Characterization of Tensile Failure Behavior of Natural Single Fibre and Single Fibre Composite by Acoustic Emission Technique

By

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BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY

2012

The thesis entitled CHARACTERIZATION OF TENSILE FAILURE BEHAVIOR OF NATURAL SINGLE FIBRE AND SINGLE FIBRE COMPOSITE BY ACOUSTIC EMISSION TECHNIQUE submitted by Md. Saiful Alam, Roll No. 100711104P, Session, October 2007 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Philosophy in Material Science on 10th July, 2012.

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Declaration

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or Diploma

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Md. Saiful Alam

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ACKNOWLEDGMENTS

There are many people I would like to recognize for their help and support with my research. This work would not have been possible to accomplish without the help and support of them. What few words are written here cannot fully express my gratitude and appreciation to those exceptional individuals. Firstly, I would like to formally thank and express my sincere, deep sense of gratitude to my academic supervisor Assistant Professor Dr. Fahmida Gulshan, Dept of MME, Bangladesh University of Engineering and Technology (BUET) who allowed me for the research work under her supervision. Her wise suggestions, guidance and encouragement have been a great source of inspiration for me through out the progress of this dissertation. I have also the pleasure to acknowledge Professor Dr. Qumrul Ahsan, Ex-Head, Department of MME, BUET for selecting me to do my research at Dept of MTM, University of KU Leuven, Belgium under the research project supported by a link program (VLIR Project on "Valorization of natural resources in Bangladesh: Polymer composite material based on Jute fibers") between BUET, Bangladesh and KU Leuven, Belgium. And I would like to convey my heartfelt thanks to my Co-supervisor Prof. Ignass Verpoest, chair of the Leuven Materials Research Centre and member of Division Metallurgy and Materials Engineering who allow me to do the research work at MTM, KU Leuven; he has always believed in my abilities and provided whatever advice and resources necessary for me to accomplish my goals. I am also grateful to Prof. Dr. ir. Martine Wevers, Coordinator NDT Group and Dr. Helge Pfeiffer, Post-Doc and Project Manager, Dept of MTM, KU Leuven, each spent countless time with me to discuss aspects of my research. And provided as much support as anyone else during my research, and added much more meaning to my work. Next, I would like to acknowledge everyone who provided technical support for this project. Thanks to Rashnal Hossain, Lina Rocio OSORIO Serna, Efrain Eduardo TRUJILLO De Los Rios Ph. D students of KU Leuven and Dr. Aart-Willem van Vuure Coordinator of "Natural Fiber- and Bio-Based Composites" for their heartfelt support and to Johan Vanhulst, Industrial Engineer and Kris Van De Staey for providing invaluable assistance with AE and tensile testing throughout research work. I would also like to acknowledge every one of CMG members of Dept of MTM of KU Leuven for their support.

I am also grateful to all teachers of Dept of MME, BUET especially Professor AWS Kurny, Dr. Mahbub Hassan who's suggestion help me to finish my dissertation in time. I am also thankful to my friends, colleagues who are always encouraging me to complete the degree. Lastly, I thank to my loving family members my parents, wife, my son and daughter for their heartfelt contribution to finish my M. Phil degree particularly over the final stages of my studies and whose support would not be valued with simple word THANKS.

Abstract:

In the present days among the different non-destructive testing methods Acoustic Emission is a suitable tool for detecting and evaluating and for better understanding the damage mechanism and failure behavior in composites during mechanical loading. Methodology was developed for natural single fibre tensile test with Acoustic Emission (AE) to assess or monitor the tensile failure behavior of natural single fibre especially for bamboo single fibre. Series of experiment performed with this methodology. Before the final failure of fibre during tensile test few (one or two) load drop observed from the time vs load graph. From AE parameter such as Amplitude, Energy, duration etc. significant information of corresponding to that load drops found. These AE signals from the load drop may occur from the failure such as debonding between two elementary fibre or from join of elementary fibre at edge. The value of load at first load drop was not found consistent for different sample (for a particular sample the value is 8N, Stress: 517.51 MPa). Final breaking of fibre gives saturated level AE amplitude of preamplifier (99.9 dB) for all samples. Therefore it was not possible to think up exact AE energy value for final breaking. The other AE signal of AE may occur for the micro failure mechanism.

Same methodology was used for tensile test of three single fibres, which gives clear indication of load drop before the final breaking of first and second fibre.

Moreover, tensile test of single fibre composite (bamboo single fibre/epoxy) was performed to identify the individual fibre and matrix failure mechanism in composites using AE technique. Experimental data from AE for SFC test shows that many of them have a clear correlation between acoustic emission amplitude and failure mechanisms in single fibre composite.

Chapter-1: Introduction

1.0 Background

There is a growing interest to properly utilize natural fibres due to their light weight, low cost and resistance to deforestation (as natural fibre by suitable modification can be used as a replacement of wood), in addition to the other usual advantages. Bamboo has considerable potential as a reinforcing fibre, in view of its high strength [1]. Natural fibres are environmentally friendly, not only during their growth stage but also after their lifetime because they are biodegradable. Studies on natural fibres and glass composites reveal that natural fibre composites are likely to be environmentally superior to glass fibre in most cases [2]. The major drawback of natural fibers is their quality, which depends on many external factors (climate, soil, plant cultivation, fiber extraction etc.)

