FLAW ANALYSIS ON GLASS FIBER REINFORCED PLASTIC INSHORE PETROL CRAFT HULL USING PULSE ECHO TECHNIQUE

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Dissertation submitted in partial fulfillment of the requirements for the degree of Master of Science in Materials Science

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DECLARATION OF THE CANDIDATE & SUPERVISOR

I declare that is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or Institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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Name of the supervisor: Mr. V Sivahar

Signature of the supervision: Date:

ACKNOWLEDGEMENT

The success and final outcome of this research involved a lot of guidance and assistance from the lecturers of Department of Material Science and Engineering, University of Moratuwa and Technicians of Sri Lanka Navy Central Non Destructive Testing unit and I am extremely fortunate to have got this all along the completion of my research work. Whatever I have done is only due to such guidance and assistance and I would not forget to thank them.

I would like to express my profound gratitude to my supervisor Mr. V Sivahar for his wise word, advices, patience and guidance throughout this research work. Further, I respect and thank Dr Shantha Amarasinghe for all the assistance and guidance provided during the research to complete the research work on time.

I profoundly thank my wife Gowri, who has sacrificed her higher education and relived me from my responsibilities as a husband and as a father in many domestic matters, my daughter Sawithmi was a great source of inspiration for me and she is the one who kept me awake most of the time to successful completion of this dissertation.

I must fondly remember my parents in this special occasion, though they may not have taught me to generate a study, but for their eternal love, support, sacrifices and confidence on me as their son, contributed significantly in making me to the individual what I am today.

Finally I would like to express my appreciation to every person who contributed with either inspirationally or in actual work to the successful completion of this study.

Abstract

The Glass fiber Reinforced Plastic (GRP) material is considered as the most prominent material for small boat industry due to the convenience of workmanship and light weight. Although the technology of GRP boat construction has been developed immensely for the last three decades, the technology related to the periodic assessment of GRP hull has not been developed in the same way compared to the steel and aluminum boat construction industry due to the inhomogeneous nature of the GRP structure.

At the designing stage of GRP boat, number of factors such as compressive modulus, tensile modulus, ultimate flexural strength, ultimate compressive strength and ultimate tensile strength will be considered in order to meet the level of performance expected by the end user. However the deterioration of the boat structure with the age, reduces the level of confidence to deploy the boat under same role.

In general flexural strength of GRP is measured destructively. However the destructive tests make the structure unusable, as such this study focuses on estimating flexural strength through nondestructive method with the aid of ultrasound technology.

The objective of this study; is to develop two independent relationships such as "Number of repeated blows Vs. Percentage Echo height" and "Number of repeated blows Vs. Flexural strength" using the data obtained from selected specimens. These specimens were obtained from the most prominent areas of damages expected on a GRP hull. These were then narrowed down to a single relationship, that is "Percentage Echo height Vs. Flexural strength".

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List of Abbreviations

IPC	Inshore Petrol Craft
GRP	Glass fiber Reinforced Plastic
NDE	Non Destructive Evaluation
TTM	Through Transmission Mode
PEM	Pulse Echo Mode
P&CM	Pitch & Catch Mode
AC motor	Alternative Current motor
SEM	Scanning Electron Microscope
LCD	Liquid Cristal Display
UWM	Under Water Maintenance

1. INTRODUCTION

"A ship is always safe at the shore - but that is NOT what it is built for."

— ***Albert Einstein***

The objective of this study is to develop, a suitable methodology to evaluate the durability of Glassfiber Reinforced Plastic (GRP) Inshore Petrol Craft (IPC) hull structure nondestructively to avail the catastrophic failures during operation and build up the confidence of operators and administration staff, as practiced in steel and aluminum hull using ultrasonic signal frequency.

Composite materials in boat building industry have started to play a major role since 1970s, due to their substantial benefits in terms of light weight, corrosion resistance and ability to be modeled in complex shapes. Even though the use of composite specially GRP material in marine construction is enormous, there is always element of fuzziness in designing of composites because of the quite complex process of composite fracture and failures .Further it is also known that GRP mechanical properties like stiffness, residual strength, buckling, load capacity may degrade severely in the presence of various types of indemnities like de lamination, de-bonding, water inclusion, fiber rupture or matrix cracking, which can occur during the manufacturing or operational life cycle.

The boats made out of GRP material are expected to operate 20 to 50 years without major structural refits (refurbish). As a result, their endurance and safety is depending on the long term fatigue performance of the GRP. The fatigue resistance of GRP composite used in boats are generally good, although fatigue damage can develop in highly stressed regions by the repeated action of tidal wave blowing against the hull and the Hogging Sagging bending motion along the boat hull at sea .This repeated number of blows can impose a serious safety problem, as these damages do not display early signs of visible damages.

In order to meet the small boat requirement in Sri Lanka Navy, the indigenous GRP boat building yard was established way back in 1985. As a result of this initiative, higher level of sheer commitment by naval engineers and technicians, the project has grown up in volume, improving the quality and types of boats. At present the yard is capable of building low profile greater speed, higher maneuverable, ultra-shallow water operating capable boats. These shallow draft GRP boats have served immensely during the historical humanitarian operation and major flood relief activities by carrying out shallow water, coastal waters and inland waters operations.

Although the GRP boats built in Sri Lanka Navy boat building yard were operated satisfactorily in Sri Lanka coastal waters, except few major incidents for last thirty years, proving the expertise of naval engineers and technicians there are no permanent method or technique developed to assess or evaluate the durability of GRP boat hull periodically to avoid catastrophic failures during her operation cycle. Figure: 1.1 illustrates the criticalness of the tidal wave blowing on GRP boat hull.

Figure 1.1: Criticalness of the tidal wave blowing force on GRP boat hull

Although the requirement of durability assessment of GRP hull is well understood, the traditional evaluation methods and techniques used on steel and aluminum hull inspection are not being able to use for the GRP hull inspection as Standard Nondestructive Examine (NDE) methods are developed only to inspect homogeneous structures to detect for any inhomogeneity in the structure whereas the GRP structures are made itself in homogeneously.

The most common five general NDE methods are Visual Test (VT), Magnetic partial Test (MT), Dye Penetrate Test (DPT), Radiographic Test (RT), Eddy current Test (ET) and Ultrasonic Test (UT). During this study, UT method is utilized to develop a suitable technique to inspect the GRP hull mainly due to convenience of the handling of the instrument.

1.1 Dissertation over View Features

The Chapter 2 of this study will cover literature review on the composite material inhomogeneous and anisotropic behavior, GRP boat building methods, stress experience on GRP boat hull and ultrasonic wave behavior on composite material. In Chapter 3, methodology proposed for thick composite nondestructive evaluation will be discussed. During Chapter 4 findings and results of the row data recorded will be elaborated along with the proposed technique. During, Chapter 5 under Discussion where the detailed explanation will be given for utilization of proposed technique after validation of developed results. Finally during Chapter 6, future proposals for improvement of proposed technique for further development will be elaborated.

2. LITERATURE REVIEW

2.1 Composite Material

"A composite material can be defined as a material system compound of a suitably arranged mixture or combination of two or more micro or macro constituents with an interface separating them that differ in form and chemical composition and are essentially insoluble in each other "[1]. During designing of the composites materials scientists and engineers combines various metal, ceramics and polymers to produce a new generation of extraordinary material which have different properties than the two parent material. The most of the composites have been designed to improve mechanical characteristics such as stiffness and toughness during ambient and higher- temperature levels.

Composite materials are composed of two main phases known as Matrix phase which is continuous and surround the other phase often called as Dispersed phase. The properties of the composites are a function of continuous phases, their relative amount and geometry of dispersed phases. The dispersed phase geometry, the shape of the particles and particle size, distribution and orientation; will define the characteristics of the composite which are represented in Figure: 2.1.

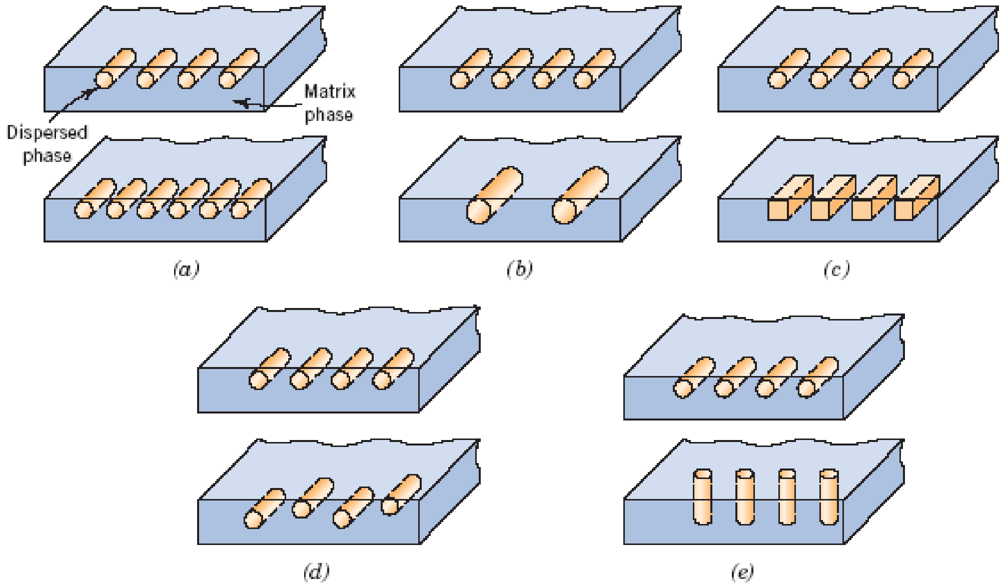


Figure 2.1: Dispersed Phase Geometry [2]

2.2 Composite Classification

Composites can be classified in many ways; the predominant types are structural-composite of structures in a matrix, Fibrous - composite of fibers in a matrix, and Particulate - composite of particles in a matrix. The simple schematic classification of composite materials is shown in Figure: 2.2 which consist of three main divisions with subdivisions.[3]

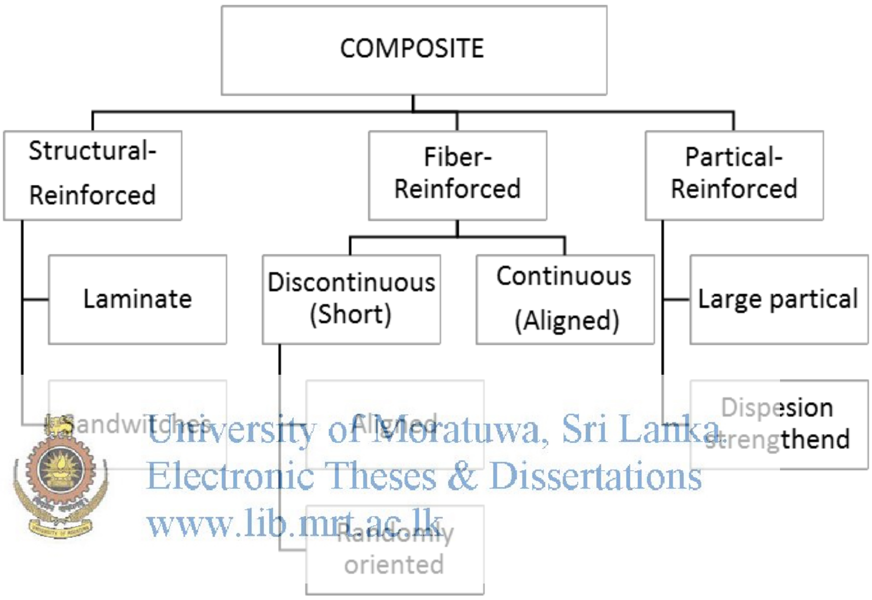


Figure 2.2: Composite Basic Classifications

Although composite materials are classified under three main streams as elaborated above, further literature study will be continued on fiber Reinforced composite as the objective of this research is to evaluate GRP nondestructively.

2.3 Glassfiber Reinforced Composites

The Designing of the Fiber-Reinforced Composites mainly focus on, either high strength or stiffness based on the material weight. These two main characteristics are expressed in terms of specific strength and specific modulus parameters and which invariably correspond to the ratios of tensile strength to specific gravity and modulus of elasticity to specific gravity. Fiber-reinforced composites with exceptionally high specific strengths and modulus have been produced by utilizing low-density fiber and matrix materials.

2.3.1 Matrix Phase

In Fiber-Reinforced composites, the matrix phase is expected to provide several functions as indicated below;

(1). To bind the fibers together and acts as the medium by which an externally applied stress is transmitted and distributed to the fibers and to minimize the proportion of an applied load in the matrix phase.

(2). To protect the individual fibers from surface damages as a result of mechanical abrasion or chemical reactions with the environment. Such interactions may introduce surface flaws capable of forming cracks, which may lead to failure at low tensile stress levels.

(3). To separate the fibers by virtue of its relative softness and plasticity prevents the propagation of cracks from fiber to fiber, which could result in catastrophic failure; in other words, the matrix phase serves as a barrier to crack propagation. Even though some of the individual fibers fail, total composite fracture will not occur until large numbers of adjacent fibers, once having failed, form a cluster of critical size.

2.3.2 Fiber Phase

The prominent characteristic of fiber expected in fiber phase is that higher strength with fine diameter. Fine diameter fiber will be having higher strength as the probability of the presence of a critical surface flaw that can lead to fracture, diminishes with decreasing specimen volume. On the basis of diameter character, fibers are grouped into three different classifications as indicated below;

(1). Whiskers:

Whiskers are very thin single crystals that have extremely large length-to-diameter ratios. As a consequence of their small size, they have a high degree of crystalline perfection and are virtually flaw free, which accounts for their exceptionally high strengths; they are among the strongest known materials. In spite of these high strengths, whiskers are not utilized extensively as a reinforcement medium because they are extremely expensive. Moreover, it is difficult and often impractical to incorporate whiskers into a matrix. Whisker materials include graphite, silicon carbide, silicon nitride, and aluminum oxide.

(2). Fibers:

Materials that are classified as fibers are either polycrystalline or amorphous and have small diameters. Fibrous materials are generally either polymers or ceramics (e.g., the polymer aramids, glass, carbon, boron, aluminum oxide, and silicon carbide).The diameters of glass fiber normally range between 3 and 20 µm.

(3). Wires:

Fibers having relatively large diameters are called wires; typical materials include steel, molybdenum, and tungsten. Wires are utilized as a radial steel reinforcement in automobile tires, in filament-wound rocket casings, and in wire-wound high - pressure hoses.

2.4 Glassfiber Reinforced Plastic (GRP) Composites

Fiberglass is simply a composite consisting of glass fibers, either continuous or discontinuous, embedded in a polymer matrix. This type of composite is produced in the larger quantities, especially in marine vessels such as yachts, life boats, fishing trawlers, petrol boats and naval mine hunting ships. The demand for GRP composite over more traditional maritime construction material like steel and aluminum alloy is higher due to their light weight, good fatigue performance, excellent corrosion resistance in sea water and low life maintenance costs.

2.4.1 Glass Fiber

In GRP, glass fiber diameters normally range between 3 and 20 µm. The two most important glasses used to produce glass fibers are E (electrical glass) and S (high -strength) glass. The "E" glass is the most commonly used glass for continuous fibers. The basic composition of 'E' glass and "S" glass ranges from 52% to 56% and 65% SiO_2 respectively. Some of the Physical and Mechanical Properties of E and S glass fiber are listed in Table: 2.1 [4]

Table 2.1: Physical and Mechanical Properties of glass fiber [4]

Property	E-Glass	S-Glass
Diameter (mm)	8-14	10
Density (kg/m3)	2540	2490
Tensile Modulus (GPa)	72.40	85.5
Tensile Strength (Mpa)	2400	3450
% Elongation	1.8-3.2	5-7
Coefficient of thermal expansion (°/C)	5	5-6
Specific Gravity	2.54	2.49

The glass is popular as a fiber in composite material for several reasons, they are as follows;

(1). Easily drawn into high-strength fibers from the molten state.

(2). Readily available and may be fabricated into a glass-reinforced plastic economically, using a wide variety of manufacturing techniques.

(3). Glass fibers are relatively strong, and when embedded in a plastic matrix, it produces a composite having a very high specific strength.

(4). When coupled with the various plastics, it possesses a chemical inertness that renders the composite useful in a variety of corrosive environments.

The surface characteristics of glass fibers are extremely important because even minute surface flaws can deleteriously affect the tensile properties. Surface flaws are easily introduced by rubbing or abrading the surface with another hard material. Also, glass surfaces that have been exposed to the normal atmosphere for even short time periods generally have a weakened surface layer that interferes with bonding to the matrix.

2.4.2 Resins

Polymers used as matrix materials are commonly referred to as resins. There are two basic classes of resin as indicated below:

(1). Thermosets – These polymers while heating undergo an irreversible chemical change called curing. During curing cross link chemically form and develop a network structure that sets them in shape. If they are heated after being cured, they would not melt.

(2). Thermoplastics – These resins melt when heated and solidify when cooled. Once they initially melt to form the composite, heating above the lower forming temperature can reshape them Prominent Physical and Mechanical Properties of resins are listed in Table: 2.2[4]

Table 2.2: Physical and Mechanical Properties of Resins [4]

Property	Polyester	Vinylester	Epoxy
Density (kg/m3)	1100-1500	970	1100-1400
Tensile Modulus (Gpa)	62	117	2-6
Tensile Strength (MPa)	2760	2580	35-150
% Elongation	3-4	4-5	1-8.5
Specific Gravity	1.1-1.5	0.97	1.10-1.14

2.4.3 Fiber Matrix Interface

A bundle of fibers by itself is useless as a load bearing structure, but embedding the fiber in a resin matrix gives the necessary stiffness in shear and compression. The fiber and the matrix are mutually reinforcing: the strong stiff fiber carries most of the stress and the polymer matrix distributes the external load to all the fibers, while at the same time protecting them. This load sharing requires that stress be transferred across the interface between the fiber and resin. There is no sharp well defined interface between the fiber and resin, for the fiber is coated with a heterogeneous mixture forming the matrix of the composite structure. The whole interfacial region is about 10^{-2} mm thick or greater.

Stress can only be transferred across an interface between two materials if they are in intimate molecular contact with each other, separated only by about the same distance as the molecules inside the bulk materials. The materials are then said to be adhering to each other. There need not be any chemical linking of the materials; they merely have to be so close that the normal intermolecular forces are operative. The plastic flow of the matrix under stress transfers the load to the fibers. As a result a high modulus composite is obtained. A typical GRP reinforcement will consist of 60% to 65% of fibers and the remaining cross section is the matrix.

2.5 Composite Manufacture

To make a composite, the pre-impregnated layup or the filament wound structure is cured by exposure to elevated temperature and pressure following a predetermined procedure. A vacuum is maintained in the curing environment to eliminate porosity in the resin. Resin is cured in three stages:

(1). The fluid stage (the resin is liquid and its molecules combine to form a reactive polymerizable material)

(2). The polymerization stage (polymers of long chains are formed)

(3). The hardening stage (polymeric chains cross link to produce a three - dimensional network).

The exact condition of the curing resin determines the duration of each stage and the times when various temperatures and pressures are applied. The resin condition must therefore be within specifications to ensure the quality of the final product.

The sequence of stacking glass fiber is determined by design requirements. Many of the techniques used have evolved from processing knowledge for plastic moulding. The tolerable cost of manufacturing is dependent upon the end use. Low-volume application areas, such as aircraft or space, typically utilize the more expensive methods, and high-volume areas, such as automotive or infrastructure, require that costs to be low. The processing methods elaborated below will follow manufacturing evolution from manual labor-intensive methods to highly automated and rapid methods [5].

(1). Manual Lay-up

The simplest technique used to make a composite structure is the manual lay-up method. Fibers are laid on a form and liquid resin is added and distributed throughout the fibers by hand rolling. After the desired thickness is attained, the product is allowed to cure, either at room temperature or in an oven. This method is time consuming and produces composites of low quality. Much effort has been undertaken in the industry to improve the manual lay-up method.

