        MsgBox(sum10)
    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        Form20.Show()
    End Sub
End Class
```

FORM 18 CODE

```
Imports WindowsApplication1.Form10

Public Class Form18

    Public Shared sum10 As Decimal
    Private Sub Form18_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
        sum10 = Form10.sum9
        Form10.count1 = 2
    End Sub

    Private Sub RadioButton1_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton1.CheckedChanged
        sum10 = Form10.sum9 + 1
    End Sub

    Private Sub RadioButton2_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton2.CheckedChanged
        sum10 = Form10.sum9 + 2
    End Sub

    Private Sub RadioButton3_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton3.CheckedChanged
        sum10 = Form10.sum9 + 1
    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
        MsgBox(sum10)
    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        Form20.Show()
    End Sub
```

```
End Class
```

FORM 19 CODE

```
Public Class Form19


    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
        Form21.Show()
    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        Form22.Show()
    End Sub

    Private Sub Form19_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load

    End Sub
End Class
```

FORM 20 CODE

```
Imports WindowsApplication1.Form12
Imports WindowsApplication1.Form17
Imports WindowsApplication1.Form18
Imports WindowsApplication1.Form21
Imports WindowsApplication1.Form22
Imports WindowsApplication1.Form14
Imports WindowsApplication1.Form15
Imports WindowsApplication1.Form16

Public Class Form20

    Public Shared sum11, sum12 As Decimal

    Private Sub Form20_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
        If Form10.count1 = 0 Then
            sum11 = Form12.sum10
        ElseIf Form10.count1 = 1 Then
            sum11 = Form17.sum10
        ElseIf Form10.count1 = 2 Then
            sum11 = Form18.sum10
        ElseIf Form10.count1 = 3 Then
            sum11 = Form21.sum10
        ElseIf Form10.count1 = 4 Then
            sum11 = Form22.sum10
        ElseIf Form10.count1 = 5 Then
            sum11 = Form14.sum10
        ElseIf Form10.count1 = 6 Then
            sum11 = Form15.sum10
        ElseIf Form10.count1 = 7 Then
            sum11 = Form16.sum10

        End If
        sum12 = sum11
    End Sub
```

```
    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
        MsgBox(sum12)

    End Sub

    Private Sub RadioButton1_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton1.CheckedChanged
        sum12 = sum11 + (0 * 0)
    End Sub

    Private Sub RadioButton2_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton2.CheckedChanged
        sum12 = sum11 + (1 * 1)
    End Sub

    Private Sub RadioButton3_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton3.CheckedChanged
        sum12 = sum11 + (1 * 2)
    End Sub

    Private Sub RadioButton4_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton4.CheckedChanged
        sum12 = sum11 + (1 * 3)
    End Sub

    Private Sub RadioButton5_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton5.CheckedChanged
        sum12 = sum11 + (1 * 4)
    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        Form23.Show()
    End Sub
End Class
```

FORM 21 CODE

```
Imports WindowsApplication1.Form10

Public Class Form21
    Public Shared sum10 As Decimal

    Private Sub Form21_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
        sum10 = Form10.sum9
        Form10.count1 = 3
    End Sub

    Private Sub RadioButton1_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton1.CheckedChanged
        sum10 = Form10.sum9 + 2
```

```
    End Sub

    Private Sub RadioButton2_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton2.CheckedChanged
        sum10 = Form10.sum9 + 0
    End Sub

    Private Sub RadioButton3_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton3.CheckedChanged
        sum10 = Form10.sum9 + 2
    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
        MsgBox(sum10)
    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        Form20.Show()
    End Sub
End Class
```

FORM 22 CODE

```
Imports WindowsApplication1.Form10

Public Class Form22

    Public Shared sum10 As Decimal

    Private Sub Form22_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
        sum10 = Form10.sum9
        Form10.count1 = 4
    End Sub

    Private Sub RadioButton1_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton1.CheckedChanged
        sum10 = Form10.sum9 + 1
    End Sub

    Private Sub RadioButton2_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton2.CheckedChanged
        sum10 = Form10.sum9 + 2
    End Sub

    Private Sub RadioButton3_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RadioButton3.CheckedChanged
        sum10 = Form10.sum9 + 1
    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button1.Click
        MsgBox(sum10)
```

```
    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Button2.Click
        Form20.Show()
    End Sub
End Class
```

FORM 23 CODE

```
Public Class Form23

    Private Sub Form23_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load

    End Sub
End Class
```

PUBLICATIONS BASED ON RESEARCH WORK

1. Dominic Manju and Nandakumar C. G., “Design of Nonmetallic Ship Hulls for Strength and Sustainability”, *International Journal of Applied Engineering Research and Development*, Vol. 5, Issue 2, Jun 2015, 1-8. ISSN(P): 2250-1584; ISSN(E): 2278-9383.
2. Dominic Manju and Nandakumar C. G., “Environmental Impact of Non Metallic Hull Ships”, *International conference on green technologies (ICGT- 2012)*,18-20 Dec 2012, 307-312. ISBN(P) 978-1-4673-2635-3.
3. Dominic Manju and Nandakumar C. G., “Investigations on strength of nonmetallic composite ship hulls” *International conference on materials for future (ICMF-2011).*