During the last decade, ecological concerns have resulted in a renewed interest in natural materials, and issues such as sustainability and eco-efficiency have gained more and more attention, thus controlling the development and introduction of new materials, products and processes. Plant fibers are currently being evaluated as environmentally friendly and low cost alternatives for glass fibers in engineering composites and structures. However, serious concerns are still present on the level of mechanical performance that can be achieved with these materials [3]. Some common methods of strength measurement of fibres include the single-filament test [4], fractography [5], load drop [6] and strain measurement [7]. These investigations are limited to single filaments and/or bundle of small numbers of filaments [8]. Also there are other methods to understand the mechanical properties of fibre such as SEM, TGA, FTIR, DSC, XRD etc.

In this regard, applying acoustic emission (AE) to monitor mechanical loading can provide useful information.

Acoustic Emission (AE) technique has been developed over the last two decades as a non destructive evaluation technique and as a useful tool for material research [9]. AE is an efficient method to monitor, in real time, damage growth in both structural components and laboratory specimens. In loaded materials, the strain-energy release due to microstructural changes results in stress-wave propagation. In the case of composite materials, many mechanisms have been confirmed as AE sources including matrix cracking, fibre–matrix interface debonding, fibre fracture and delamination [10]. AE deals with the detection of such waves at the materials surface. Therefore, this technique potentially allows not only the location of the source of the emission, but also the determination of its nature. Nevertheless, the use of such techniques needs a clear understanding of relationships between the recorded signal and the damage process. However the stress waves resulting from the microstructural changes depend on the propagation conditions including attenuation, damping and boundary surface interactions in a heterogeneous medium. So the signal delivered by the sensor is a strongly modified representation of the original source. Nevertheless, it is realistic to consider that this signal contains some representative features of the source in such a manner that direct correlation exists between the damage mechanisms and the magnitude of the various AE parameters. Consequently, each signal can be considered as the acoustic signature of the different damage modes.

Many authors have already worked in this field. Barré and Benzeggagh [11], tested glass fibre reinforced polypropylene samples and reported that the acoustic signal amplitude varies with the corresponding damage mode: AE amplitude range from 40 to 55 dB corresponds to matrix cracking, 60–65 dB to debonding, 65–85 dB to pull-out and 85–95 dB to fibre fracture. Ely and Hill [10] showed that when fibre breaks and longitudinal splitting occurs at the same location in unidirectional graphite/epoxy specimen, the stronger signals (high amplitude, energy, counts and long duration) resulted from fibre breakage and the weaker ones (low amplitude, energy, counts and short duration) resulted from longitudinal split. Suziki et al. [12] observed the following correlation between failure mechanisms and AE frequency in glass/polyester composite: matrix cracking (30–150 kHz), fibre debonding and pull-out (180–290 kHz), fibre breaking (300–400 kHz). Uenoya [13] proposed a rising-slope criterion to discriminate AE source mechanisms in laminated composites (glass-fibre-fabric/epoxy). Barnes and Ramirez [14], testing carbon fibre reinforced pipes, used correlation plots of event amplitude and duration time to characterise the different modes of failure. They reported that high duration-low/intermediate amplitude (45–70 dB) events are associated with delamination and debonding while high amplitude-high duration events are associated with fibre fracture.

However, a single damage mechanism such as matrix cracking can produce a wide range of AE signal parameters [15]. For the various mechanisms, overlap of the AE parameters distributions results from signal attenuation, closely occurring emissions from different sources, equipment setting and large data sets. Thus, multiparameter analysis using many AE waveform parameters should be necessary to improve the identification of damage modes. Pattern recognition has been proposed as a suitable multivariable technique for the classification of AE events [16]. If supervised pattern recognition is used, the number of damage mechanisms must be known in advance. The term unsupervised pattern recognition is used to describe the complete methodology consisting of procedures for descriptors selection, cluster analysis and cluster validity. Ono and Huang [17] proposed a distinction between several damage mechanisms with waveform-based analyses associated to advanced pattern recognition techniques. They identified six different types of damage in carbon fibre and glass fibre composites subjected to tensile loading in different configurations.

Anyway, the experimental evidence of assigning any kind of damage mechanism to a peculiar signal cluster is rather difficult when many damage mechanisms take place in the same composite material. Besides, the above referenced authors do not proceed to such an evidence after they classified the AE signals. Therefore, the purpose was to use a methodology with the aim of identifying the acoustic signatures of the damage mechanisms. For that purpose, tensile stresses have been applied on samples of pure resin and of composite under different conditions that were expected to produce preferential damage mechanisms [18].