(2). Filament Winding

The filament winding process can be a very cost-effective method for producing a composite part. As its name implies, the method consists of wrapping fibers around a mandrel in layers until the desired thickness is reached. A winding machine allows the fiber orientation to be varied there by allowing the composite part to develop the design property profile. Matrix curing is most often done in an oven.

(3). Pultrusion

Pultrusion is the process where bundles of resin-impregnated fibers are cured by pulling them through a heated die. The addition of glass or carbon fiber to the pulling process yields a product that maximizes strength and stiffness in the pulling direction. When combined with part rotation and overwrapping techniques, Pultrusion can produce a wide variety of structural composite shapes.

(4). Resin Transfer Moulding (RTM)

In RTM, a mould is filled with reinforcement and injected with resin. Curing takes place in the mould and the composite takes the shape of the mould. There are variations on this basic technique depending upon how and when the fiber and reinforcement are combined and cured. Reaction injection moulding (RIM), structural reaction injection moulding (SRIM), vacuum-assisted resin transfer moulding (VARTM), and resin film infusion (RFI) are types that have been developed.

2.6 Composite in Service Defects

The physical behavior of composite materials is quite different from that of most common engineering materials that are homogeneous and isotropic. Metals will generally have similar composition regardless of where or in what orientation a sample is taken. On the other hand, the makeup and physical properties of composites will vary with location and orientation of the principal axes. These materials are termed anisotropic, which means they exhibit different properties when tested in different directions.

A fundamental problem concerning the engineering uses of fiber reinforced plastics (FRP) is the determination of their resistance to combined states of cyclic stress. Composite materials exhibit very complex failure mechanisms under static and fatigue loading because of anisotropic characteristics in their strength and stiffness. Fatigue causes extensive damage throughout the specimen volume, leading to failure from general degradation of the material instead of a predominant single crack. A predominant single crack is the most common failure mechanism in static loading of isotropic, brittle materials such as metals. Figure 2.3 illustrates comparison of the composites and metals fatigue damage over time.

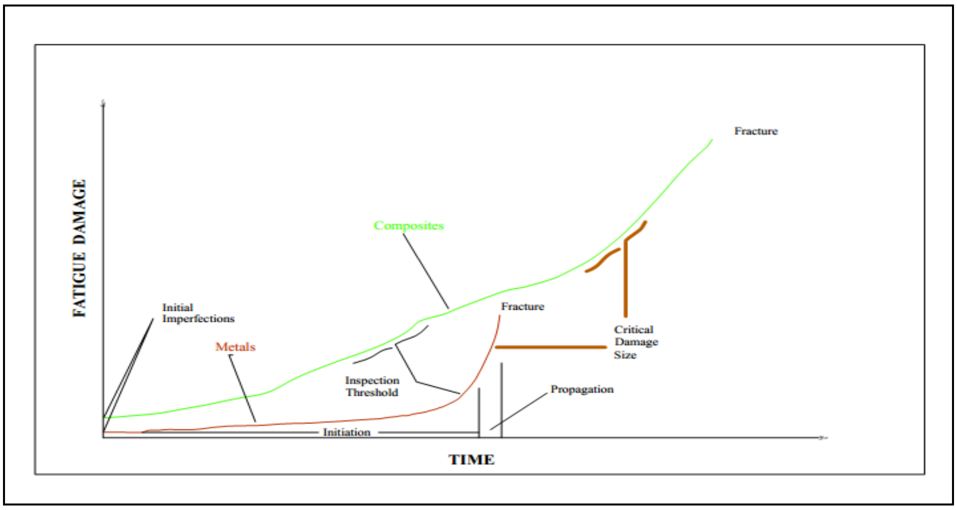


Figure 2.3: Comparisons of the composites and metal fatigue damage [6]

2.7 Composite Damage

Failure can be defined either as a loss of adequate stiffness, or as a loss of adequate strength. There are two approaches to determine life; constant stress cycling until loss of strength and constant amplitude cycling until loss of stiffness.

In general, stiffness reduction is an acceptable failure criterion for many components which incorporate composite materials. Figure 2.4 shows a typical curve of stiffness reduction for composites and metals. Stiffness change is a precise, easily measured and easily interpreted indicator of damage, which can be directly related to microscopic degradation of composite materials.[6]

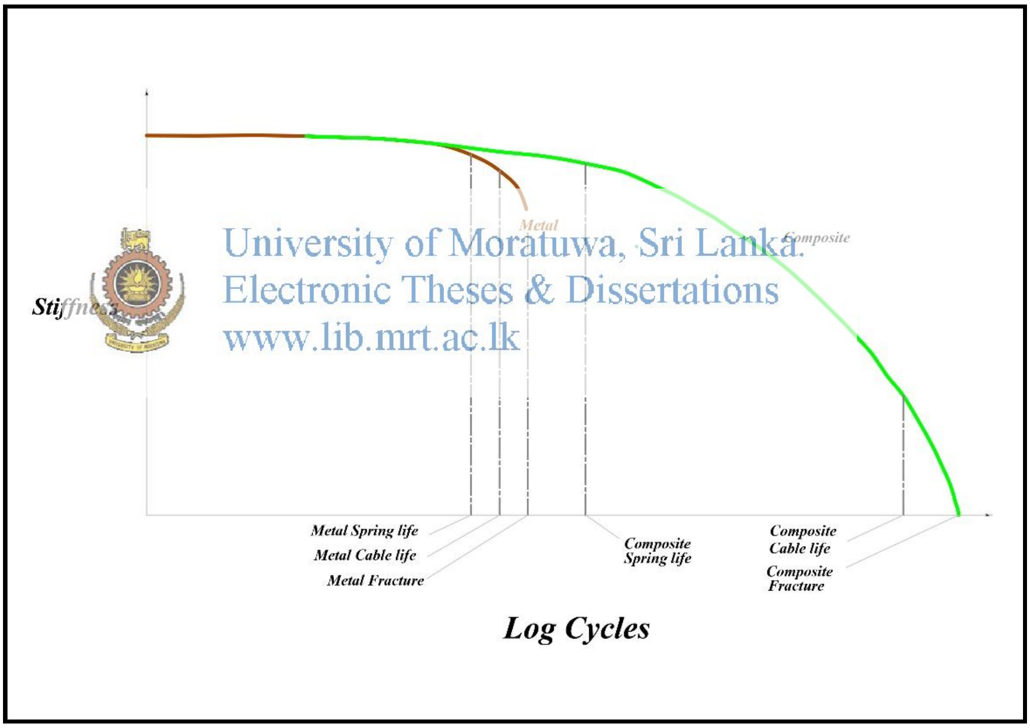
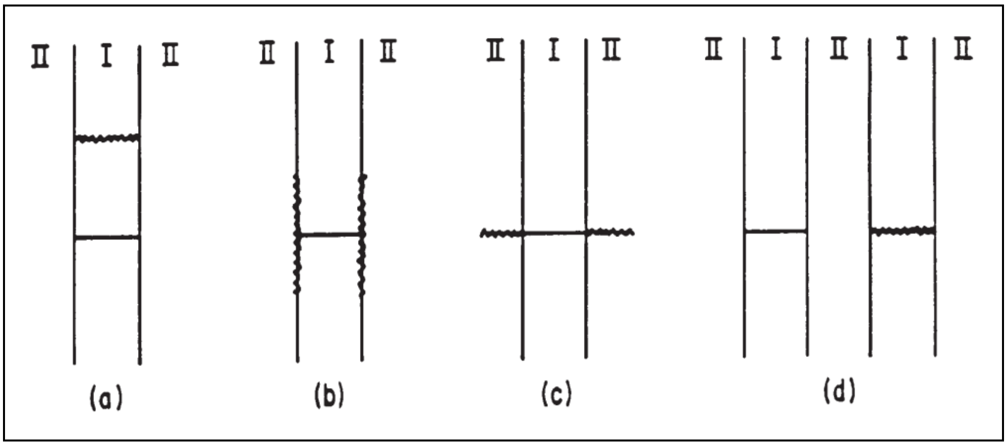


Figure 2.4: Comparison of Metal and Composite Stiffness Reduction [6]

In a constant amplitude deflection loading situation, the degradation rate is related to the stress within the composite sample. Initially, a larger load is required to deflect the sample. This corresponds to a higher stress level. As loading continues, a lesser load is required to deflect the sample; hence a lower strength level can exist in the sample. As the strength within the sample is reduced, the amount of deterioration in the sample decreases. The reduction in load required to deflect the sample corresponds to a reduction in the stiffness of that sample. Therefore, inconstant amplitude loading, the stiffness reduction is dramatic at first, as substantial matrix degradation occurs, and then quickly tapers off until only small reductions occur.

In a unidirectional fiber composite, cracks may occur along the fiber axis, which usually involves matrix cracking. Cracks may also form transverse to the fiber direction, which usually indicates fiber breakage and matrix failure. The accumulation of cracks transverse to fiber direction leads to a reduction of load carrying capacity of the laminate and with further cycling may lead to a jagged, irregular failure of the composite material.

There are four basic failure mechanisms in composite materials as a result of loading; matrix cracking, delamination, fiber breakage and interfacial de-bonding. The different failure modes combined with the inherent anisotropies, complex stress fields, and overall non-linear behavior of composites severely limit our ability to understand the true nature of loading. This failure mode is drastically different from the metal failure mode, which consists of the initiation and propagation of a single crack. The cracks in composite materials propagate in four distinct modes [7].These modes are illustrated in Figure. 2.5 where region I corresponds to the fiber and region II corresponds to the matrix.



Mode (a) - tough matrix where the crack is forced to propagate through the fiber

Mode (b) -occurs when the fiber/matrix interface weak (de-bonding effect)

Mode (c) -matrix weak and has relatively lower toughness

Mode (d) -strong fiber/matrix interface and a tough matrix

Figure 2.5 : GRP Materials Failure Modes [7]

Minor cracks in composite materials may occur suddenly without warning and then propagate at once through the specimen. It should be noted that even when many cracks have been formed in the resin, composite materials may still retain respectable strength properties. The retention of these strength properties is due to the fact that each fiber in the laminate is a load-carrying member and once a fiber fails the load is redistributed to another fiber

2.7.1 Composite Fatigue Theory

There are many theories used to describe composite material strength and fatigue life. Since there is no single analytical model that can account for all the possible failure processes in a composite material, because of that statistical methods developed to describe fatigue life have been adopted. Weibull distribution has proven to be a useful method to describe the material strength and fatigue life. Weibull distribution is based on three parameters; scale, shape and location. Estimating these parameters is based on one of three methods: the maximum likelihood estimation method, the moment estimation method, or the standardized variable method [8][9].

It has been shown that the moment estimation method and the maximum-likelihood method lead to large errors in estimating the scale and the shape parameters, if the location parameter is taken to be zero. The standardized variable estimation gives accurate and more efficient estimates of all three parameters for low shape boundaries [9].

Another method used to describe fatigue behavior is to extend static strength theory to fatigue strength by replacing static strengths with fatigue functions. The power law has been used to represent fatigue data for metals when high numbers of cycles are involved. By adding another term into the equation for the ratio of oscillatory-to-mean stress, the power law can be applied to composite materials [10] . Algebraic and linear first-order differential equations can also be used to describe composite fatigue behavior [11].

Despite the lack of knowledge, empirical data suggest that composite materials perform better than some metals in fatigue situations. Figure 2.6 depicts fatigue strength characteristics for Steel, Aluminum and composite materials.

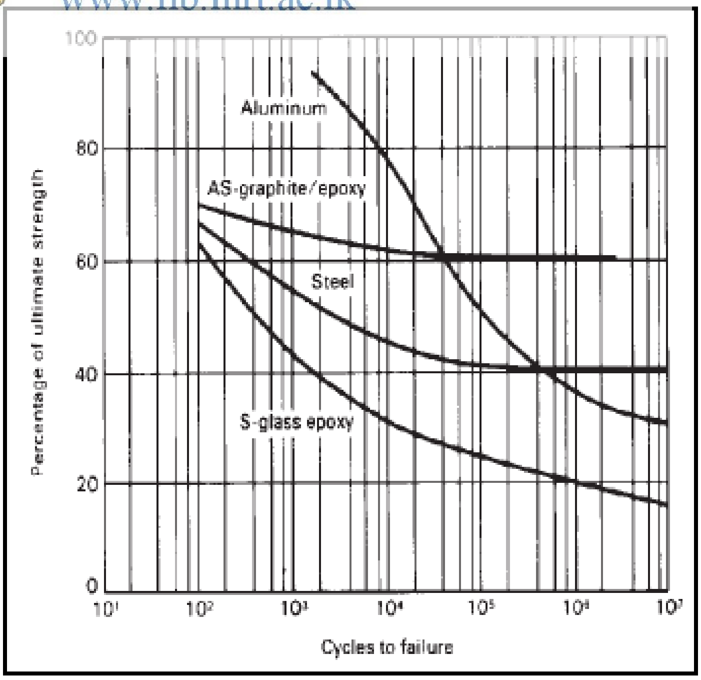


Figure 2.6: Fatigue strength characteristics for Steel, Aluminum and composite materials [11]

2.8 GRP Boat Building Process

The construction of GRP boat can be undertaken through different boat building techniques. However the main methodology of boat building technique is same in all the construction work. The first step of GRP boat construction is to prepare plug which is exactly same as the expected GRP boat and then to prepare the mould using a plug. The only purpose of plug is to provide a base for lamination of the mould; the plug does not have to be as rigid as a boat. The boat plug consists of the main plug jig, or hull plug, and separate center and athwart plugs, and a deck plug[13].

2.8.1 Plug Construction

A plug consists of a number of separate parts that can be made of wood, gypsum, metal or any other material which is not attacked by styrene monomer. While preparing the plug it is essential to maintain the surface of the mould (and the boat) is mirrored in the surface of the plug. The smoother plug will gives the better the final finish of the boat. Achieving a good finish involves the elimination of any imperfection by using putty and by sanding and polishing the resulting surface. In case of using, porous material like wood or gypsum, it is important to finish the plug with a good two-component paint which is resistant to styrene monomer. Figure: 2.7 illustrate the Principle build-up of the plug surface on wooden structure.

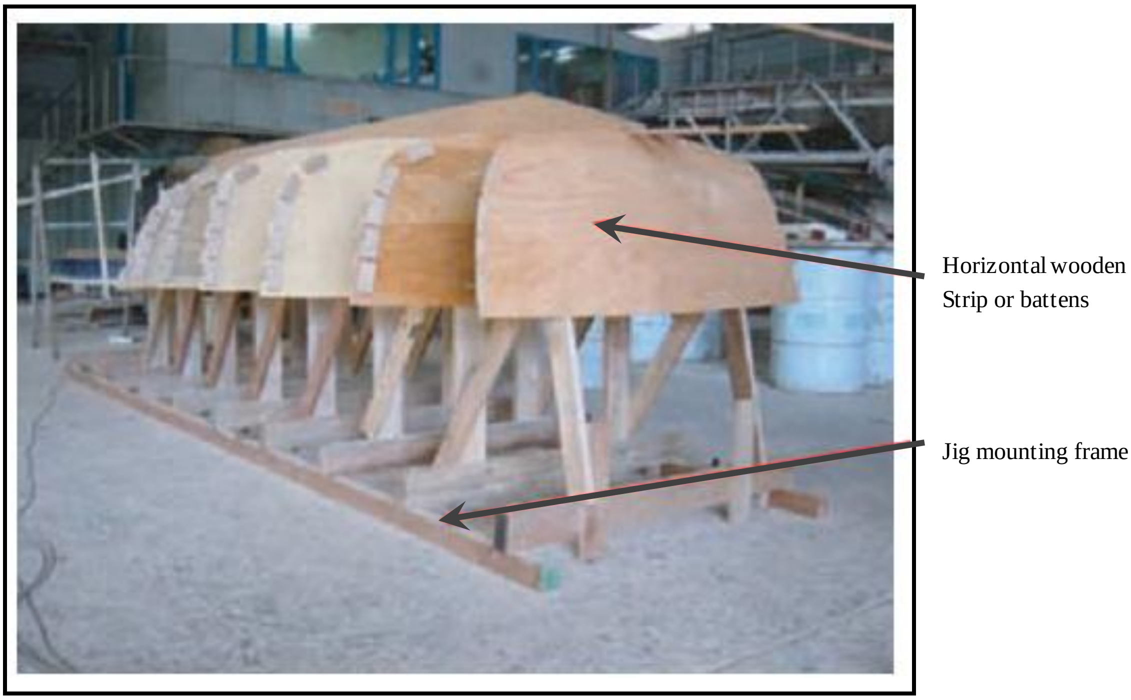


Figure 2.7: Principal build-up of the plug

2.8.2 Mould Construction

Most moulds in common use are "female" moulds. The mould being the mirror image of the plug, every blemish is transferred to the mould and will show on the final product. The lifespan and value of a mould is largely determined by the surface quality of the plug. If improvements or repairs to the surface of the mould are needed after the mould is pulled off the plug, valuable time will be lost. As long as the surface of the mould remains unbroken, only polishing or buffing is needed between uses and more products can be pulled off the mould in a shorter period of time. Preparation of the surface of the plug with 5 to 10 layers of wax is needed to achieve a perfect finish. The gel coat on the plug requires 2 to 3 weeks' time for a proper pre-cure.

The procedure for building up the laminate to create a mould is more or less the same as for building up the laminate to create a boat. It is very important to ensure that the surface layer is totally free of trapped air.

Ideally, a new mould should be placed in a tent, heated to maybe 40 ºC, to pre-cure for a couple of days. In a tropical climate, maintaining the high temperature should be an easy task. The pre-cure should drive off most of the active styrene on the tooling surface and help prevent the fresh mould from sticking to the gel coat on the first boat produced. Figure 2.8 illustrates the cross section of laminate in a mould.

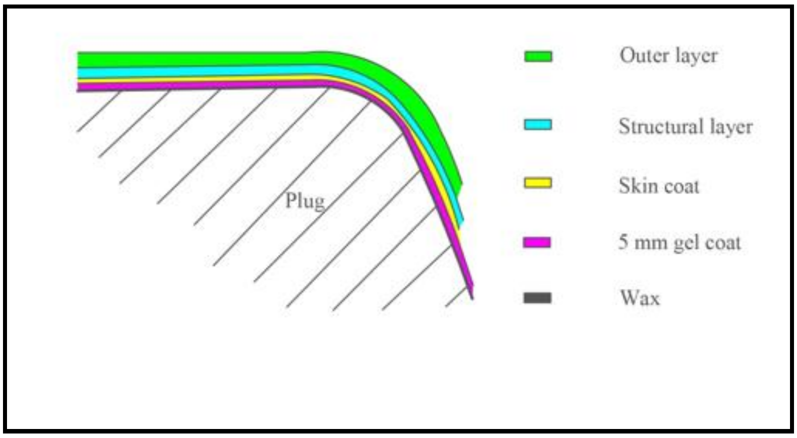


Figure 2.8: Cross-sections showing the build-up of laminate in a mould

2.8.3 GRP Boat Construction

Constriction of the actual boat starts with the application of the proper thickness of gel coat to the prepared mould. Two layers applied by brush (0.4 to 0.8 mm) are sufficient. Laying down the skin coat laminate and bulk (structural) layers are the next steps. As per the purpose of GRP boat utilization , the boat designer calculate the design pressure expected on boat, such as Static force, Pitching force impact force, flexural force etc… and decide upon the number of laminate layers on boat hull. The processes of lay-up will be scheduled accordingly. Step wise GRP boat building process is illustrated in Figure 2.9.