Considerable research work has been done using AE to identify the damage mode for glass fibre composite materials, not for single fibre. Very little research work has been done to assess the tensile failure behavior of single fibre either it is glass fibre or natural fibre using AE technique. A method based on AE generated by fibre fractures during tensile test has been developed for the determination of the strength distribution of E-glass fibre strands containing as many as 4000 fibres (filaments) [19]. Idealized composite systems were studied by Fuwa et al (1976) and Narisawa and

Oba (1984). Hamstad and Moore (1986) considered Kevlar fibres, and Netravali et al (1989) have investigated acoustic emission from a single glass fibre in epoxy resin. AE monitoring of the tensile fracture of single carbon fibres set in to resin dogbone samples has been reported by Favre and Jacques (1990). Farrow et al(1994) reported result of a number of experiments performed to measure the acoustic emission from the fracture of single carbon fibre alone and of single fibres in microcomposites and reported by. However, the main purpose was to count fibre breaks in order to evaluate the interfacial shear strength and no attempt was made to characterize the source. [20]

For natural fibre it is really difficult to arrange experimental setup to assess the tensile failure behavior using AE. G. Romha´ny et al. described the tensile strength of single flax fiber as a function of clamping length, and to clarify the related failure mode by AE technique. The failure sequence detected by *in situ* SEM inspection was as follows: (1) axial (longitudinal) splitting along the boundaries of the elementary fibers, (2) radial (transverse) cracking of the elementary fibers, and (3) fracture of elementary fibers and their microfibrils. The above events are superimposed on one another. They succeeded in assigning an AE amplitude range for each of the above failure mechanisms {(1): _35 dB; (2): 35–60 dB; and (3): 60 dB}[21].

1.1 Objectives of the Present Study

Present work is aimed at development of methodology to assess the tensile failure behavior of natural single fibre or technical fibre and single fibre composite (SFC) using AE technique.

The methodology for equipment setup associated with AE and experimental setup for mini tensile machine for bamboo single fibre has been proposed.

The objectives were as follows:

a) Development of methodology for natural single fibre tensile test simultaneously with AE method.

b) Understand the reliable description of the tensile failure behavior of natural single fibre, specifically bamboo and to clarify the related failure mode by AE technique.

c) Understand the tensile failure behavior of Single Fibre Composite (SFC) during tensile test using AE technique; specifically identify the fibre failure and matrix failure by AE method. .

The thesis consists of five chapters. The second chapter of this thesis presents an analysis of the relevant literatures about natural fibers and natural fiber composites particularly for bamboo fibers and SFC and Non Destructive Testing (NDT) Methods that are used for damage detection of natural fibre and its composites, especially details of AE method.

In the third chapter, development of methodology and experimental setup that were used during the study has been described. First, the technique used to perform single fiber tensile tests was explained. Subsequently the technique used for SFC was described.

In the fourth chapter, the experimental results i.e. observations are given, discussed and analyzed.

Finally, in chapter five general conclusions have been presented and a suggestions future work based on the results obtained has been formulated.

Chapter-2: Literature Review

2.0 Fibres

Fibers or **fibres** (spelling differences) are a class of hair-like materials that are continuous filaments or are in discrete elongated pieces, similar to pieces of thread. They can be spun into filaments, thread, or rope. They can be used as a component of composite materials. They can also be matted into sheets to make products such as paper or felt [22].

Natural fibres function as reinforcement by enhancing the mechanical and insulative properties of the composite. Natural fibres are typically used for textiles, weaving, paper, and as stuffing material. A greater interest has been developed in recent years to use natural fibres as reinforcement in the composites industry. The properties of natural fibres may vary significantly, while traditional reinforcement's (carbon, glass, and aramid) exhibit very little variation. Natural fibres can be classified by their origin, variation of their properties depending on the quality, location, and the age of the plant [23, 24]

Currently, many types of natural fibers have been investigated for use in plastics including flax, hemp, jute straw, wood, rice husk, wheat, barley, oats, rye, cane (sugar and bamboo), grass, reeds, kenaf, ramie, oil palm empty fruit bunch, sisal, coir, water, hyacinth, pennywort, kapok, paper mulberry, raphia, banana fiber, pineapple leaf fiber and papyrus [25]. Bamboo is an abundant natural source in Asia and South America and has been used to develop bamboo reinforced thermosetting plastic (epoxy and polyester) [26, 27]. Thwe *et al.* [28] have investigated the effect of environmental aging on the mechanical properties of bamboo-glass fiber reinforced polymer matrix hybrid composite. Okubo *et al.* [29] have fabricated bamboo fiber eco-composites for ecological purposes with the conventional hot press method. They studied their static strength and internal state after their fabrication, and concluded that high weight content of bamboo fiber enabled the bamboo composites to increase their strength in the most effective way, when the bamboo fiber was modified into the cotton shape [25].

2.1 Constituents of Natural Fibres

The properties of natural fibres mainly depend upon its chemical composition. Chemical composition of fibres depends on various factors. It varies with the geographic location, climate, type of fibre, plant part and soil conditions etc. Natural fibre consists of carbohydrates, lignin, and extraneous components. Carbohydrate portion of fibre comprises cellulose, hemicelluloses etc. Natural fibres along with wood fibre and other plant fibres are composed of a large percentage of cellulose, making cellulose the most abundant natural polymer. The repeating unit of cellulose is the cellobiose unit which consists of two β-D1,4-glucopyranose units. Cellulose is principally responsible for strength of natural fibre because of its specific properties such as high degree of polymerization and linear orientation. Mechanical properties of these fibres are dependent on the cellulose content in the fibre, the degree of polymerization of the cellulose and the micro fibril angle. Fibres with higher cellulose content, higher degree of polymerization and a lower microfibrillar angle exhibit higher tensile strength and modulus. These fibres exhibit variations in mechanical properties both along the length of an individual fibre and between fibres. Hemicelluloses act as a matrix for the cellulose. It is supposed to act as a link between the fibrous cellulose and the amorphous lignin. Lignin is a phenolic compound that holds the fibres together. Lignin acts as a stiffening agent for the cellulose molecules within the fibre cell walls. All three cell wall components contribute in different extents to the strength of fibre [30]**.**