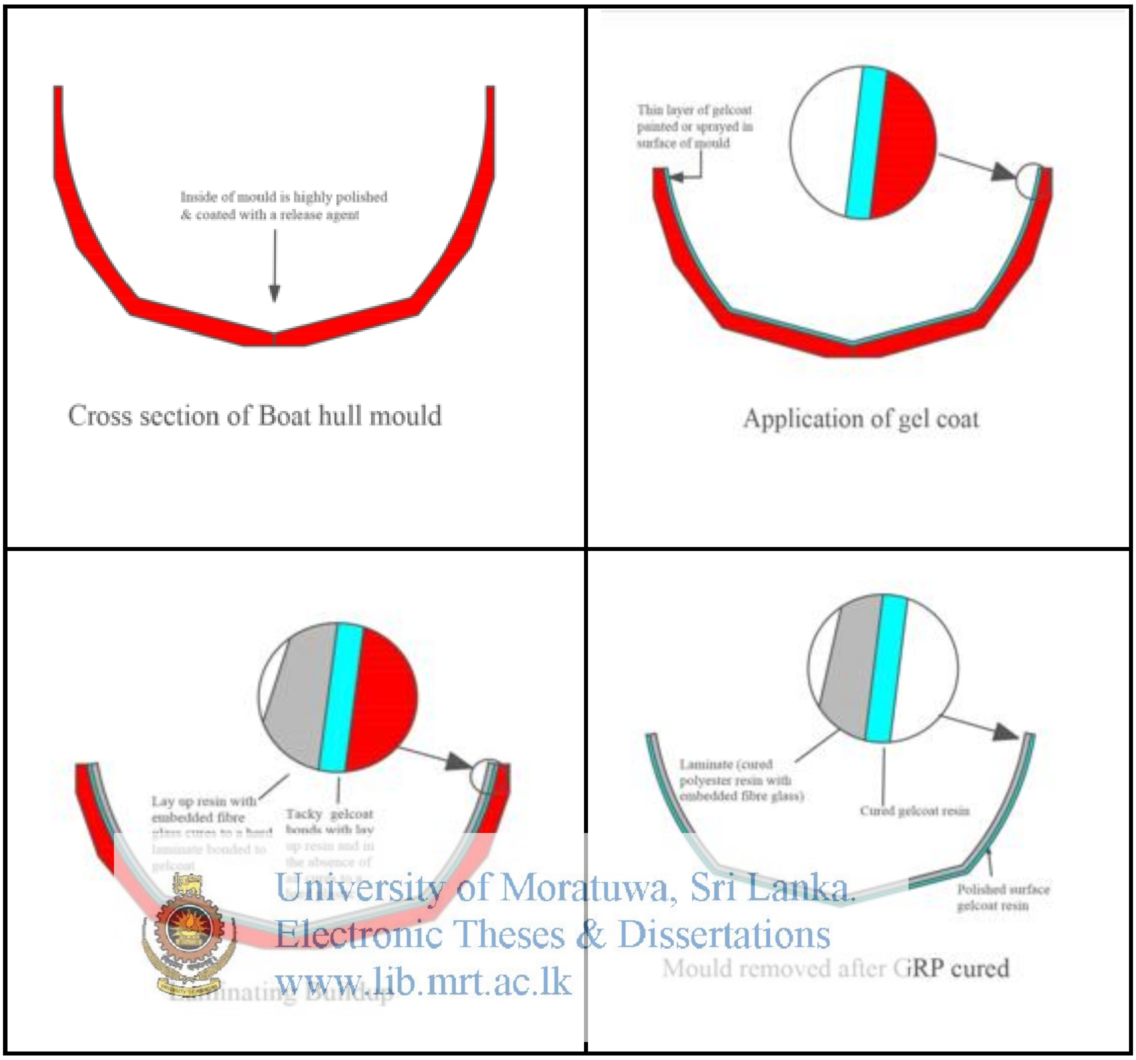


Figure 2.9: Step wise GRP boat building process

2.9 GRP boat in service damage

In service, structural composites are exposed to condition that can induce discontinuities different from those produced during construction. In service damages includes environmental degradation, erosion during service and damage due to impact loads, weather and fatigue loads. During the service, GRP boats are subjected to number of forces especially static, fatigue, torsion and impact forces. These forces have the potential to degrade the performance of the GRP hull [14] and shorter the expected life span. Erosion caused by rain, hail, dust or sand degrade the performance of the composite skins.

The various types of in-service damage differ insignificantly, but all of them have some or the other effect on the performance of the GRP. Matrix cracking and fiber –matrix de-bonding can allow water to penetrate the material, causing reductions in their modulus. Delamination will reduce the compressive strength, due to the possibility of buckling, whilst fibers breaking will reduce the tensile performance [14].

The generic type of composite damage is often classed as barely visible impact damage (BVID) which takes place due to sudden impact force. The most GRP laminates do not show external evidence of damage in most of the cases. This is because; most of the damages are inside the GRP material or on the back face (i.e. the side opposite the impact).

General applicability for fatigue-critical GRP structures cannot be easily established. Different material systems, that is, type of reinforcement and matrix, lamination sequence, load cases definition, and geometry of structural component usually result in case-specific situations treated more or less as in service, structural composites are exposed to conditions that can induce discontinuities such. The reason is that aforementioned parameters affect differently a multitude of failure mechanisms; for example, fiber breaks, matrix cracking, de-bonding and de-laminations are propagating in a different way and rate.

2.10 Importance of GRP boat hull in-Service damage evaluation

GRP composites generally have low stiffness, hence large composite ships should have thicker hull than those in metallic ships. The hull thickness is typically a few millimeters for small sail-boats and varies above to 20 mm for larger mine hunters (class of naval ships). The structure of the Sri Lanka Navy inshore shore petrol craft (IPC) thickness varies between 06 mm to 10 mm.

Although the fatigue resistance of GRP composites used in boats hull is generally good, fatigue damage can develop in highly stressed regions by the repeated action of tidal waves blowing against the hull and by the hogging sagging bending motion along the vessel in heavy seas without any visible indication. The IPC constructed at Naval Ship Building yard is illustrated in Figure: 2.10.

Figure 2.10: Inshore Petrol Craft built in Sri Lanka Navy Boat yard

2.10.1 Composites Non-Destructive Evaluation (NDE)

In all NDE methods, material is assessed by the detection of some signal, which is used specifically to derive material integrity. Composites materials (In-homogeneous) generally give poor flaw indication than homogeneous, isotropic material because of the greater contribution of noise from matrix-fiber additive boundaries. Further there are several other factors also influence the choice of inspection method. Some composite material absorbs moisture and there for any technique that involves substantial wetting of the surface cannot be used. On the other hand some method can only be applied to materials which exhibit certain properties like ferromagnetism and because of that, particular methods are limited for composite inspection than metals. There for very few NDE techniques are available for composite evaluation.[15]

2.10.2 Thick GRP Composites Ultrasonic Inspection

The NDE techniques will be further limited depending on the mobility of instrument, in ships use at sea or in a Dry-dock. The most appropriate NDE method for ship use out of common NDE method is Pulse-Echo ultrasonic. The popularity of pulse-echo ultrasonic is due to a number of practical features of the technique, such as its safety and reliability, necessary to access only one side of a ship structure (e.g. bulkhead, deck) to make an inspection, and portability of the ultrasonic instrument.

Despite above advantages, the ultrasonic method is normally applied to detect fatigue damage in Carbon-Fiber Reinforced Plastic (CFRP) composites used in aircraft structures which is having low thickness. Since aircraft composites are much thinner than the GRP, used in ships, they are usually easier to inspect using ultrasonic.[15]

Several studies have been carried out on success full detection, initiation and spread of fatigue cracks in GRP composites with through-transmission ultrasonic. Most of this techniques are able to detect small de-lamination cracks induced by fatigue loading, but only when the cracks grew in the direction transverse to the transmission path of the ultrasound waves and the other types of fatigue damage are more difficult to detect, such as fiber splitting or cracks parallel to the transmission path of the ultrasound waves [16 -19]

In aerospace composites certain types of fatigue damage e.g. de-laminations, fiber de-bonding can be detected using of through-transmission ultrasonic as aerospace composites are several millimeters thinner. However, very limited researches have been carried out on the detection of fatigue damage in thicker GRP composites with pulse-echo ultrasonic. Tsushima and Ono [20] recently reported that it was possible to monitor the initiation and growth of the damage in marine-grade GRP composites generated by zero-to-tension fatigue loading with the use of pulse-echo ultrasonic.

The thickness of the composites varies between 4.5 and 5.8 mm, which is about the hull thickness in racing yachts and small boats. Tsushima and Ono[20] monitored a steady increase in the attenuation of the ultrasonic signal with the number of fatigue cycles due to an increasing number of fatigue cracks being initiated within the resin matrix. Apart from this work, there have been no published studies on the NDE of fatigue induced damage in thick composites by the use of pulse-echo ultrasonic.

2.11 Flexural strength

The Flexural modulus is the ability of flexural material with a specific cross-section to resist bending when placed under stress. Flexural Modulus is an important calculation in boat building industry and ship architectural fields, since it indicates designers and builders the maximum weight that different boat building materials can bear. Since ships always subjected to continuous hogging and sagging stress, the flexural strength uses frequently to select the correct materials for ship hull that will support loads without flexing or warping.

Composites useful working portion of their Stress-Strain curve is very often not straight as illustrated in Figure: 2.11.

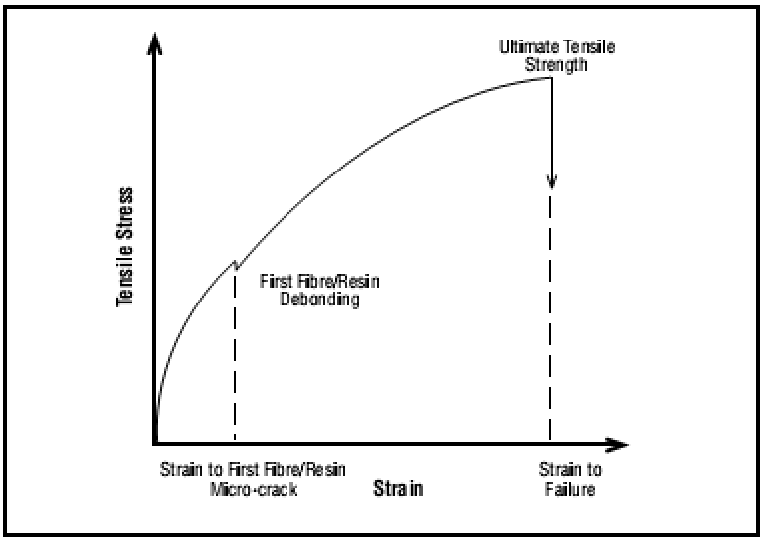


Figure 2.11: Stress-Strain curve [16]

In an isotropic material experienced a range of stresses across its depth as illustrated in Figure: 2.12. The upper side of the beam above will be loaded in compression, the lower surfaces, in tension.

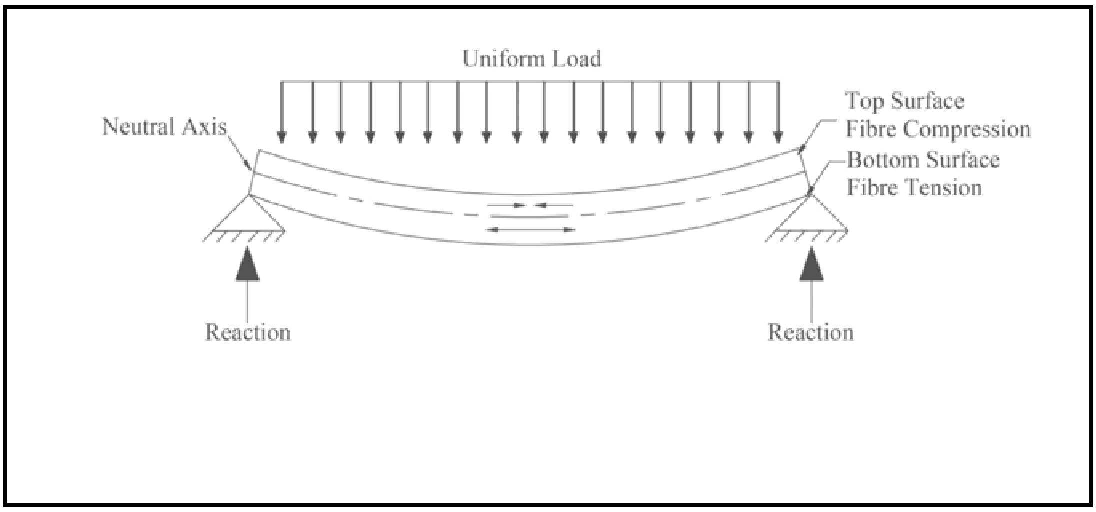


Figure 2.12: Range of stresses across the depth

The outer surface of the object on the inside of the bend that is concave face, the stress will be at its maximum compressive stress value and at the outside of the bend that is convex face, the stress will be at its maximum tensile value. For a material which is equally strong in tension as in compression, it is expect that the neutral surface (dashed line) to be right in the middle of the beam. But for many composites, the compressive stiffness is higher than the tensile stiffness, shifting neutral surface upward, (a smaller net cross-sectional area in compression is hard enough to resist the larger cross-sectional area under tension). Based on above it is prudent that the Compressive stiffness is not same as tensile stiffness.

Generating precise measurement on flexural modulus is complicated, but is almost always determined through a series of intensive laboratory tests on specimen of the intended material, with a specific shape and known dimensions. The “flexural test” is essentially a measurement of the force necessary to bend a sample, often known as a “beam,” that has defined dimensions. Technicians typically apply force at three points: the beam is usually supported on the bottom side near both ends and a force is applied to the top at the center point, between the bottom supports known as three-point loading during test. Once the force has been entered, any deflection or movement of the beam is measured and recorded, and then later analyzed.

2.11.1 Standard three point bend test

The standard three point bend test methods is used to determines the flexural strength of the unreinforced and reinforced composite materials , including high-modulus composites in the form of rectangular bars moulded directly or cut from sheets, plates, or moulded shapes. However flexural strength cannot be determined for those materials that do not break or that do not fail in the outer surface of the test specimen within the 5.0 % strain limit of the test methods. The test methods utilize a three-point loading system applied to a simply supported beam as per ASTM D790 standard or ISO 178 Plastics. The three point bend test method illustrated in Figure: 2.13.

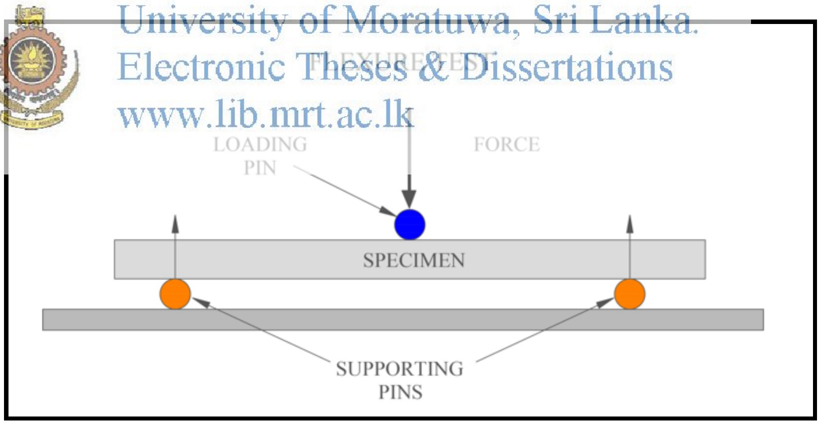


Figure 2.13: Three Point Bend Test Method

2.12 Ultrasonic Wave Propagation in material

The principal of ultrasonic testing involves a measure of the time required by ultrasonic vibration to penetrate the material of interest, reflect from the opposite side or from an internal discontinuity and return to the point where the wave were first introduced. The behavior of wave through such a cycle of travel with regard to time is appropriately recorded on Liquid Cristal Display (LCD) screen.[21]

2.12.1 Standard Ultrasonic Inspection method

There are three standard method of application of Ultrasonic beam in to that is Pulse-echo method and Through Transmission method. Pulse echo ultrasonic method is widely used in the mechanical, aerospace and nuclear industry, to investigate the presence of manufacturing and in-service defects in homogeneous metallic alloys. This method, based on transmitting a collimated ultrasonic beam into a material under test and record the echoes reflected by the discontinuities that the beam meets along its path& evaluating the echo delay. The depth of the discontinuity is easily identified, as the sound speed in medium is constant and known. The function of Ultrasonic Beam in homogeneous material and detection illustrated in Figure: 2.14.

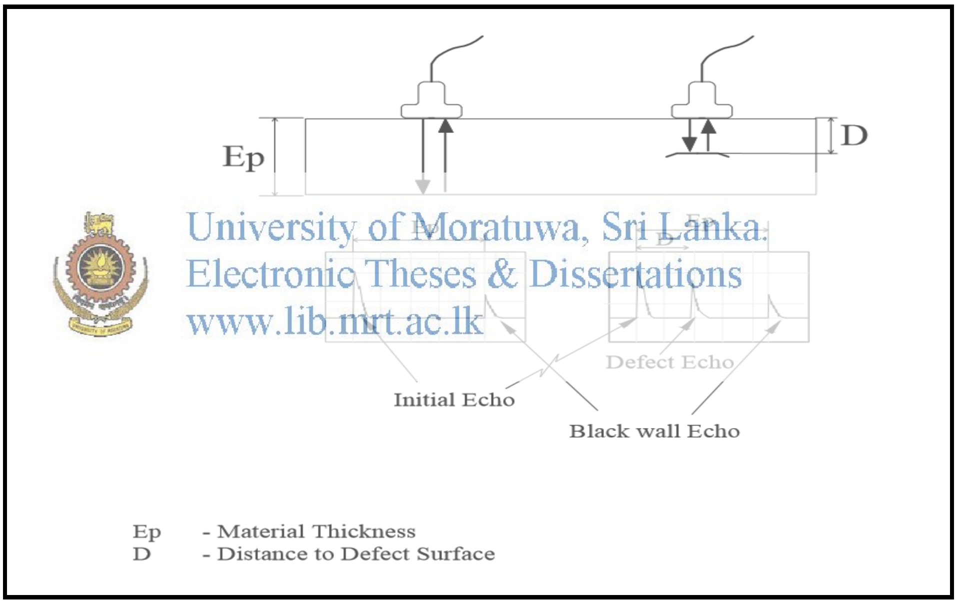


Figure 2.14: Functions of Ultrasonic Beam and Detection

In pulse echo inspection, several parameters can be evaluated, they are as follows;

(1) Changes in the back reflection amplitude

(2) Amplitude of extraneous reflections

(3) Variations in time of flight measured from the front reflection to the back reflection or the extraneous reflection.

2.12.2 Ultrasonic wave behavior in Composite

The ultrasonic behavior of GRP materials can be assumed similar to that of the homogeneous media, when the dimension of the typical discontinuity i.e. the fiber diameter is much smaller than the wave length of the ultrasonic signal where Lower frequency probes used and also this remain true as long as the ultrasonic wave propagate in the direction orthogonal to the fiber axis. This condition easily verified in usual applications where fibers lie in strengthening plane.

In case of external strengthening applied roughly to inhomogeneous materials, such as concrete and brick masonry, the time based technique is no longer effective. This is due to the high scattering attenuation of inhomogeneous medium, which behaves almost like a perfect absorber and generates a great number of short-spaced echo peaks that make the defect echo not easily distinguishable. The only way to avoid scattering is to use waves longer than the discontinuity dimensions but this heavily degrades resolving power and makes bonding defect undetectable.[23]

2.12.3 Attenuation Measurements

Ultrasonic wave propagation is influenced by the microstructure of the material through which it propagates. The velocity of the ultrasonic waves is influenced by the elastic moduli and the density of the material, which in turn are mainly governed by the amount of various phases present and the damage in the material. Ultrasonic attenuation, which is the sum of the absorption and the scattering, is mainly dependent upon the damping capacity and scattering from the grain boundary in the homogeneous material.