2.2 Types of Natural Fibres

Natural fibres used in textiles are primarily grouped into seed and fruit fibres; soft (or bast) fibre; and hard (or leaf) fibres. The extraction of fibres from plant stems is achieved by various methods such as mechanical, physical, and steam explosion techniques. Retting is a process of controlled degradation of the plant stem to allow the fibre to be separated from the woody core. Microbial or enzymatic retting is one of the widely used techniques to extract good quality cellulosic fibres from the agricultural plants such as hemp, flax, jute, and kenaf [31]. **Figure 2-1** shows the different types and sources of natural fibres containing lignin and cellulose (lignocellulosic) in their cells as the major chemical constituents [32].

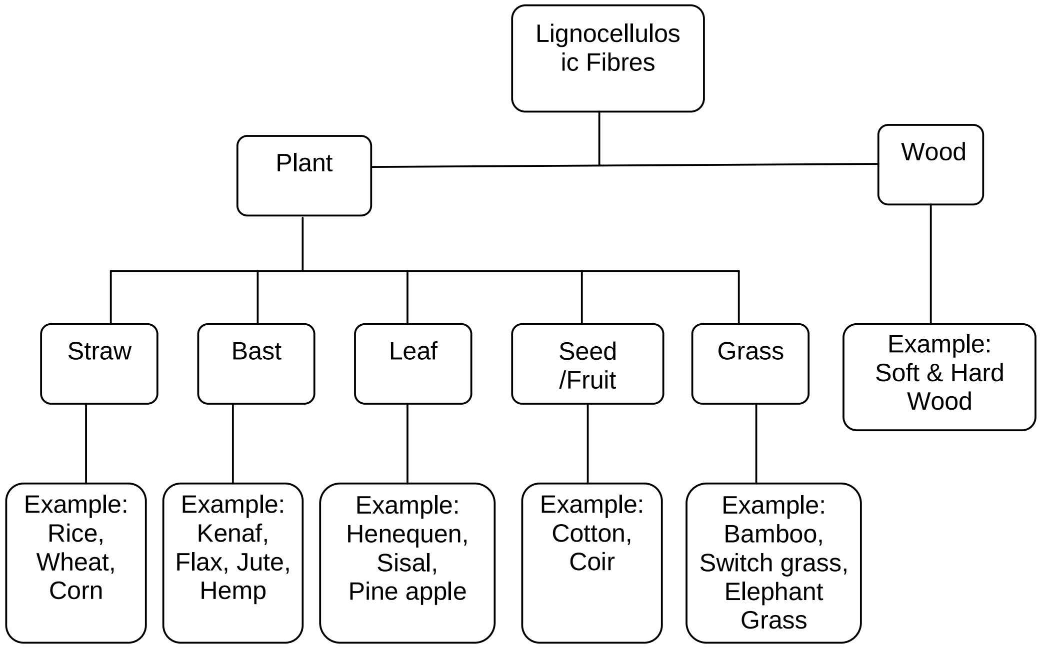


Figure 2-1: Flow Chart of different types of natural fibre

Table 2-1 gives the world production of natural fibres for different industrial uses. By far wood is the largest source of natural fibres produced in the world for various applications [32].

Table 2-1 Commercially Important Fibre Sources

Fibre Source	**Species**	**World Production (103 tons)**	**Origin**
Wood	(>10,000 species)	1,750,000	Stem
Bamboo	(>1250 species)	10,000	Stem
Cotton lint	Gossypium sp.	18,450	Fruit
Jute	Corchorus sp	23,00	Stem
Kenaf	Hibiscus cannabinus	970	Stem
Flax	Linum usitatissimum	830	Stem
Sisal	Agave sisilana	378	Leaf
Rosselle	Hibiscus sabdariffa	250	Stem
Hemp	Cannabis sativa	214	Stem
Coir	Cocos nucifera	100	Fruit
Ramie	Boehmeria nivea	100	Stem
Abaca	Musa textiles	70	Leaf
Sunn hemp	Crorolaria juncea	70	Stem

2.3 Characteristics of Commonly Found Natural Fibers

A brief description for some of the more commonly found natural fibers with their properties (Table 2-2) is presented here [33]:

a. Coconut fiber. A mature coconut has an outer covering made of fibrous material (Figure 2-2). This part of the coconut, called the husk, consists of a hard skin and a large amount of fibers embedded in a soft material. The fibers can be extracted simply by soaking the husk in water to decompose the soft material surrounding the fibers. This process, called retting, is widely used in the less developed countries. Alternatively, a mechanical process can be used to separate the fibers. Coconut cultivation is restricted to the tropical regions of Africa, Asia, and Central America.

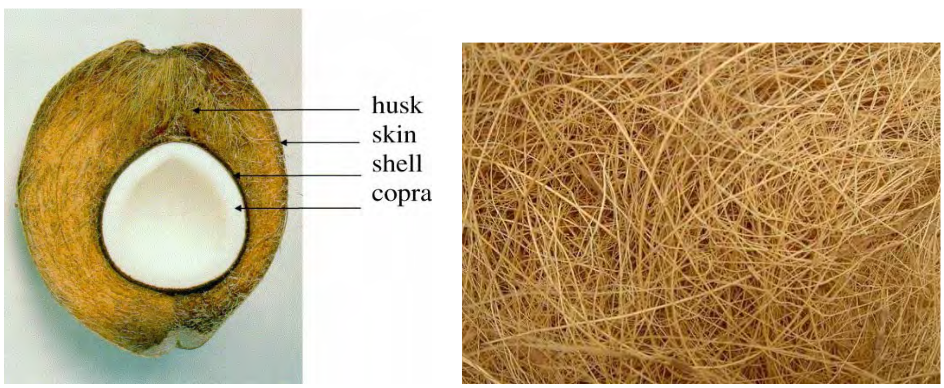


Figure2-2: Typical Coconut Fibre

b. Sisal fiber: In Australia, sisal fibers (Figure 2-3) have been successfully used for making gypsum plaster sheets. A considerable amount of research has been carried out in Sweden for developing good quality concrete products reinforced with sisal fibers.

Figure2-3: Typical Sisal Fibre

These fibers are stronger than most of the other natural fibers, as can be seen from the table 2-2.

c. Sugar cane bagasse fiber: Sugar cane (Figure 2-4) is cultivated in both tropical and sub-tropical regions. Sugar cane bagasse is the residue remaining after the extraction of the juice and contains about 50 percent fiber and 30 percent pith with moisture and soluble solids constituting the remaining 20 %. In order to obtain good quality fibers, the pith and other solids are removed from the fibers. The properties of bagasse fibers depend, to a very large extent, on the variety of the sugar cane, its maturity, and on the efficiency of the milling plant. The properties given in the table 2-2 are considered to be typical.

Figure2-4: Typical Sugarcane

***d. Bamboo fiber*:** Bamboo belongs to the grass family and can grow to a height of 15 m with diameters varying within the range of 25 to 100 mm. It grows naturally in tropical and sub-tropical regions. Dried bamboo stems are commonly used for building temporary structures such as scaffolding. They may also be fabricated to form a continuous reinforcing material for concrete. Bamboo fibers (Figure 2-5) are strong in tension (table 2-2) and can be used as a reinforcing material. However, they have a high water absorption capacity, low modulus of elasticity, and special equipment may be needed to extract them from the stems.

Figure 2-5: Typical Bamboo Fibre

e. Jute fibe:. *J*ute is grown mainly in Bangladesh, India, China, and Thailand. It is grown solely for its fiber, which is traditionally used for making ropes and bags to transport grains and other materials ranging from cement to sugar.

Figure2-6: Typical Jute Fibre

Strong in tension (table2-2), jute fiber (Figure 2-6) can also be used in a cement matrix. The process of obtaining jute fibers is very simple. Mature plants are cut and soaked in water for about four weeks, which completely decomposes the bark. The fibers thus exposed are then stripped from the stem, washed, and dried. A new technique is now available. It is claimed that this technique will give a better product.

f. Flax: Flax (Figure 2-7) is a slender and erect plant grown mainly for its fiber. Both the tensile strength and the modulus of elasticity of flax are extremely high compared to those of other natural fibers, as may be seen from the table 2-2.

Figure2-7: Typical Flax Fibre

g. Other vegetable fibers: Of the various vegetable fibers, only a few have been found to be potentially suitable as reinforcing materials. The mechanical properties of the more promising fibers, namely elephant grass, water reed, plantain, and musamba, are listed. Investigations have also been carried out to explore the possibility of using other natural fibers such as palm fiber and akwara fiber as reinforcing materials for concrete. These fibers are usually removed manually from the stem of the plant.

Table 2-2 : Typical Properties of Natural Fibers

Fiber type	Fiber length [mm]	Fiber diameter [mm]	specific gravity	Modulus of elasticity [10^6 GPa]	Ultimate tensile strength [10^3 MPa]	Elongation at break [%]	Water absorption [%]
Coconut	51-102	0.10-0.41	1.12-1.15	19-26	120-200	10-25	130-180
Sisal	N/A	N/A	N/A	13-26	276-568	3-5	60-70
Sugar cane Bagasse	N/A	0.20-0.41	1.2-1.3	15-19	184-290	N/A	70-75
Bamboo	N/A	**0.05-0.41**	**1.5**	**33-40**	**350-500**	**N/A**	**40-45**
Jute	178-305	0.10-0.20	1.02-1.04	26-32	250-350	1.5-1.9	N/A
Flax	508	N/A	N/A	100	1000	1.8-2.2	N/A
Elephant grass	N/A	N/A	N/A	4.9	178	3.6	N/A
Water reed	N/A	N/A	N/A	5.2	70	1.2	N/A
Plantain	N/A	N/A	N/A	1.4	92	5.9	N/A
Musamba	N/A	N/A	N/A	0.9	83	9.7	N/A
Wood fiber (kraft pulp)	3-5	0.03-0.08	1.5	N/A	700	N/A	50-75

2.4 'Bamboo Fibres' – Their Structure and Properties

In the last few years on the world market, more and more products from so-called bamboo fibres have been appearing. In the media, a campaign promoting their advantages is underway, which encourages companies to elevate the prices of the "new" products [34].

What is so special about bamboo fibres?