Relative measurements such as the change of attenuation and simple qualitative tests are easier to make than absolute measure. Relative attenuation measurements can be made by examining the exponential decay of multiple back surface reflections. However, significant variations in microstructural characteristics and mechanical properties often produce only a relatively small change in wave velocity and attenuation.

Absolute measurements of attenuation are very difficult to obtain because the echo amplitude depends on factors in addition to amplitude. The most common method used to get quantitative results is to use an ultrasonic source and detector transducer separated by a known distance. By varying the separation distance, the attenuation can be measured from the changes in the amplitude. To get accurate results, the influence of coupling conditions must be carefully addressed. To overcome the problems related to conventional ultrasonic attenuation measurements, ultrasonic spectral parameters for frequency-dependent attenuation measurements, which are independent from coupling conditions are also used. For example, the ratio of the amplitudes of higher frequency peak to the lower frequency peak, has been used for microstructural characterization of some materials. Figure: 2.15 illustrate the back wall wave attenuation.[24]

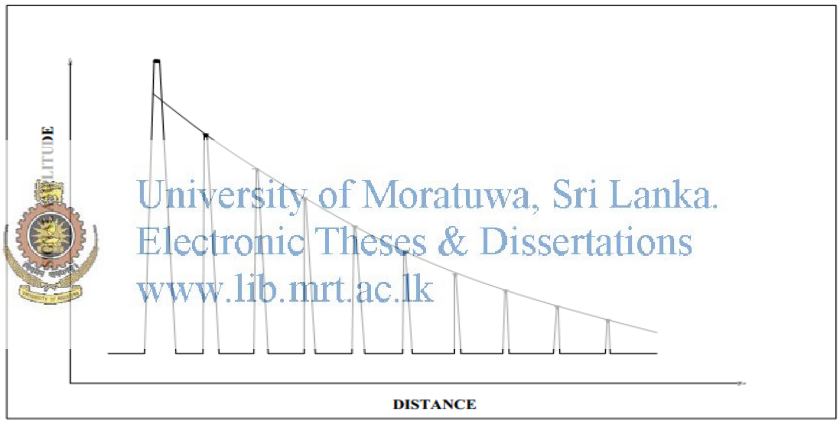


Figure 2.15:Back wall wave attenuation

2.12.4 Time of Flight

The depth of discontinuities in composite laminates can be determined with relatively high precision using time of flight measurements. For this purpose, short duration pulses are used in the pulse echo method and the test procedure is similar to those for metallic objects. The accuracy of assessing the depth depends on,

(1). Consistency of the ultrasonic velocity across the material

(2). Similarity of velocity in the test material to velocity in a reference material [24]

In composites, this accuracy is limited because of elastic property variations within the materials and between various components. These property variations are caused by non-uniform resin/ fiber volume ratio, differences in polymerization levels and variation in material content between batches of the same composite.[23]

2.12.5 Velocity Measurements

Using time of flight measurements, the ultrasonic velocity of a given mode along the material can be determined. Studies of both longitudinal and shear wave velocities can be used to determine some of the elastic constants of a composite. The anisotropic nature of composites is evident when examining the ultrasonic velocities of modes parallel and normal to the fibers.[23]

3. METHODOLOGY

In view of the facts explained under the literature review, since there is no standard Non Destructive Evaluation (NDE) procedure for thick composite inspection, it was decided to carry out a few trial attempts initially to check possibility of obtain; repeatable ,clearly differentiate ultrasonic signal on thick composite specimens. The initial experiment had been carried on a few specimens prepared at the workshop and found that there is a possibility of getting repeatable signal with the use of low frequency probes. However, during the experiment experienced difficulty of preparation of identical composite specimens due to the certain uncontrollable parameters like environmental conditions and identical manual laying skills. In order to overcome above obstacle, during study it was decided to extract specimen from original boat hull. The third and the main obstacle of this study was to find a suitable mechanism to simulate the repeated tidal wave blows on the boat hull.

During this chapter, a detailed explanation will be given, on the procedure adopted to overcome the above obstacles and the methodology adopted to establish the research findings.

3.1 Specimen Fabrication

Four groups of specimens were fabricated according to the intended procedure of the study. They are; the initial specimens, stage one specimens, stage two specimens and specimens used for validation. The detailed description of specimens are tabulated and indicated in Table 3.1.

Table 3.1: Specimen description

Description	Specimen details	Number of Specimens and their identification		Utilization
Initial specimens (Sec 3.1.1)	Fabricated	4		To build up confidence of ultrasonic utilization
Stage one specimens (Sec 3.1.2)	Extracted from transom plate	3	A,B,C	
Stage two specimens (Sec 3.1.3)	Extracted from boat keel	26	Category X – one specimen split into five specimens named S1,S2,S3,S4 and S5	For scanning electron microscope inspection
			Category Y- twenty specimens into five category. name group A,B,C,D and E which include five specimens per each group	To undergo flexural test after stimulation by tidal wave blow simulation machine
			Category Z- five specimens	To undergo flexural test without stimulation
Validation specimens (Sec 5.5)	Extracted from boat keel	3	P,Q,R	To compare destructive flexural strength and nondestructive flexural strength

3.1.1 Initial specimen

Initially four specimens were fabricated with four layers of woven glass fiber fabric with general purpose polyester resin, named Ortho-Polyester resin similar to resin used for IPC hull GRP schedule. These specimens were fabricated with artificially introduced de-lamination in order to check the possibility of generating reproducible signals. Figure 3.1 illustrates the initial specimen, with the cross section of an artificially created de-lamination.

Figure 3.1: Specimen with artificially created de-lamination

During the inspection it was found that the change of specimen conditions has contributed considerable effect on reproducing the same signal pattern and confused with the artificially introduced delamination with back wall reflected signal.

3.1.2 Stage One specimen

With the above experience on specimen preparation, it was decided to extract material from the boat hull and machined in to a required specifications. This approach was extremely difficult as in this approach the boat hull needs to be damaged, without any proof of success. In order to establish the confidence over the study, it was decided to carry out a research experimental work in two stages;

Stage one; using less number of specimens extracted from the boat transom plate material, where the boat builder removes considerable amount of GRP material for propulsion system installation. In this stage, three specimens were machined into a dimension of 250X60X10 mm from the transom plate material. The density of the Glass Fabric per specimen is 12.75g.The Figure 3.2 illustrates the IPC transom plate, where the material obtained for stage one specimen preparation.

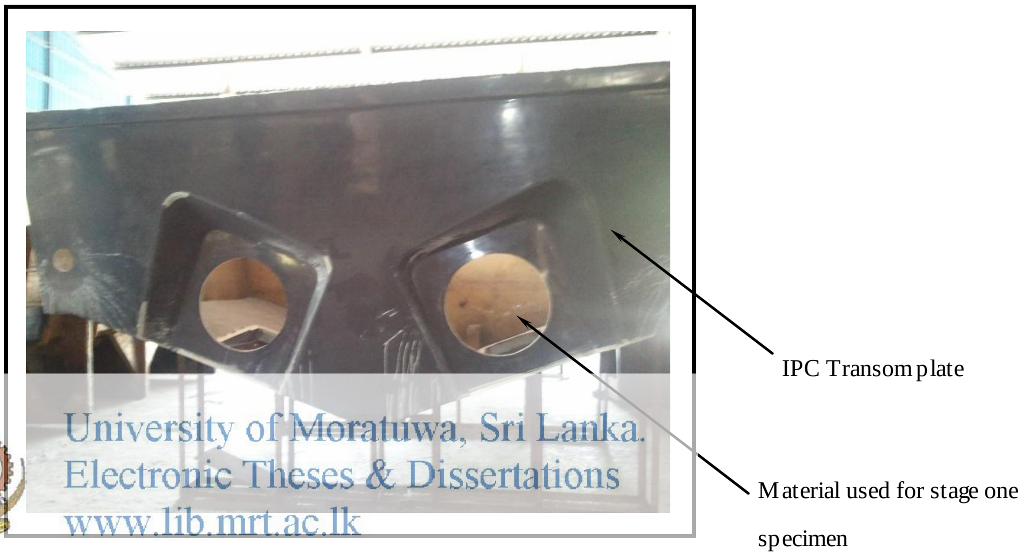


Figure 3.2: Transom plate

3.1.3 Stage Two Specimen

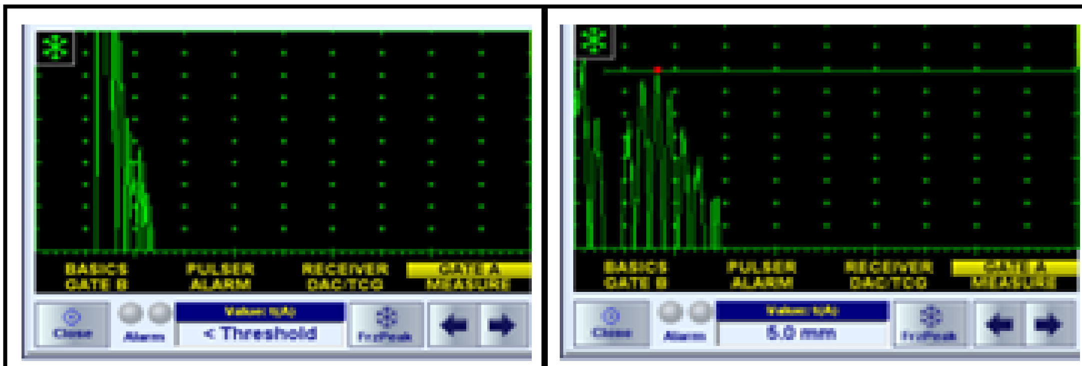
On the successful completion of the experiment in stage one, approval was granted to extract twenty six specimens from IPC keel area, place where more susceptible for tidal wave hammering and hogging-sagging stress on IPC hull. The dimension and the GRP thickness (schedule) of each specimen will be similar to the stage one specimens as mentioned above. Figure 3.3 illustrates the stage two specimen extraction from IPC Keel area.

Figure 3.3: Specimens Extraction IPC keel area

3.2 Thick GRP Ultrasonic Inspection

During the experiment, the longitudinal ultrasonic beam directed, normal to the thick GRP specimen front surface by neglecting the effect of material anisotropy. The approach of inspection will be similar to the inspection of isotropic media since the dimension of the typical discontinuity i.e. the fiber diameter is considered much smaller than the ultrasonic wave length and this assumption will remain accurate, as long as the acoustic waves propagate in a direction longitudinal to the fiber axis. However, even though the specimen assumed as isotropic, during the inspection, the layered nature of GRP contributes to extraneous reflections and increased attenuation. The only way to minimize scattering is that, to use longer ultrasonic wave longer than the fiber diameter; sacrificing the resolution that limits the discontinuity finding below fiber diameter.

In order to achieve the above wave length requirement, it was decided to use lower frequency probes that are 0.5 MHz, 1MHz and 2 MHz probes, avoiding commonly used higher frequency probes. The comparison of higher and lower frequency probe signal pattern on the same specimen is illustrated in Figure 3.4. The detailed specifications of probes are discussed under the heading of instrument specification.



Higher Frequency Probe | Lower Frequency Probe

Figure 3.4: Comparison of higher and lower frequency probes back wall signal readings

3.2.1 Ultrasonic Wave Attenuation as Measurement

Generally, there are three basic inspection modes practiced in straight beam ultrasonic inspection in homogeneous materials, namely Through Transmission Mode (TTM), Pulse Echo Mode (PEM) and Pitch & Catch Mode (P&CM). Nevertheless, the PEM is utilized during this study due to a number of practical convenience of the mode, primarily due to the minimum access requirement in pulse echo technique. The attenuation of PEM is relatively high in composite material than homogeneous material. This is because of the repetitive scattering by the fibers and isothermal absorption in the resin.

The use of attenuation as a characterization parameter is expected to be hampered by a few variables such as surface roughness and coupling effect. These effects are not distinguish or identified from the final signal formation. In addition, the transducer and instrument characteristics are also difficult to control in a reproducible manner. Therefore, percentage attenuation measurements are applied mainly to identify a significant deviation of material response from the base attenuation value for the tested specimen. The expected percentage attenuation change is illustrated in Figure 3.5.

Without stimulation inspected using 1MHz | After 18 hrs. simulation inspected using 1MHz

Figure 3.5: Expected percentage attenuation change

3.3 Repeated tidal wave blow simulate Mechanism

To overcome the obstacle experienced in simulating repeated tidal wave blow on boat hull; it was decided to build up a simple mechanism for steady hammering action at continuous steady speed on to the one fixed location. This machine is designed to power by A/C motor, which will transfer rotary motion into vertical hammering motion through mechanical lever system. This simulated repeated tidal wave blow which counted as per the revolutions of the A/C motor. The tidal wave blow simulation machine used during this study is shown in Figure 3.6.

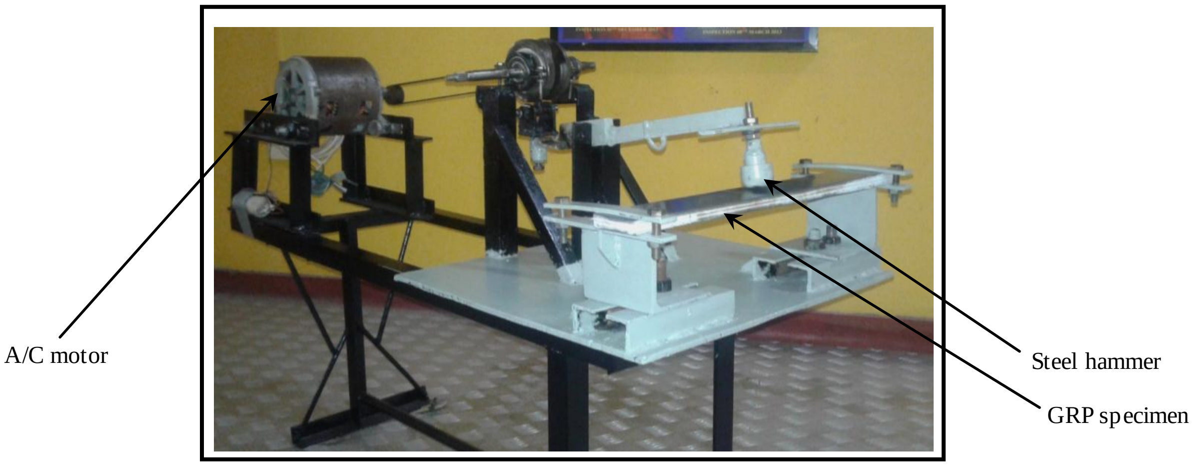


Figure 3.6: Tidal wave blow simulation machine

The machine is designed to accommodate for thick composite specimens, from 7mm to 10 mm as IPC hull thickness may vary between above range. The repeated waves blowing, hogging-sagging and bending movements are experienced on the IPC hull during her deployment at sea. While loading of the GRP specimens through this simulation machine, continuous steady hammering force is applied to the center of the specimen with predetermined number of hours to simulate the repeated tidal wave blow experienced on IPC hull. Further during this study it was assumed that the loading exposed on boat hull as a steady hammering load, although the actual loads/stress are not continuously steady.

As illustrated in Appendices B; Flow chart stage two experimental procedure, Group B, C, D and E specimens are stimulated by predetermined number of repeated blows using the above simulation machine. The percentage Eco height data was recorded subsequently through ultrasonic machine on all five group specimens and developed the stage two graph one (Figure: 4.2.2) which will be further explained in the Chapter 4 – Findings and Results.

3.3 Three Point Bend Test (Universal Testing Machine)

The Universal Testing Machine at Department of Material Science and Engineering, University of Moratuwa, Sri Lanka is utilized to carry out the "Three Point Bend Test" over stage one and stage two specimens and acquire maximum Flexural strength of each specimens. The detail of testing machine is discussed under the instrument specification in the later part of the Chapter.

During testing of thick GRP specimens, in flexure as a simple beam supported at two fixed points and loaded at midpoint. The maximum stress in the outer surface of the test specimen occurs at the midpoint.

As elaborated in stage two experimental procedure in Appendix B, flow chart; the stage two graph one (Figure: 4.5 and Figure: 4.6) that is "Number of repeated blows Vs. Percentage Echo height" was drawn and the same specimen Groups;

namely Group A, B, C, D and E underwent a three point bend testing (Flexural load testing) in accordance with the ASTM D790 M Standard through the Universal Testing machine until the disruption of each specimen. These findings were recorded and utilized to develop stage two graph two – (Figure: 4.7) "Flexural Strength Vs Number of repeated blow" which will be further explained in the Chapter 4 – Findings and Results. Figure: 3.7 illustrates the specimen tested by Universal Testing Machine during standard three point bend test.

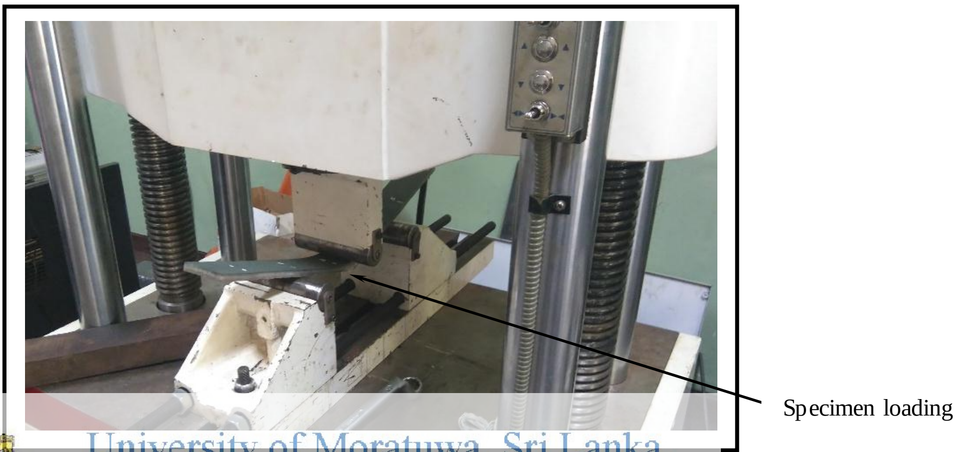


Figure 3.7: Specimen tested by Universal Testing Machine

3.4 GRP structural change in Microscopic view

The facility of Scanning Electron Microscope (SEM) was used during the study to establish the visually undetectable damages expected to take place during repeated blows experienced by the specimens.

As elucidated in Appendix B, the Stage Two test procedure, specimens, (here after mentioned as specimen "S-1, S-2, S-3, S-4 and S-5") were extracted from category X specimen before it undergoes each predetermined number of repeated blows. The each "S" specimen is extracted from 10 mm width strip from category X specimen before subjected to predetermine number of repeated blows in four steps and labeled as S 1 to S 5. These "S" specimens are machined in to a dimension of

10mmx10mmx10cm size, to meet the SEM test chamber specimen dimension requirement. The SEM findings will be utilized to further elaborate, the stage two graph one readings (Figure 5.2). The inspection of specimen through SEM is illustrated in Figure: 3.8.