Bamboo is the biggest grass in the world. It belongs to the *Poaceae* family, a subfamily of *Bambusoideae*. There are more than 1250 species within 75 genera of bamboo in the world, mainly distributed in tropical and subtropical areas. China is one of the centres of bamboo growth, possessing about 400 species of 50 genera. The area of bamboo growth exceeds 4.21 million ha. As a grass, bamboo can grow in very hard conditions without any need of pesticides and herbicides. Bamboo is the fastest growing plant in the world - some species grow even one meter per day. It has a great ability to reduce green house gases, absorbing five times more CO_2 than an equivalent stand of trees and producing 35% more oxygen. Bamboo constantly improves its solidity, thereby preventing its erosion. In addition it retains water in its watersheds. The species of bamboo used for fibre production are not eaten by the endangered Giant Panda. Fortunately there is also no information about genetically modified bamboo.

Bamboo is known as a very tough and durable plant. It is one of the oldest building materials used by human kind. Bamboo has been widely used in household products and extended to industrial applications due to advances in processing technology and increased market demand.

Bamboo fibres are mainly produced from bamboo Phyllostahys Edulis, called ‘Moso’, which is the biggest bamboo in the world. With respect to their structure, natural bamboo fibres are similar to ramie fibres; however, they are finer and shorter. Their length varies from 1 to 5 mm (with an average of 2.8 mm) and the diameter 14-27 μm (average - 20 μm). They form technical fibres. As can be seen, the length of natural bamboo fibres is very low, and therefore there might be problems with their processing. However, in the industry it is said that many woven and nonwoven products are made from such fibres.

The amount of positive aspects of bamboo fibres is quite exceptional:

- natural antibacterial and antifungal properties, making clothes made from bamboo fibres hygienic and odour resistant. However, this effect starts to wither after fifty washings;
- smoothness, proving bamboo fibres to be non irritating for sensitive skin;

- bamboo fabric is soft and silky with a natural sheen, making it close to natural silk but less expensive and more durable;
- hypoalergic and deodorant properties;
- high water absorption and fast drying caused by a high amount of microcracks and grooves on the fibre's surface;
- higher breathability and thermo regulating properties than cotton and even hemp. They are also said to be 2 - 3 °C cooler than the surrounding temperature ;
- a high durability in comparison to other fibres.
- UV protection abilities
- a high sorption of dyes and better colour clarity;
- bamboo fabrics have low shrinkage;
- bamboo fibre does not need to be mercerized to receive natural luster;
- clothes made from bamboo fibre are more wrinkle resistant than cotton and can be ironed at lower temperatures;
- bamboo products are biodegradable and some companies have a utilization program that allows consumers to return a worn-out product and buy another at a lower price, which is a very good policy for encouraging others to do the same .

As a result of the beneficial properties mentioned above, bamboo fibre has found its way into the fashion world. Many well known designers, like Kate O'Connor and Oscar de la Renta have tried their hand at using the new material with good results. Because of its antibacterial and temperature- regulating features, bamboo fibre has found its place in the sports clothing industry. A most noticeable increase in bamboo fibre application can be seen in yoga and fitness clothing, which are mostly of the women's sports and proecological kind; the oriental touch of bamboo fibre blends well with women's needs.

In the present research, Bamboo, ***Guadua angustifolia*** fibres are used. Some details on this bamboo category as described by Osorio et al [2] is given below:

Among the well-known natural fibers, bamboo has one of the most favorable combinations of low density and high mechanical strength, that is, it has high specific stiffness and strength. In terms of specific properties, it is claimed they can be compared with glass fibers. According to several authors, bamboo fiber bundles are distributed densely in the outer region of the culm wall and sparsely in the inner region, and also concentrated in the upper part of the culm compared with the base (Figure 2-8(b)). Elementary fibers in such a bundle consist of thick and thin layers with different (nano) fibrillar orientation (Figure 2-8(f)). In the thick layers, the fibrils are oriented at a small angle to the fiber axis, whereas the thin ones show mostly a more transverse orientation. This structure does not exist in the cell walls of fibers of normal wood and leads to an extremely high tensile strength of the culm. In the case of Bamboo Guadua angustifolia, the average value of the tensile strength of the culm is 190 MPa. This is the reason why the fibers, the structural part of the culm, are often called ‘natural glass fibers. The elementary fiber length and fiber diameter for this species are on average 1.6mm and 11 mm, respectively, and they constitute about 40–50 wt% of the total bamboo plant tissue and between 60 and 70wt% of the total culm tissue. It is technically difficult and expensive to extract fine, long, and straight technical bamboo fibers. Only few efforts have been carried out worldwide to extract long bamboo fibers from the culm to be used as reinforcement in composites. Because of the limited availability of fibers, only in the recent years, there has been an increasing interest to study scientifically the potential of bamboo fibers as reinforcing material for polymer matrix composites, despite its high mechanical properties, biodegradability, and cost. To practically apply the benefits of bamboo fibers, it is necessary to develop a process to extract high-quality fibers (i.e., undamaged fibers) from bamboo trees in a controlled way as well as to tailor processes to produce bamboo fiber composites. Studies setting out the utilization of bamboo G. angustifolia fibers as the reinforcement of polymeric matrices are practically non-existent, even though it is the most important bamboo species of America and one of the three largest bamboos in the world. This is due to its size, high performance, and its impact for the local economy where it grows. It also has a high growth rate, between 11 and 21 cm per day, reaching its definitive height 6–7 months after the shoot emerges, coming into maturity when it is 4–6 years old. This bamboo is one of the tropical species that has been identified as having a great potential to fix atmospheric carbon dioxide which makes it an effective plant in terms of global warming prevention and a suitable resource for fiber production. G. angustifolia fibers were characterized in a previous study, where it was found that the best properties come from fibers extracted from the inner part of the culm wall, whereas the location of the fiber over the culm length does not have a significant influence on the mechanical properties. Also, several studies have been published of other bamboo fiber-reinforced composites using thermoset, thermoplastic, and biodegradable matrices. The results of these researches suggest that there is a good potential for this reinforcing material to be used in light, high strength polymeric composites.

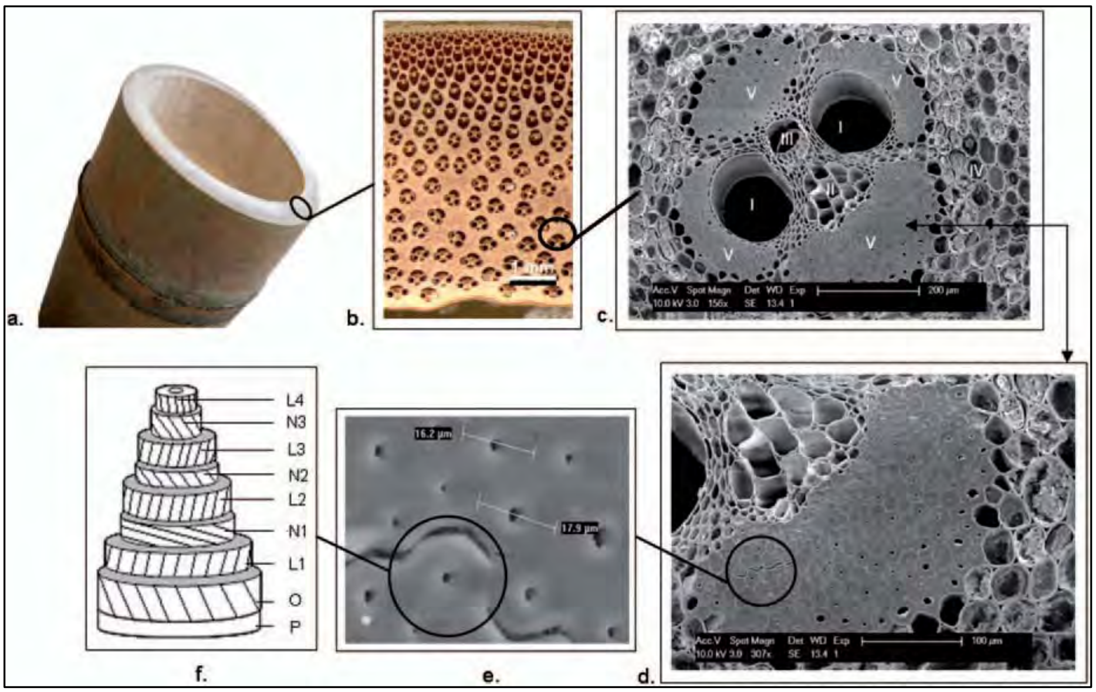


Figure 2-8. Bamboo G. angustifolia microstructure: (a) bamboo G. angustifolia culm, (b) cross-section of the culm showing the fiber distribution through the wall thickness, (c) vascular bundle, the main anatomical constituent of the plant, composed of vesselsI, floemII, protoxilemIII, parenchyma tissueIV, and fiber bundlesV, (d) bamboo fiber bundle composed by several elementary fibers, (e) elementary fibers with pentagonal or hexagonal shape, and (f) model of polylamellae structure of a thick-walled elementary fiber proposed by Liese,21 where, in the thick lamellae (L1–L4), the cellulose fibrils are oriented at a small angle to the fiber axis, whereas the thin ones (N1–N3) show mostly a more transverse orientation, P, primary wall, O, external sheet of secondary wall.

2.5 Composite

2.5.1 Definition

A "composite" is when two or more different materials are combined together to create a superior and unique material. This is an extremely broad definition that holds true for all composites, however, more recently the term "composite" describes reinforced plastics.

2.5.2 Background on Composites

The history of composites dates back to ancient times for construction applications; straw was mixed with mud to form a building material known as adobe. The straw provided the structure and strength, while the mud acted as a binder, holding the straw together in place.

Since the days of adobe, the use of composites has evolved to commonly incorporate a structural fiber and a plastic, this is known as Fiber Reinforced Plastics, or FRP for short. Like straw, the fiber provides the structure and strength to the composite, while a plastic polymer holds the fiber together. Common types of fibers used in FRP composites include:

- Fiberglass
- Carbon Fiber
- Aramid Fiber
- Boron Fiber
- Basalt Fiber
- Natural Fiber (Wood, Flax, Hemp, Bamboo, Jute etc.)

In the case of fiberglass, hundreds of thousands of tiny glass fibers are compiled together and held rigidly in place by a plastic polymer resin . Common plastic resins used in composites include:

- Epoxy
- Vinyl Ester
- Polyester
- Polyurethane
- Polypropylene

2.5.3 Examples of Composites

The most common example of a "composite" in a broad sense is concrete. In this use, structural steel rebar provides the strength and stiffness to the concrete, while the cured cement holds the rebar stationary. Rebar alone would flex too much and cement alone would crack easily. However, when combined to form a composite, an extremely rigid material is created.