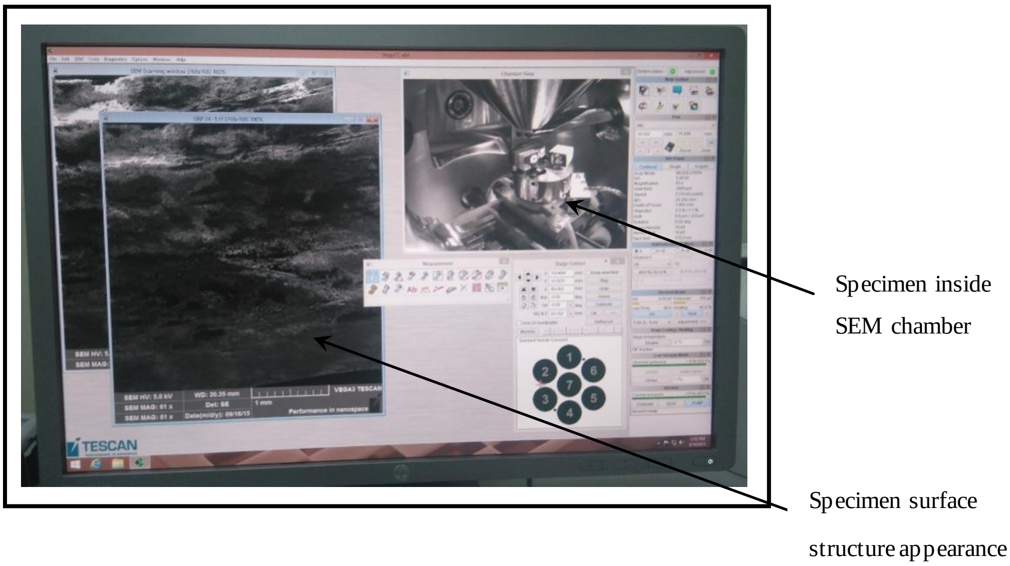


Figure. 3.8: inspection of specimen through SEM

3.5 Test Approach

The experiment activity was carried out in two stages; the first stage and the second stage experiment activity and their expectation were as follows;

3.5.1 First stage experiment

During first stage, specimens were stimulated by Tidal wave blow simulation machine in predetermined number of repeated blows in four phases and recorded the percentage of Echo height in each specimen using 1MHz and 2 MHz probes. The flow chart for the First stage experiment approach is illustrated in Appendix A.

The first stage recorded data utilized to generate stage one graph one (SOGO) that is “Number of repeated blow Vs. Percentage Echo height”. On completion of

SOGO preparation, same specimens were subjected to three point bend test to record Flexural Strength which will be calculated using formula given below.

$$\sigma_f = 3\,PL/2bd^2 \qquad (3.1)$$

σ_f $- Flaxural\ strength$

P $- Load$

L $- Span$

b $- Width$

d $- Depth$

The Number of repeated blow Vs Flexural Strength graph drawn and named as stage one graph two (SOGT).The stage one findings and respective graphs will be discussed under the Chapter 4 “Result and Discussion”.

3.5.2 Second Stage experiment

On receipt of favorable results from the stage one findings, the study was further extended by taking more specimens from IPC hull. During this stage Category Y specimen which includes five specimens in each Group namely B, C, D and E (altogether 20 specimens) were stimulated into predetermined Number of repeated blows and Category Z which include Group A, five specimen without stimulation were scan through ultrasonic scanning machine and record relevant percentage Echo height reading. During this process, standard deviations of five specimens in each group were taken into consideration while collecting Echo height data, for more accurate result. The graph for stage two graph one (STGO) is drawn percentage Echo height against Number of repeated blows.

The second graph of stage two (STGT) is drawn Number of repeated blows against Flexural Strength, according to the destructive test carried out on Group A, B, C, D and E specimens by three point bending machine according to ASTM D790 M Standards.

Further Five Specimens were extracted from Category X specimen, examined after the predetermined Number of repeated blows, through a Scanning Electron Microscope (SEM) to establish the development of fiber and resin damage with increment of number of repeated blows. This micro level findings will be utilized to describe the changes experienced in the ultrasonic Echo height. The specimen, view through SEM is illustrated in Figure: 3.9.

Figure: 3.9: S -specimen view through Scanning Electron Microscope

The flow chart for Second Stage Experiment procedure, with the steps of generating two relationships along with microscopic level inspection procedure is illustrated in Appendix B.

3.6 Instrument Specification used during research

The principal instruments utilized for study with their specification and their limitations are explained below;

3.6.1 Ultrasonic Instrument and accessories

The main instrument used for detecting ultrasonic back wall signal is illustrated in Figure: 3.10

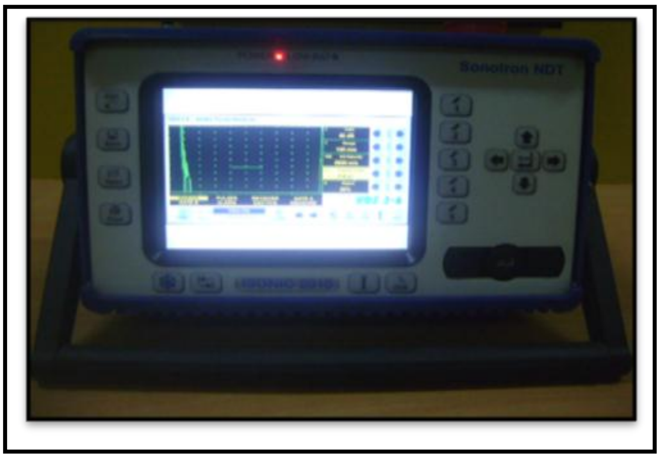


Figure 3.10: ISONIC 2010 Ultrasonic Instrument

Ultrasonic Instrument	ISONIC 2010
Probes used	Straight Beam 0.5MHz, 1MHz and 2MHzprobes
Manufactured .	General Engineers
Couplent	Industrial Grease
Instrument Echo Gain Increment	0.5db

3.6.2 Universal Testing Machine

The Universal Testing Machine is utilized to carry out the three point bend test and findings will be utilized to calculate Flexural strength of the specimens.The Universal Testing Machine is shown in Figure: 3.11.

Figure 3.11:WAW-1000E Hydraulic Universal Testing Machine

Hydraulic Universal Testing Machine	WAW-1000E
Manufactured .	General Engineers
Load capacity	1000 KN Load
Accuracy	±1
Power supply	3 phase, 380VAC, 50Hz, or 3 phase,
20VAC, 60Hz.	

3.6.3 Scanning Electron Microscope

The Scanning Electron Microscope is utilized to view the structural changes experienced on the specimens, after the repeated blows; is illustrated in Figure: 3.12.

Figure 3.12:TESCAN Scanning Electron Microscope

Scanning Electron Microscope	TESCAN
Resolution	3.0 nm at 30kv
Image size	Up to 8,192x8.192 pixels in 16-bit
quality	
Electron gun	Tungsten heated cathode filament
Magnification	Continuous from 2.5x to 1,000,000 x
Manufactured .	Tescan.
Instrument Echo Gain Increment	0.5db

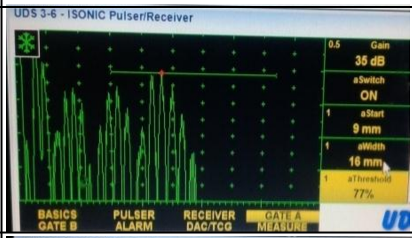
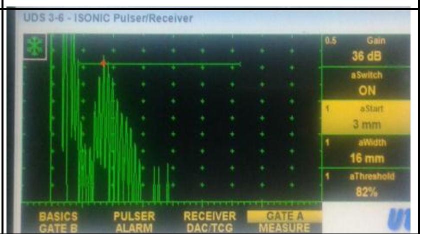
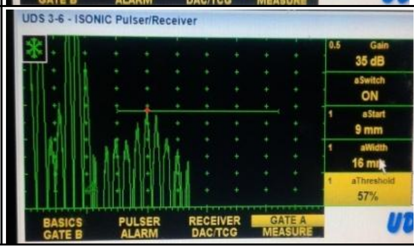
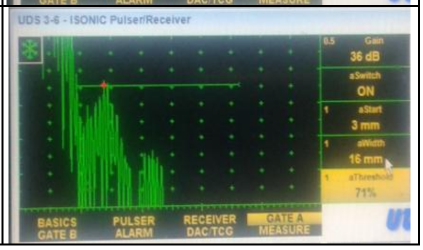
4. FINDINGS AND RESULTS

The focus of this study is to develop a method to evaluate GRP IPC hull durability non-destructively, since there is no standard method to evaluate GRP hull periodically as practiced in steel hull. The concept and the methodology were used to achieve the specific objective explained in the Chapter 3 and the results and findings will be further discussed in the course of this chapter. The percentage echo height is taken as the main tool for evaluating the durability of the hull.

4.1 Stage One Recorded Data

4.1.1 Step one- Percentage Echo height readings

The percentage echo height readings were recorded using 1MHz and 2MHz probes as described in flow chart of Appendix A and the relevant raw data reading are tabulated at Appendix C, Table: 1.1. The screen shot of the LCD display of ultrasonic machine with respect to each step is illustrated in Figure: 4.1.

Specimen (Number of repeated blows)	**1 MHz probe**	**2 MHz probe**
A (0)		
B (3600)		

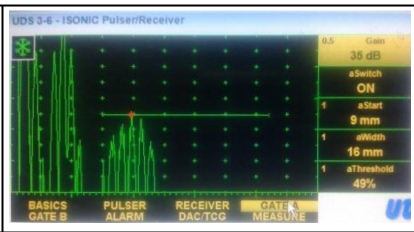
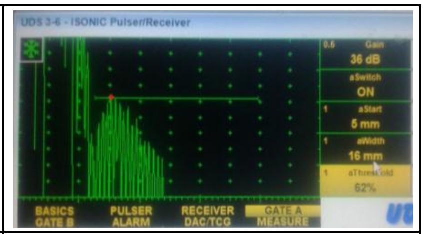
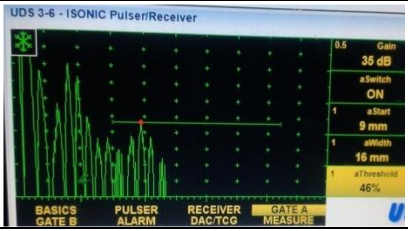
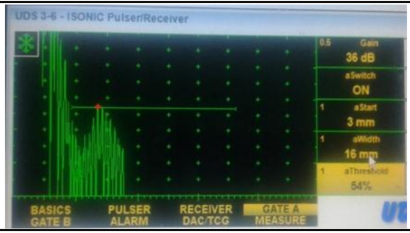
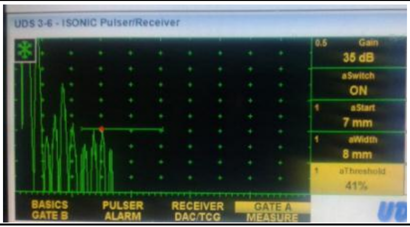
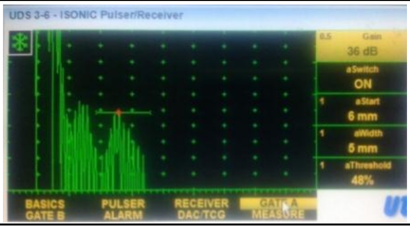
C (72000)		
D (108000)		
E (216000)		

Figure 4.1: Echo height LCD Screen Shot

4.1.2 Stage One Graph One (SOGO)

Two graphs are drawn for Number of repeated blows vs Percentage echo height with the readings obtained from 1MHz and 2MHz probes. The relevant graphs are illustrated in Figure: 4.2 and Figure 4.3 respectively.

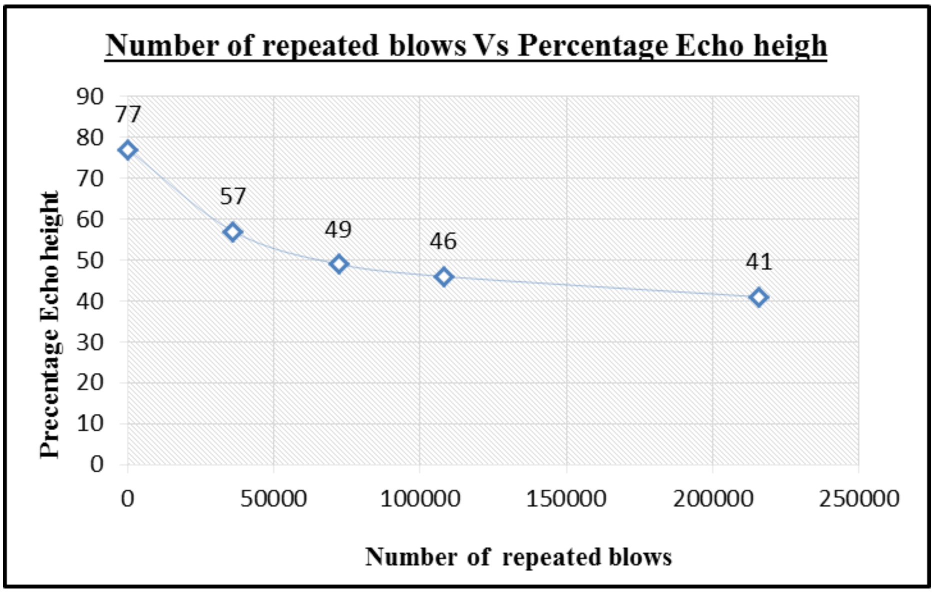


Figure 4.2: Number of repeated blows Vs Percentage echo height (1MHz probe)

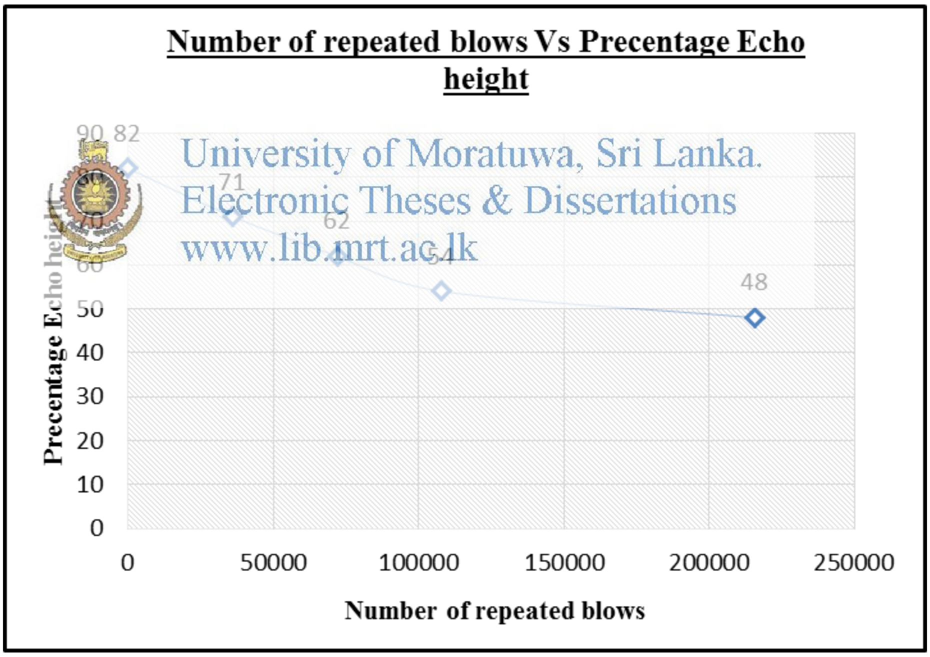


Figure 4.3: Number of repeated blows Vs Percentage echo height (2 MHz probe)

4.1.3 Step two- Flexural strength

At the completion of the first step of the first stage as explained above, the study proceeds to the second step of the first stage, that is to calculate Flexural strength according to the three point bend test results. The relevant raw data were tabulated as Table: 2.1 in Appendix C.

4.1.4 Stage One Graph Two (SOGT)

The graph two was drawn Number of repeated blows Vs Flexural strength according to the data recorded during step two finding during three point bend test. The graph two, Number of repeated blows Vs Flexural strength is illustrated in Figure 4.4

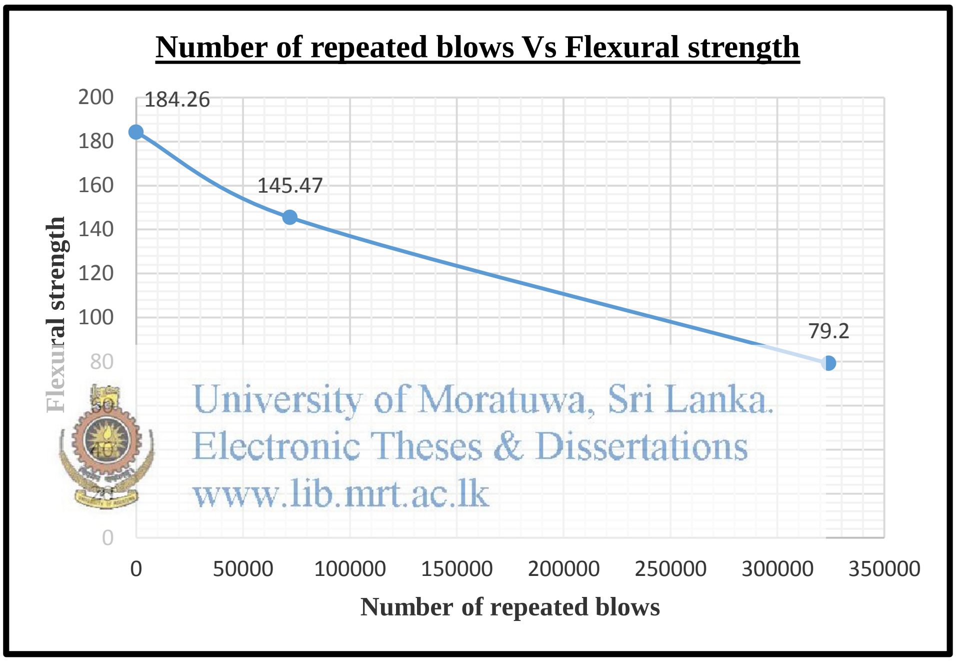


Figure 4.4: Number of repeated blows Vs Flexural strength

4.2 Stage Two Recorded Data

On receipt of favorable results from stage one findings, the study was extended to Stage two. As explained during specimen preparation under section 3.1.3 in Chapter 3, the stage two specimens were extracted from IPC hull keel area. The procedure of stage two was implemented as elaborated in Chapter 3 sub-section 3.5.2 according to the second stage flow chart at Appendix B.

4.2.1 Step two - Percentage Echo height reading

The stage two specimens were extracted from a newly constructed unused IPC hull keel area assuming specimens are free of stress. During the stage two process, five groups of specimens are stimulated into predetermined number of repeated blows and error analysis were carried out on final reading in order to get more accurate results[1].

4.2.2 Stage Two Graph One (STGO)

As explained in Chapter 3 section 3.5.2, two graphs were drawn on Number of repeated blows Vs Percentage Echo height utilizing the readings obtained from 1MHz and 2MHz probes. The relevant graphs are illustrated in Figure: 4.5 and Figure: 4.6 respectively.

[1]The readings taken through 1MHz probe and 2MHz probe on Group A, Group B, Group C, Group D and Group E specimens are tabulated and illustrated in Table: 2 of Appendix C.

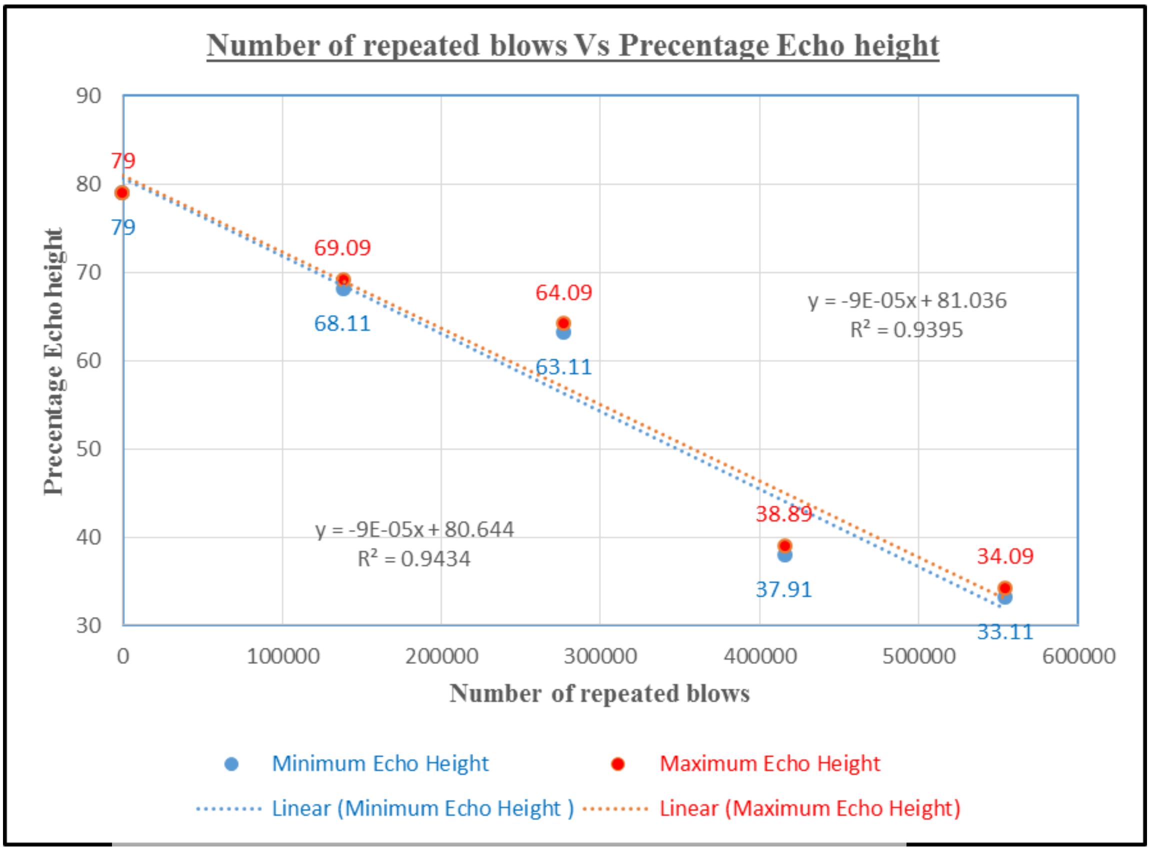


Figure 4.5: Number of repeated blows Vs Percentage Echo height (1MHz probe)

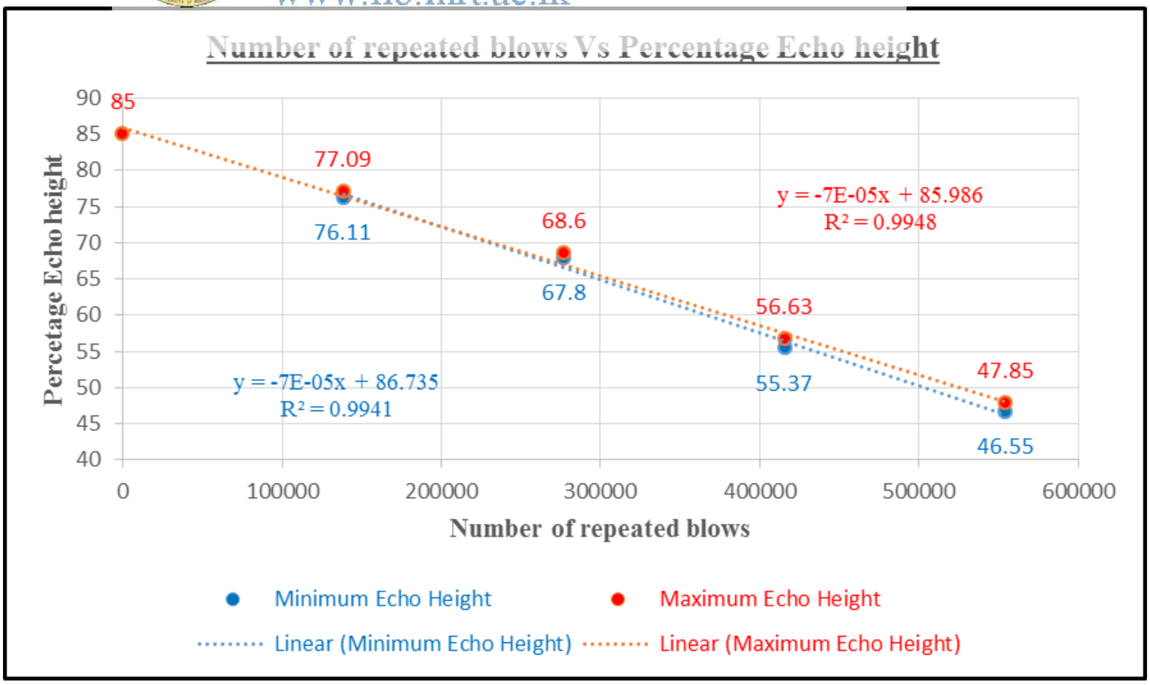


Figure 4.6: Number of repeated blows Vs Percentage Echo height (2 MHz probe)

4.2.3 Step two- Flexural strength

On completion of the first step of the second stage the study will be continued to the second step of the second stage, to calculate Flexural strength as per the three point bend test results. The relevant raw data were tabulated as Table: 2.2 in Appendix C.

4.2.4 Stage Two Graph Two (STGT)

The STGT, Number of repeated blows Vs Flexural strength relationship was developed, using the data obtained during three point bend test carried out according to the Flow chart of Appendix B, as elucidated in section 3.5.2 in Chapter 3. The reading taken during the study is tabulated as the Table 2.2 of Appendix C and the relevant graph is illustrated in Figure: 4.7 respectively.

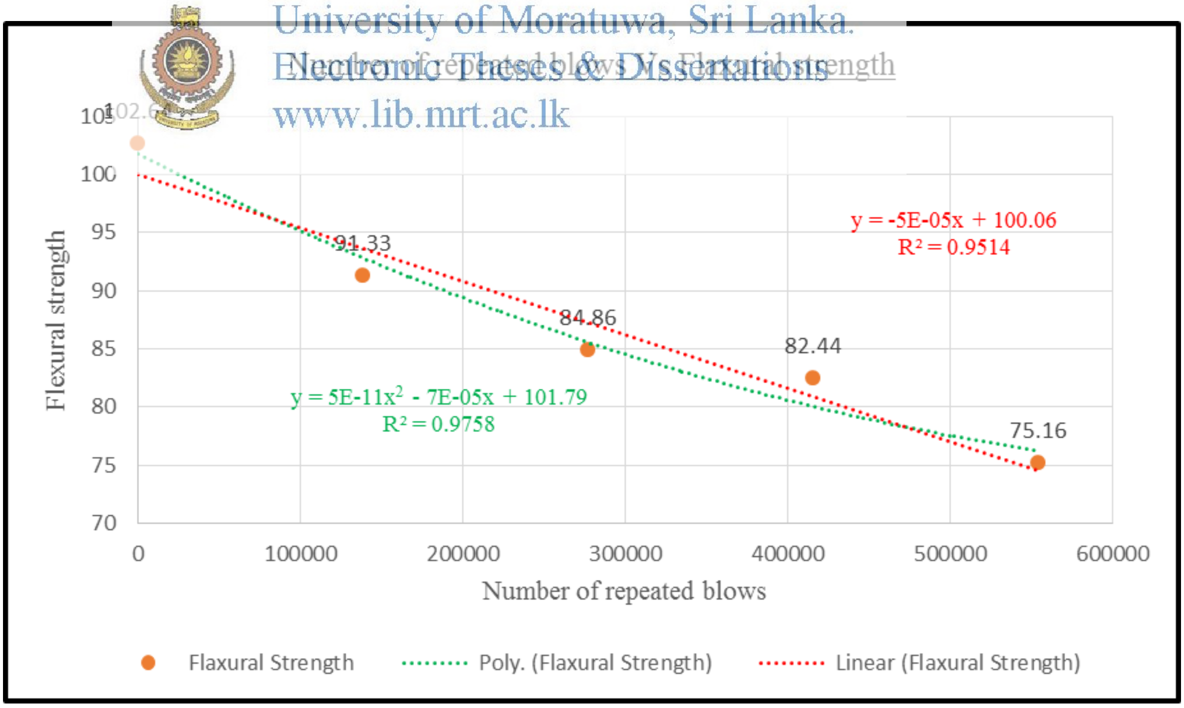
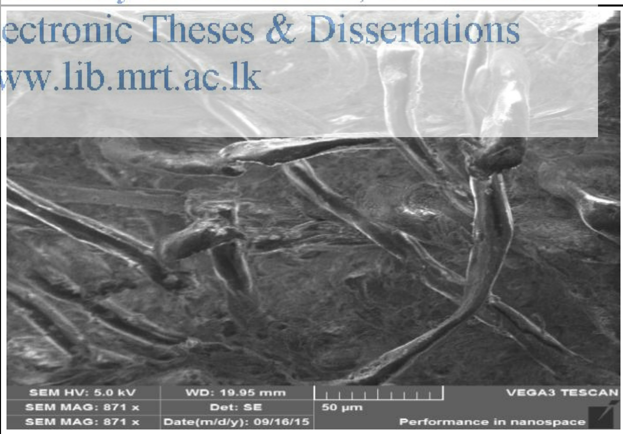
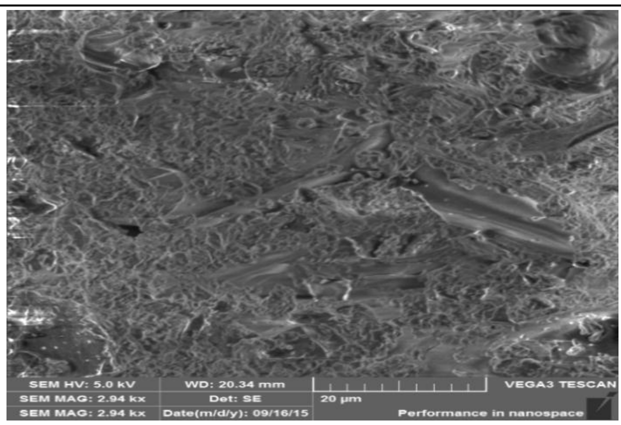


Figure 4.7: Number of repeated blows Vs Flexural strength

4.3 Scan Electron Microscopic Analysis

As explained in Appendix B, the category X specimen was subjected to preset, number of repeated blows, in four steps. These specimens are machined to suite with SEM chamber requirements and label them as S1, S2, S3, S4 and S5 respectively.

The group "S" specimens were examined through Scanning Electron Microscope to magnify the surface of the matrix and dispersed phases after number of repeated blows and visualized the change of composite structure due to the repeated blows. Further to analyze the echo height change with structural change. The SEM photograph with visual remarks are illustrated in Figure: 4.8.

Specimen	Repeated number of blows	SEM view	Visual remarks
S1			Fibers are clealy identy fiable. No damages found either Matix or Dispersed phase.
S2	138600		No damages found either Matix or Dispersed phase.

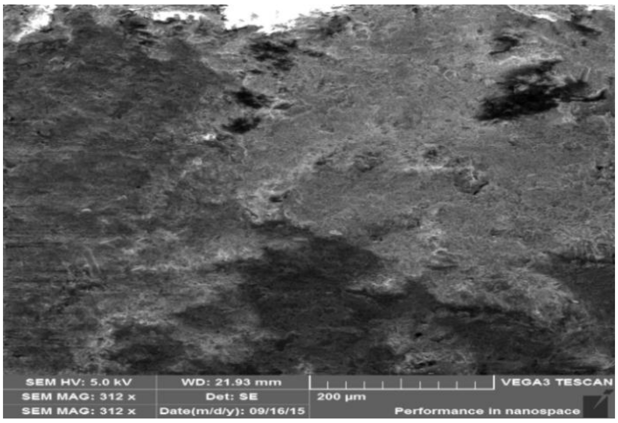
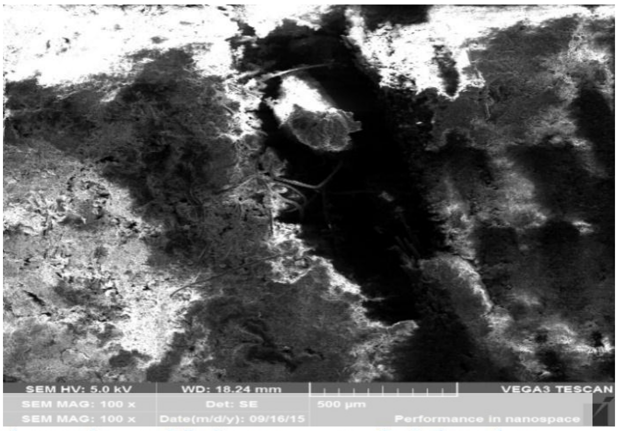
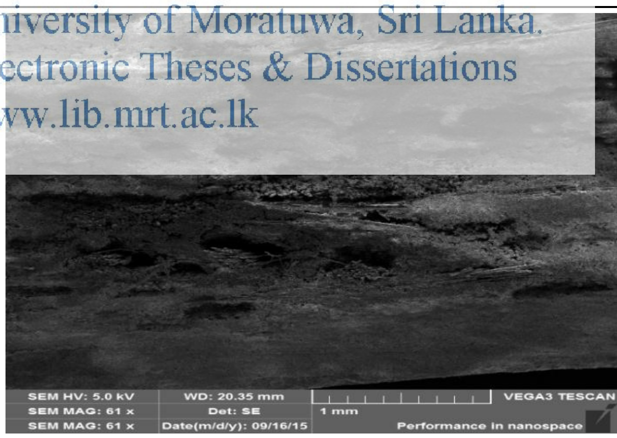
S3	277200		Found formaion on voids on specimen surface.
S4	415800		Found debonding of Fiber from resin Matrix.
S5	554400		Clealy visibal voids and de bonding of GRP stracture.

Figure 4.8: SEM photograph with visual remarks

5. DISCUSSION

As elaborated in Chapter2; literature review, the GRP hull is built up by blending layers of resin with Glass fibers creating material with two distinct natures known as composite. Due to this inhomogeneous nature of the material arrangement, the general nondestructive evaluation methods are not being able to apply to assess the material integrity as practiced in homogeneous material.

Based on the findings and results generated during the previous chapters, this chapter discusses the technique to predict the Flexural strength of the GRP material nondestructively to evaluate the GRP durability.

5.1 Glass Reinforced Plastic Ultrasonic Inspection

In traditional ultrasonic inspection, using a transducer the beam of high frequency ultrasonic signal directs through the inspection medium. The reflected or through transmitted signal picked up by the same or another transducer is used to analyze the exact condition of the material.

5.1.1 Selection of Transducer

The acoustic properties of the wave propagation in materials are wavelength, frequency, and velocity. The wavelength is directly proportional to the velocity of the wave and inversely proportional to the frequency of the wave. This relationship is shown in equation5.1.

$$wavelength(\lambda) = \frac{Velocity\,(v)}{Frequency\,(f)} \qquad 5.1$$

The Non audible mechanical sound wave generated by piezoelectric crystals inside the transducers, named as probe or search unit in ultrasonic inspection also undergo above wave transmission phenomena.

According to the above acoustic equation; higher frequency, narrow wave length probe will have more energy to penetrate deeper inside the material and in contrary wider wave length with lower energy wave, diminishes the reflected signal inside the composite structure itself without giving signal to the receipt mode of the probe due to further loosing of energy inside the composite due to repetitive reflection of beam inside the inhomogeneous composite structure. In lower frequency probe with low energy, wider wave length utilizing in composite structure gives larger reflected signal spectrum due to surface irregularities leading the operator for fault identification. However, to neglect or minimize the composite discreet nature, it is necessary to use longer wave length signal to avoid or minimize the "dispersed phase" encountered during wave traveling in the composite structure. By selecting lower frequency probe as mentioned above, the operator sacrifices the penetration power, sensitivity as well as resolution up to some extent[2].

In order to select the best suited probe/s during this study, the Initial specimen inspection was carried out using four types of probes, starting from 0.5 MHz, 1MHz, 2MHz and 4 MHz probes. The probes "Back Wall Echo" was recorded and illustrated in Figure: 5.1.

2 The sensitivity, means the ability of an ultrasonic inspection system to detect a very small discontinuity in the inspection material. The resolution, means the ability of the system to give separate identification from irregularity that are close together.

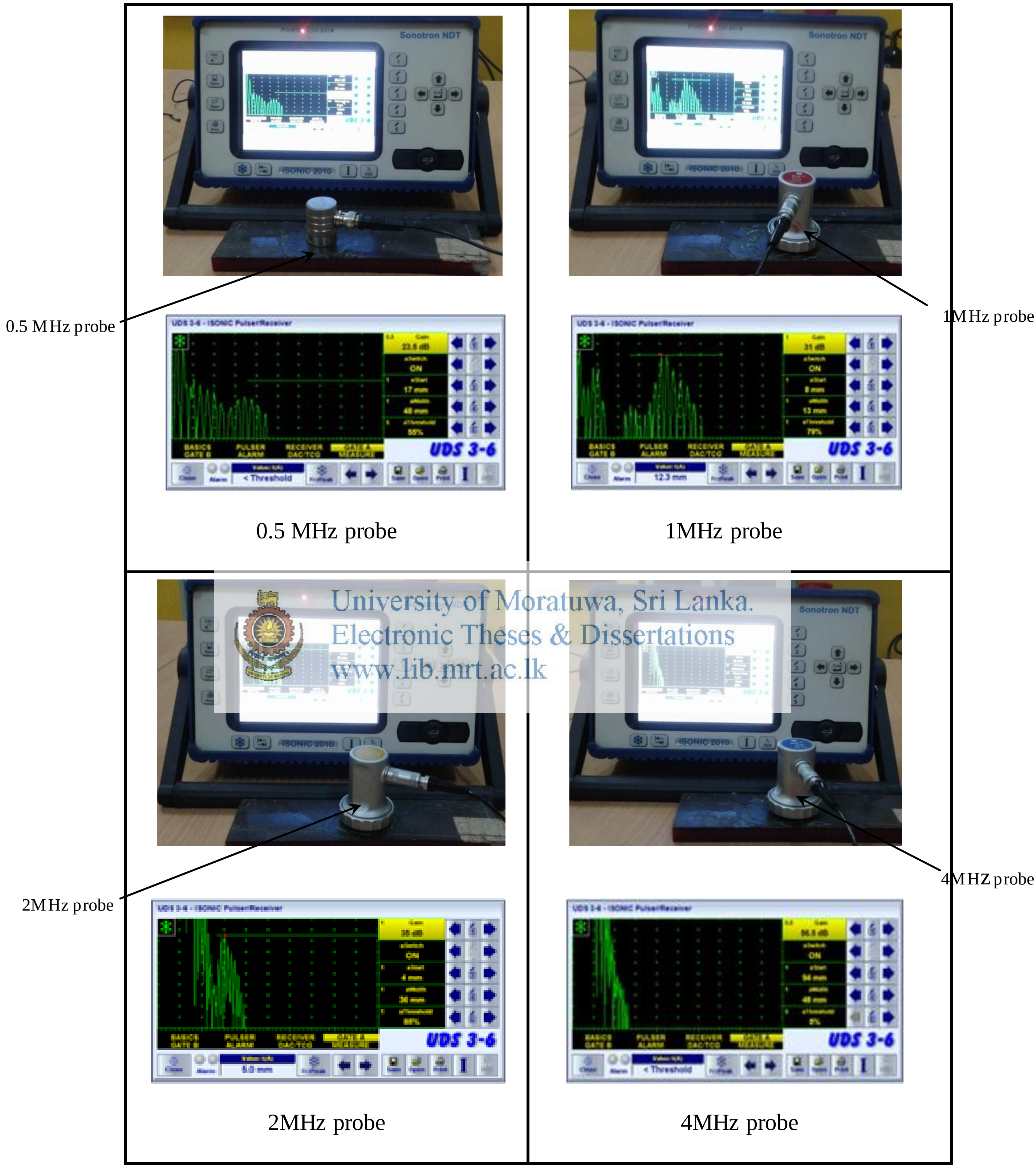


Figure 5.1: Back wall Echo screen appearance

During practical application it is evident that, the higher frequency probe that is 4MHz does not give any indication on reflected signal as expected and also in the case of 0.5 MHz probe has given a wider spectrum creating confusion on "Back wall echo" and initial pulse. Since both higher-end and lower-end probes are not suited theoretically as well as practically, it has been decided to carry out the research using 1MHz and 2 MHz probes which will be having comparatively a higher sensitivity and resolution.

5.2 Impedance Vs Fatigue

As per the concept of acoustic impedance(Z), when ultrasonic wave traveling through one medium and impinging on the boundary of a second medium, a portion of the incident acoustic energy is reflected back from the boundary while the remaining energy is transmitted into the second medium. The amount of ultrasonic energy transmission or reflected depend on the acoustic impedance of the two medium. If the difference is higher, then most of the energy is reflected and only a small portion of energy transmitted across the boundary. In contrast, if the difference is low, large number of energy is transmitted and small portion is reflected back. The impedance of the material depend on the density of the material and the velocity of the ultrasonic wave in the material.

$$Z = \rho v \qquad 5.2$$

Z – Impedance

ρ – Density

v – Velocity

When the frequency is low, a larger wave length ultrasonic wave travels through the composite material neglecting the "dispersed phase". This larger wave length ultrasonic wave will minimize two different density mediums, keeping minimum reflection at the interface between "matrix phase" and "dispersed phase".

With the increment of number of repeated blows on the specimens, the inside structure of the composite will be disturbed and the number of void spaces will be increased. This void spaces may either be filled up with gasses or water with deferent density than the internal structure of the material, changing the mating surface impedance causing reduction of energy of the “Back wall”.

Further transmitted ultrasonic signal inside the voids may not be reflected or transmitted in the same direction due to the change of incident angle inside the voids. This is called scattering effect which contributes for the decrement of Ultrasonic energy of the “Back wall”.

The above theoretical explanation over the reduction of “Back wall Echo height” with the increment of number of repeated blows can be further analyzed with SEM findings by synchronizing the Number of repeated blows Vs Percentage Echo height graph (STGO). The Number of repeated blows Vs Percentage Echo height graph drawn from the data extracted through 2 MHz probe is synchronize with the Scan Electron Microscope findings is illustrated in Figure: 5.2.

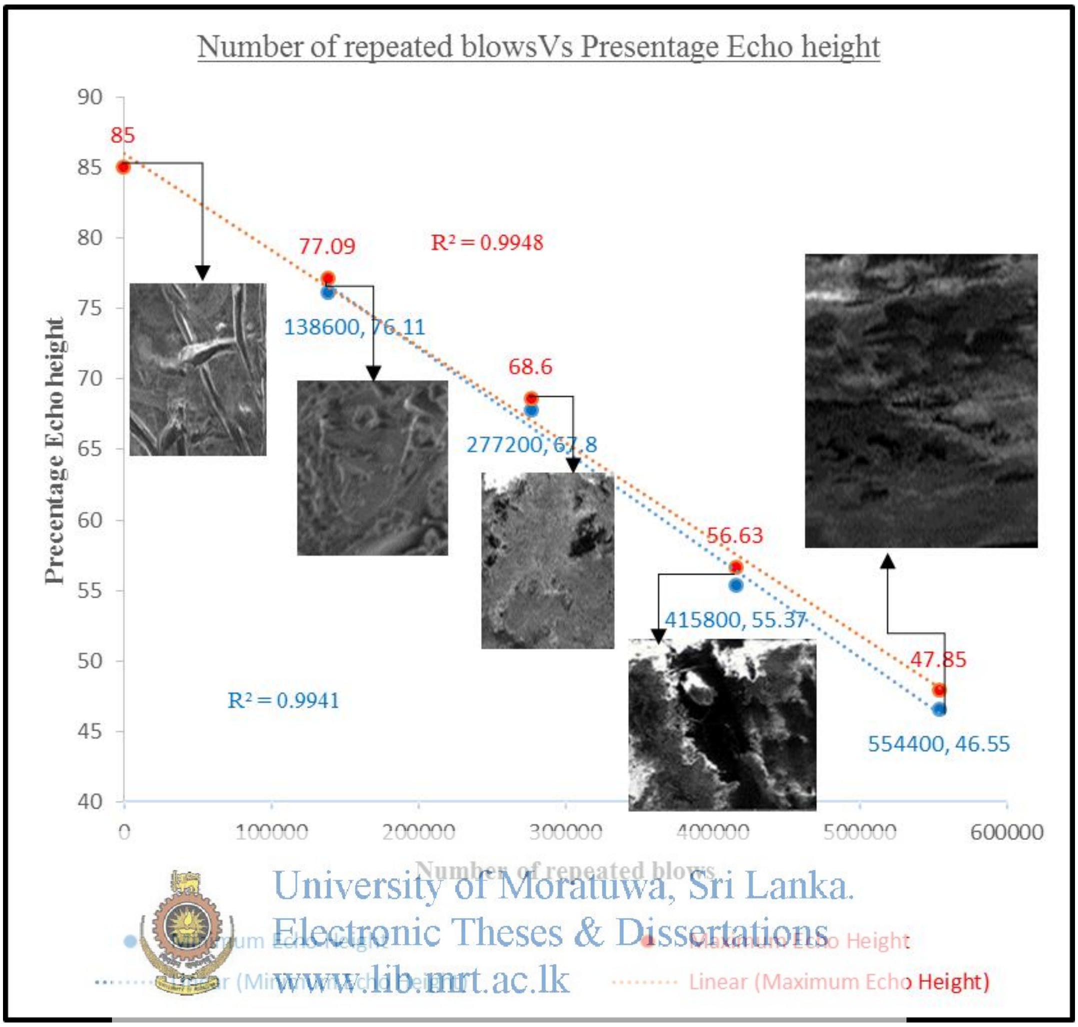


Figure 5.2: Number of repeated blows Vs. Percentage Echo height graph combine with scanning electron microscopic findings

According to the above relationship, it is evident that at ‘no-load condition ’the highest eco height is experienced. The relevant SEM findings confirmed that there is no delamination or disturbance on composite structure.

At 138600 fatigue cycles (effected specimen Group B) Ultrasonic scan indicates decrease of Echo height than previous findings. The relevant SEM finding – S2 does not give a clear indication on composite structure disturbance.

At 277200 fatigue cycles, (effected specimen Group C), SEM findings – S3 gives indication of generation of “voids” inside the composite and ultrasonic scan confirms further reduction of echo height.

At 415800 fatigue cycles, (effected specimen Group D), give a considerable lower echo height and SEM findings – S4 confirms increment of internal "void" size.

Finally at 554400 fatigue cycles, (effected specimen Group E), scan gives the lowest echo height and a SEM finding – S5 indicates the increment of voids/delamination of composite structure.

5.3 Flexural strength assessment

The maximum amount of bending stress that can be applied before rupture or failure of the composite depending on the flexural strength, which often described the strength where composite material stands prior failure.

According to the ASTM D790 M or ISO 178 Plastic Standard flexural strength test method, the specimens will be damaged and therefore, the standard destructive method of assessment cannot be employed to evaluate GRP hull. However as explained above, if there is any technique to evaluate and record reading on GRP hull with repeatable reading will increase the confidence of the boat crew and boat deployment authority.

5.4 Generate relationship between Percentage Echo height Vs Flexural strength

5.4.1 The relationship on Number of repeated blows Vs Percentage Echo height

Two relationships are generated on Percentage Echo heights against the Number of repeated blows from the data extracted through 1MHz and 2MHz probes during stage two experiment, keeping all other parameters, i.e. resin/ glass fiber layup sequence, layup procedure, curing temperature, and specimen geometry, constant for all the specimens.

$y_1 = f(x)$

$x = Number\ of\ repeated\ blows$

$y_1 = Precentage\ Echo\ height\ from\ 1MHz\ probe$

$y_2 = Presentage\ Echo\ height\ from\ 2MHz\ probe$

According to the graphs generated in section 4.2.2 in Chapter 4, once the relationship is built up, the variable at x axis represents Number of repeated blows, while y_1 axis represents the Percentage Echo height reading from 1MHz probe and y_2 axis represents the Percentage Echo height reading from 2MHz probe of the same set of specimens. This four linear relationships can be further elaborated as below;

Two relationship for 1MHz that is y_{1max} maximum Percentage Echo height reading and y_{1mini} minimum Percentage Echo height reading, as in;

$$y_{1max} = -9E - 05x + 81.036 \qquad 5.3.1$$

$$R^2 = 0.9395$$

$$y_{1mini} = -9E - 05x + 80.644 \qquad 5.3.2$$

$$R^2 = 0.9434$$

Two relationship for 2MHz that is y_{2max} maximum Percentage Echo height reading and y_{2mini} minimum Percentage Echo height reading, as in;

$$y_{2max} = -7E - 05x + 85.986 \qquad 5.3.3$$

$$R^2 = 0.9948$$

$$y_{2mini} = -7E - 05x + 86.735 \qquad 5.3.4$$

$$R^2 = 0.9941$$

While generating the relationships, it is found that the linear co-relationship provides the best fit, through the points as the coefficient of determination that is R^2 is closer to 1 at linear relationship. Further each point in the graph represents Percentage Echo height at particular Number of repeated blow.

5.4.2 The relationship on Number of repeated blows Vs Flexural strength relationship

The Number of repeated blows Vs Flexural strength relationship build up from the data extracted on same specimens destructively according to, ASTM D790 M Standard keeping all other parameters constant.

$z = g(x)$

$x = Number\ of\ repeated\ blows$

$z = Flaxural\ strength$

According to the graphs generated in section 4.2.4 in Chapter 4, the relationship is built up taking variable at x axis to represent the Number of repeated blows and z axis to represent the Flexural strength. During relationships built up, it is found that the coefficient of determination that is R^2 is much closer towards 1 at linear relationship.

$$z = -5E-05x + 100.06 \qquad 5.3.5$$

$$R^2 = 0.9514$$

5.4.3 Generating relationship on Percentage Echo height Vs Flexural strength

The data generated in section 5.4.1 and section 5.4.2 are combined and tabulated as indicates on Table 5.1 and the relevant graphs of Percentage Echo height vs Flexural strength illustrated in Figure 5.3 for 1MHz & 2MHz probes.

Table 5.1: Stage Two combined data

Specimen	Number of repeated blows	Flexural strength	Percentage Echo height 1 MHz Probe		Percentage Echo height 2 MHz Probe	
A	0	102.64	79	79	85	85
B	138600	91.33	69.09	68.11	77.09	76.11
C	277200	84.86	64.09	63.11	68.6	67.8
D	415800	82.44	38.89	37.91	56.63	55.37
E	554400	75.16	34.09	33.11	47.85	46.55

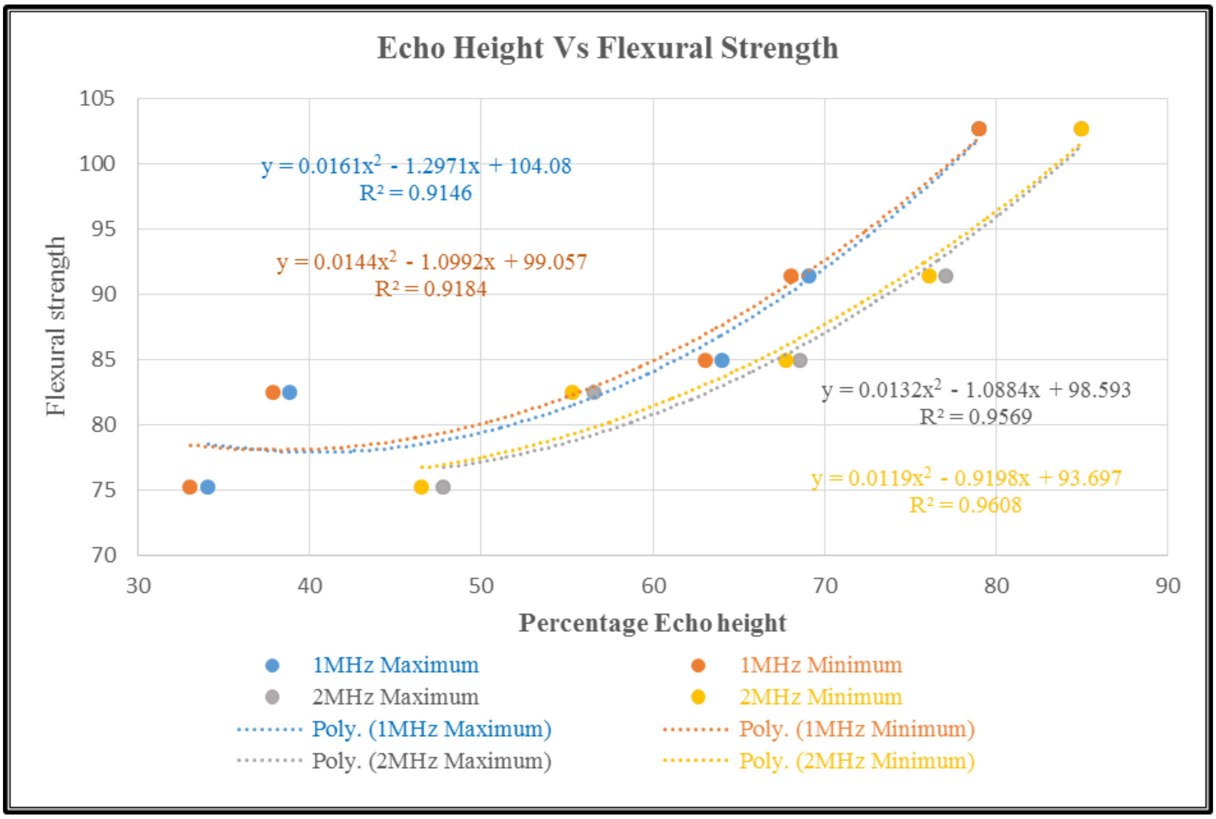


Figure 5.3: Percentage Echo height Vs Flexural strength for 1MHz & 2MHz probes

According to the above Percentage Echo height against Flexural strength four polynomial relationships are built up as indicated below and also it is found that when the coefficient of determination that is R^2 is much closer towards 1 when relationship is polynomial. The under mentioned polynomial relationship, x represents the Percentage Echo height and y represents the Flexural strength respectively.

$$y = 0.0161x^2 - 1.2971x + 104.08 \quad (5.3.6)$$

$$R^2 = 0.9146$$

$$y = 0.0144x^2 - 1.0992x + 99.057 \quad (5.3.7)$$

$$R^2 = 0.9184$$

$y = 0.0132x^2 - 1.0884x + 98.593$ 5.3.8

$R^2 = 0.9569$

$y = 0.0119x^2 - 0.9198x + 93.697$ 5.3.9

$R^2 = 0.9608$

The relationship 5.3.6 and 5.3.7 predicted from data generated from 1MHz probe and relationship 5.3.8 and 5.3.9 generated from the data extracted from 2MHz probe. Further each point in the graph is expected to represent Flexural strength at a particular Echo height.

The generalized quadratic polynomial function as follows;

$$y = a_n x^2 + a_{n-1} x + C \qquad 5.3.10$$

Where;

y – Flexural strength

x – Echo height

C – constant

Since specimens are extracted from GRP boats hull itself, the above relationship can be used to assess the Flexural strength of GRP boat nondestructively as expected during the study.

5.5 Validation of Percentage Echo height Vs. Flexural strength relationship

In order to assess the results generated from the relationship of Flexural strength against Echo height and to select the most effective probe out of two probes used during the study, the validation test was carried out as explained below.

Three specimens, labeled as P, Q and R were extracted from the same GRP hull, adjacent to the place where the stage two specimens were extracted. The extracted specimens are machined and prepared according to the standard dimensions used during the stage two experiments. On the completion of preparation stage, the specimens were subjected to three different Number of repeated blows through the same Tidal blow simulation machined and inspected & record the ultrasonic Echo height and followed by three point bend destructive test as illustrated in Figure 5.4 flow chart.

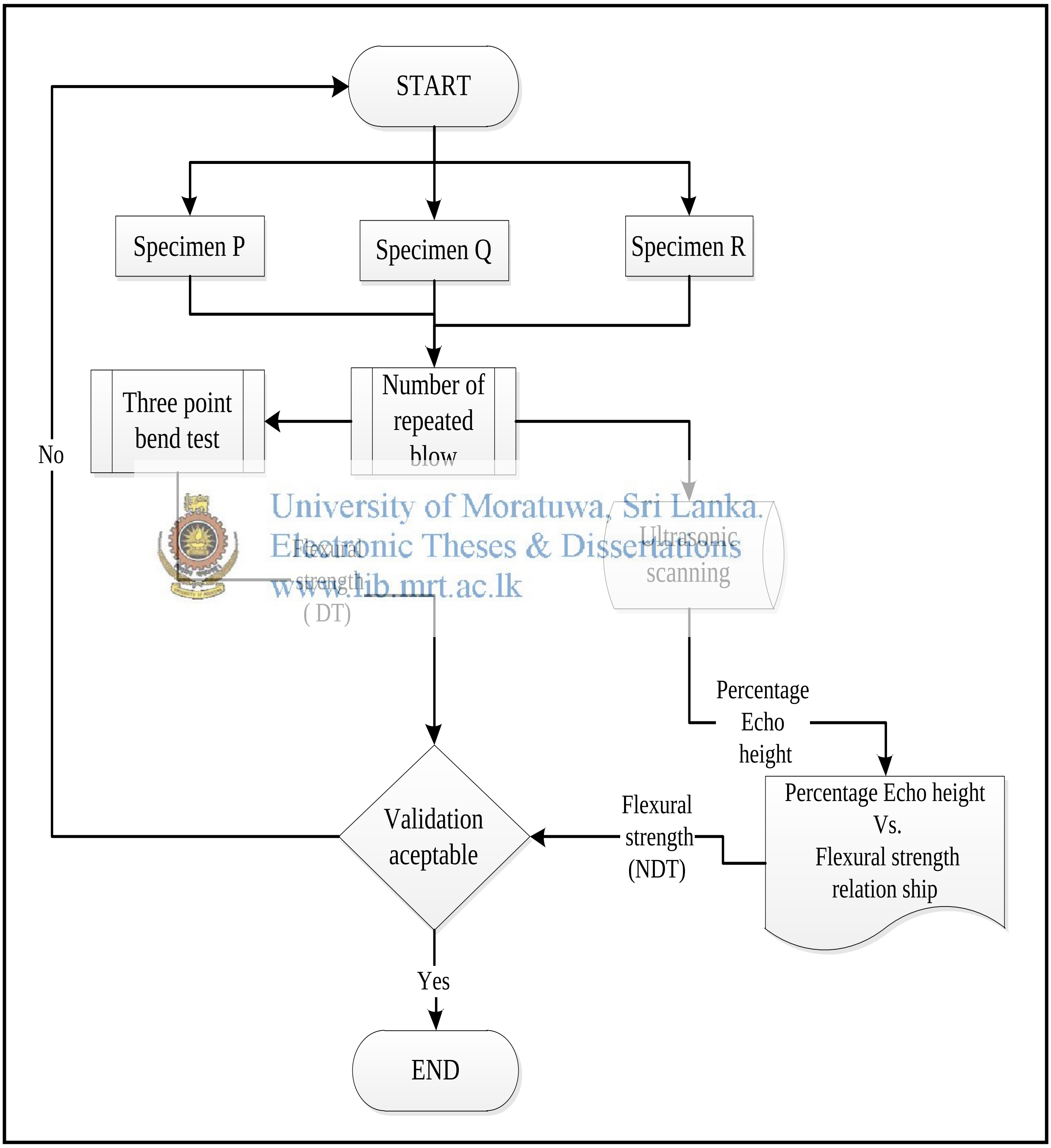


Figure 5.4: Validation procedure flow chart

According to the above procedure, the screenshots of the LCD display illustrate in Figure: 5.5, elaborates the data obtained through Ultrasonic inspection on P, Q, and R specimens nondestructively during the validation test. The extracted Ultrasonic data are tabulated in Table 5:2 and the destructive three point bend test data are tabulated in Table 5:3 for further analysis.

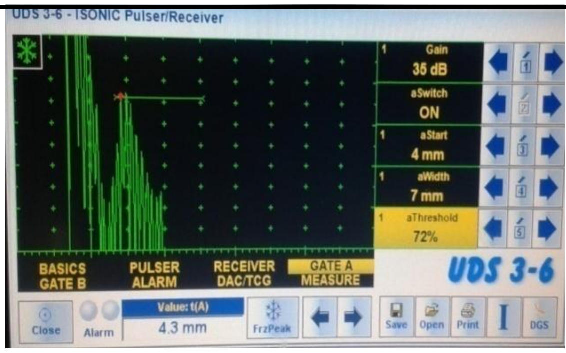
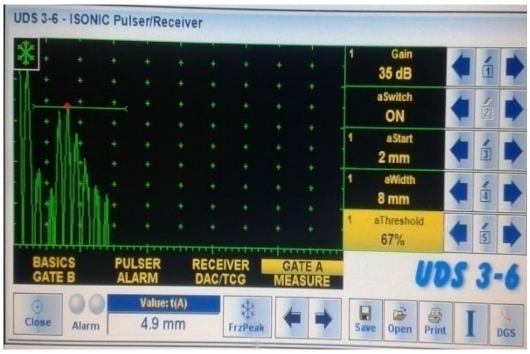
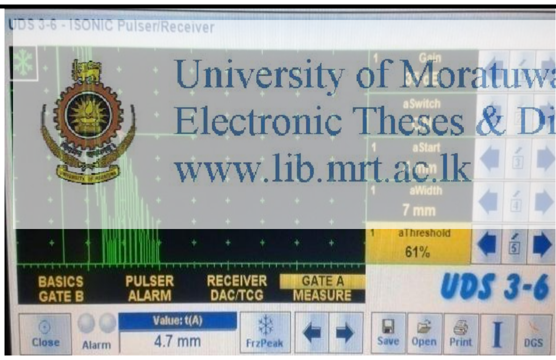
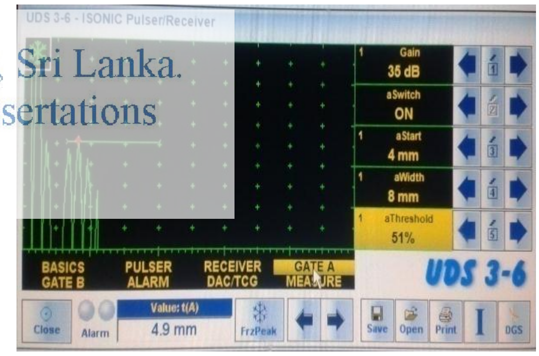
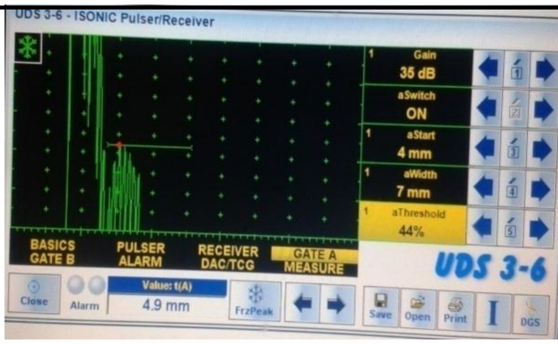
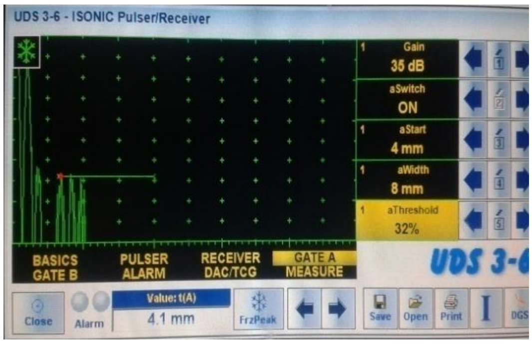
Specimens	**2 MHz Probe**	**1 MHz Probe**
P		
Q		
R		

Figure 5.5: Ultrasonic inspection LCD Screen Shot

Table 5.2: Ultrasonic inspection data

Specimen	Number of repeated blows	Percentage Echo height	
		2MHz	1MHz
P	207900	72	67
Q	346500	61	51
R	623700	44	32

Table 5.3: Three point bend test data

Specimen	Number of repeated blows	Flexural strength
P	207900	93.75
Q	346500	109.88
R	623700	82.44

Comparison of nondestructive and destructive Flexural strength validation test results are illustrated in Table: 5.4

Table 5.4: Comparison of non-destructive Flexural strength with destructive Flexural strength

Specimen	Destructive Flexural strength	Nondestructive Flexural strength			
		2MHZ probe		1MHz probe	
		Y_{max}	Y_{mini}	Y_{max}	Y_{min}
P	93.75	88.6570	89.1610	89.4472	90.0522
Q	109.88	81.3178	81.8691	79.8040	80.4522
R	82.44	76.2586	76.2642	79.0592	78.6282

A detailed error percentage was calculated in order to assess validation of the research outcome and also to choose the most suitable probe for practical usage. The detailed error percentages are tabulated in Table:5.5 and Table: 5.6 for 1MHz and 2MHz probe readings respectively.

specimen	Echo Height	Destructive reading (DT)	Predictive NDT reading (NDT)		Error percentage $\left\{\frac{DT - NDT}{DT}\right\} X100$
P	67	93.75	89.7497 ±0.3025	*89.4472 #90.0522	3.94432
Q	51	109.88	80.1281 ±0.3241	*79.8040 #80.4522	26.78176
R	32	82.44	78.8437 ±0.2155	*79.0592 #78.6282	4.100922

Table 5.5: 1 MHz probe error percentage

$^{*}y_{max} = 0.0161x2 - 1.2971x + 104.08$
$^{\#}y_{mini} = 0.0144x2 - 1.0992x + 99.057$

specimen	Echo Height	Destructive reading (DT)	Predictive NDT reading (NDT)		Error percentage $\left\{\frac{DT - NDT}{DT}\right\} X100$
P	72	93.75	88.9090 ±0.2520	*88.6570 #89.1610	4.894933
Q	61	109.88	81.5935 ±0.2757	*81.3178 #81.8691	25.49226
R	44	82.44	76.2614 ±0.0028	*76.2586 #76.2642	7.491266

Table 5.6: 2MHz probe error percentage

$^{*}y_{max} = 0.0132x2 - 1.0884x + 98.593$
$^{\#}y_{mini} = 0.0119x2 - 0.9198x + 93.697$

During the validation inspection of Q specimen under three point bend test, the universal testing machine hydraulic ram slipped away from the test specimen giving an incorrect reading. Hence the destructive reading on the Q specimen cannot consider as an accurate reading.

According to the validation results, it is evident that the nondestructive findings have maximum of 4% and 7% error when using 1MHz probe and 2MHz probes respectively, except on the Q specimen validation results. Further based on above validation results, it is proven that, the usage of 1MHz probe generate more accurate results than 2MHz probe for composite Flexural strength assessment.

6. CONCLUSIONS

As discussed in the above chapters, the relationship of Echo height against Flexural strength relationship can be utilized to measure the existing Flexural strength of the GRP structure without destructing the structure and the durability of the GRP boat can be ensured comparing designed ultimate Flexural strength.

The Glass fiber Reinforced Plastic Inshore Petrol Crafts, built in Sri Lanka Navy are designed by an outside organisation and unwilling to disclose raw design data to Sri Lanka Navy boat yard according to the construction agreement, hence the designed Flexural strength not available at this movement to predict expected life of the IPCs. The communication has started on this regard and hope get favourable result in due course. However due to this unavoidable situation of comparison of the designed Flexural strength detail with the Flexural strength measured through this technique to predict the expected life time as proposed in this study is not being able to achieve as expected.

In order to overcome this difficulty, it is recommended to measure and record the proposed flexural strength during routine underwater maintenance for next five years and generate an average reduction of flexural strength per boat per year. This result can be used to predict the life of the particular class of IPC.

Further it is proposed to continue this study on different types of GRP boat hull with different GRP thickness to develop standard relationship on flexural strength over ultrasonic signal height, in order to generalise and make standard method for the assessment of GRP boat hull.

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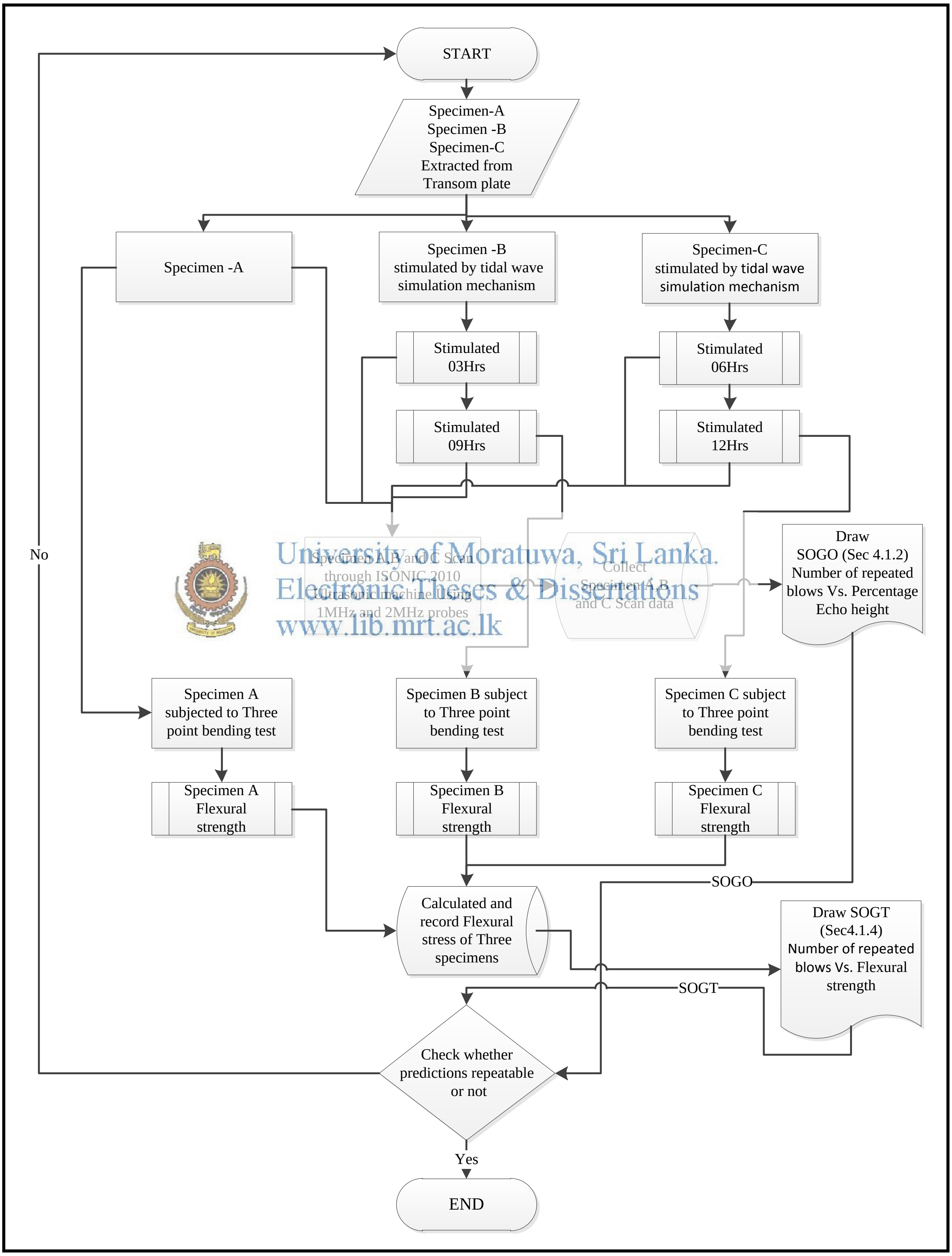
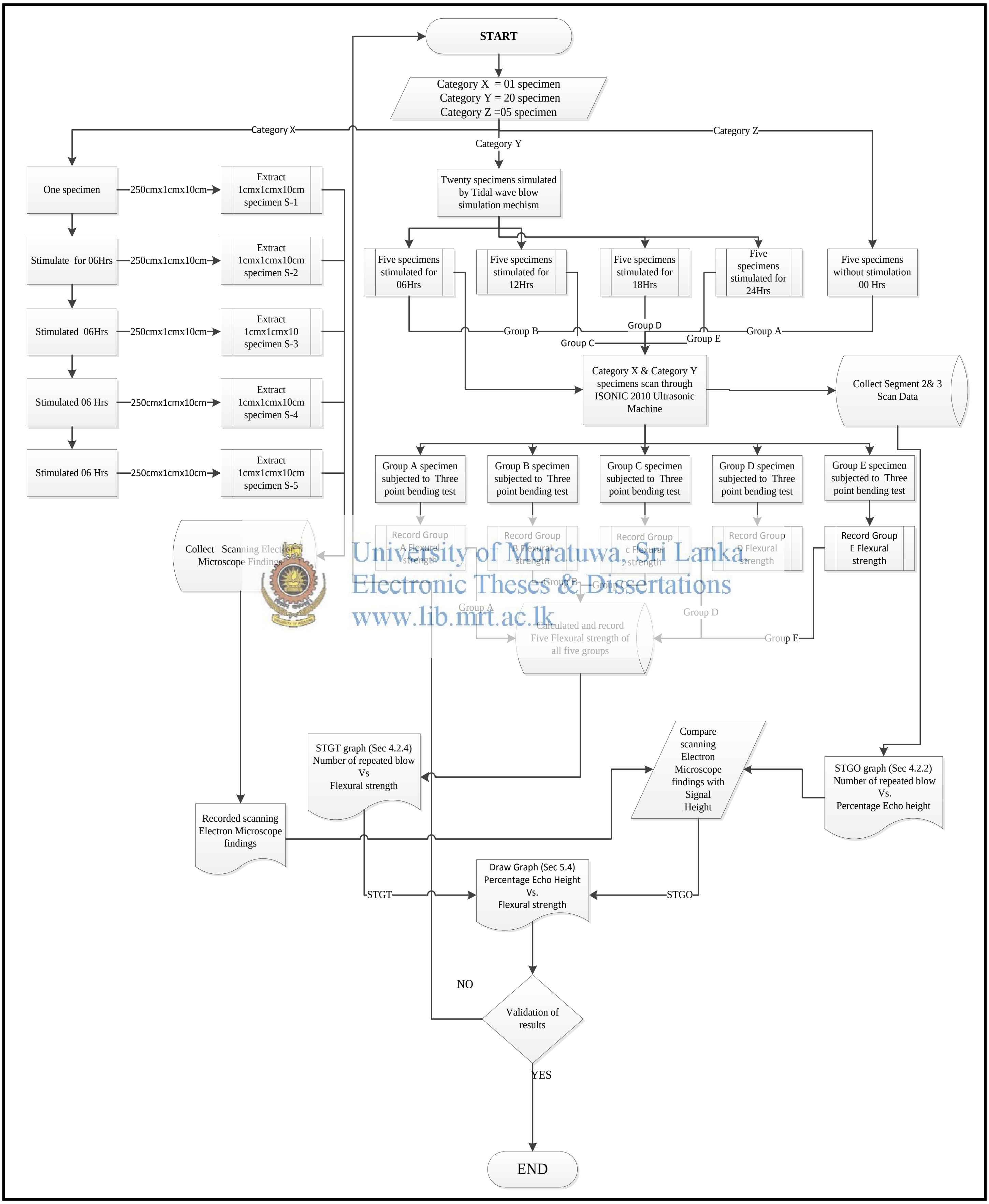
Appendix A - Flow Chart Stage One



Appendix B - Flow Chart Stage Two



Appendix C - Raw Data

(1) Echo Height Reading -Stage One & Stage Two

Table 1.1: Stage One-Echo height readings utilizing 1MHz and 2MHz probes

Specimen	Number of repeated blow	Percentage Echo height 1 MHz probe	Percentage Echo height 2 MHz probe
A	0	77	82
B	36000	57	71
C	72000	49	62
D	108000	46	54
E	216000	41	48

Table 1.2: Stage Two-Echo height readingsutilizing1MHz probe

Specimen		Percentage Echo height (H) reading Y_i	$\bar{Y}$	deviation $d_i = Y_i - \bar{Y}$		$H = \bar{Y} \pm \sigma_y$		Number of repeated blow (L)
	A_1	79		0				
	A_2	79		0				
A	A_3	79	79	0				
	A_4	79		0	0	79	79	0
	A_5	79		0				
	B_1	68		-0.6				
	B_2	69		0.4				
B	B_3	68	68.6	-0.6	0.49	69.09	68.11	138600
	B_4	69		0.4				
	B_5	69		0.4				
	C_1	64		0.4				
	C_2	63		-0.6				
C	C_3	64	63.6	0.4	0.49	64.09	63.11	277200
	C_4	64		0.4				
	C_5	63		-0.6				
	D_1	39		0.6				
	D_2	39		0.6				
D	D_3	38	38.4	-0.4	0.49	38.89	37.91	415800
	D_4	38		-0.4				
	D_5	38		-0.4				
	E_1	34		-0.4				
	E_2	33		0.6				
E	E_3	34	33.6	-0.4	0.49	34.09	33.11	554400
	E_4	34		-0.4				
	E_5	33		0.6				

Table 1.3: Stage Two- Echo height readings utilizing 2MHz probe

Specimen		Percentage Echo height (H)						Number of repeated blow (L)
		reading Y_i	$\bar{Y}$	deviation $d_i = Y_i - \bar{Y}$	σ_y	$H = \bar{Y} \pm \sigma_y$		
A	A_1	85	85	0	0	85	85	0
	A_2	85		0				
	A_3	85		0				
	A_4	85		0				
	A_5	85		0				
B	B_1	76	76.6	-0.6	0.49	77.09	76.11	138600
	B_2	77		0.4				
	B_3	77		0.4				
	B_4	76		-0.6				
	B_5	77		0.4				
C	C_1	68	68.2	-0.2	0.40	68.6	67.8	277200
	C_2	68		-0.2				
	C_3	69		0.8				
	C_4	68		-0.2				
	C_5	68		-0.2				
D	D_1	56	56	0	0.63	56.63	55.37	415800
	D_2	56		0				
	D_3	55		-1				
	D_4	57		1				
	D_5	56		0				
E	E_1	48	47.2	0.8	0.65	47.85	46.55	554400
	E_2	46		-1.2				
	E_3	47		-0.2				
	E_4	48		0.8				
	E_5	47		-0.2				

(2) Flexural Strength reading- Stage One & Stage Two

Table 2.1: Stage one-Flexural Strength through Three Point Bend Test

Specimen	Number of repeated blow	Span L (mm)	Width b (mm)	Depth d (mm)	Load P (N)	Flexural Strength (MPa)
A	0	250	58	10	2850	184.26
B	72000	250	58	10	2250	145.47
C	324000	250	58	10	1225	79.20

Table 2.2: Stage Two-Flexural Strength through Three Point Bend test

Specimen	Number of repeated blow	Span L (mm)	Width b (mm)	Depth d (mm)	Load P (N)	Flexural Strength (MPa)
A	0	250	58	20	6350	102.64
B	138600	250	58	20	5650	91.33
C	277200	250	58	20	5250	84.86
D	415800	250	58	20	5100	82.44
E	554400	250	58	20	4650	75.16