The composite material most commonly associated with the term "composite" is Fiber Reinforced Plastics. This type of composite is used extensively throughout our daily lives. Common everyday uses of fiber reinforced plastic composites include:

- Aircraft
- Boats and marine
- Sporting equipment (Golf shafts, tennis rackets, surfboards, hokey sticks, etc.)
- Automotive components
- Wind turbine blades
- Body armor
- Building materials
- Water pipes
- Bridges
- Tool handles
- Ladder rails

2.5.4 Benefits of Composites

In comparison to common materials used today such as metal and wood, composites can provide a distinct advantage. The primary driver and advantage in the adoption of composites is the lightweight properties. In transportation, less weight equates to more fuel savings and improved acceleration. In sporting equipment, lightweight composites allow for longer drives in golf, faster swings in tennis, and straighter shots in archery. While in wind energy, the less a blade weighs, the more power the turbine can produce. Besides weight savings, the most important benefits of composites include Non-corrosive, Non-conductive, Flexible, will not dent, Low maintenance, Long life, Design flexibility [35]

2.6 Single Fibre Composite:

The single-fiber composite (SFC) has been widely used to quantify fiber strength and fiber–matrix interfacial properties of fiber-reinforced composites. Usually the frequently used SFC test is fragmentation test. The fragmentation test is developed from the early work of Kelly and Tyson [36], who investigated brittle tungsten fibers that broke into multiple segments in a copper matrix composite. Each test specimen for the fragmentation test consists of one fiber encapsulated in a chosen polymer matrix. The specimen normally has a dogbone shape as shown in **figure 2-9.** Elongating the specimens in a tensile tester results in fiber breakage. The fiber inside the resin breaks into increasingly smaller fragments at locations where the fiber's axial stress reaches its tensile strength. This requires a resin system with a sufficiently higher strain-to-failure than the fiber's.

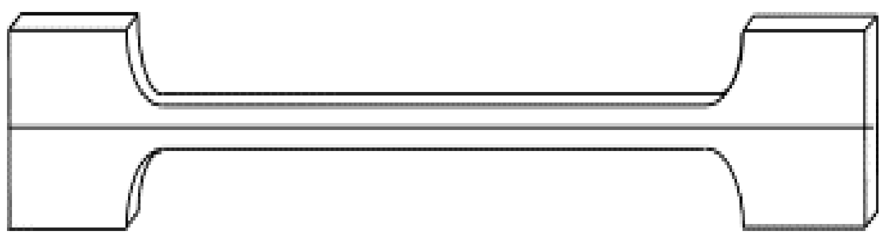


Figure-2-9 Dog bone shape SFC

2.7 Non Destructive Testing Methods for determination of Damage of Composite

This section presents a survey of damage detection methods for composite materials. Composite materials are gaining acceptance and demand in several commercial markets including sporting goods, construction and transportation. For many of these applications however, such as aircraft, without a reliable damage detection approach, the total cost of ownership may become a limiting factor for the structure's use. Several non –destructive evaluation techniques are used for in –service testing of composite materials.

There are several inherent difficulties in detecting damage in composite materials as opposed to traditional engineering materials such as metals or plastics. One reason is due to its in homogeneity and anisotropy; most metals and plastics are formed by one type of uniformly isotropic material with very well known properties. Laminated composite materials on the other hand can have a widely varying set of material properties based on the chosen fibers, matrix and manufacturing process. This makes modeling composites complex, and often non -linear. Another obstacle to many detection techniques is the fact that composites are often a mix between materials with widely differing properties, such as a very good conducting fiber in an insulating matrix. A last difficulty is that damage in composite materials often occurs below the surface, which further prevents the implementation of several detection methods. The behavior of composite material is much less well understood, and an unexpected failure of the composite part could prove catastrophic to a component [37].

The specific nature of defects (external and internal) in polymer composites causes some difficulties in the choice of equipment and development of methods for detecting the defects. External defects include scratches and wrinkles, irregularities of the decorative layer, separation of the filler texture, visible disruption of the filament orientation, and the adherence of the binder. Internal defects include delamination and cracks, cavities, porosity, extraneous inclusions, uneven distribution of the binder (portions with insufficient or excess resin), and incomplete curing.

The norms for allowable defects in polymer composites are determined by the conditions and technical capabilities of the NDT equipment. Most often, the defects in polymer composite products are revealed and what caused those defects is determined **(Table 2-3)** by using acoustic, radiation, optical, thermal, radio-frequency, and other methods that can check almost all characteristics of composites **(Table 2-4).**

Table-2-3 Types of defects detected by suitable NDT Methods

Defects	**NDT Methods**	**Causes**
Increased or decreased viscosity	Ultrasonic(US), Super High Frequency(SHF)	Disruption of the thermal conditions of the medium
Increased moisture content of filter	SHF, electric(E), Radiation, Infrared(IR)	Disruption of the moisture content of the medium
Excess content of volatile components	SHF, E, US	Disruption of the binder batching
Deterioration of adhesive and physico-mechanical properties	US, SHF	Disruption of the chemical composition of the binder
Incomplete curing of binder	US, SHF	Batching Error
Delamination, cracks	IR, US, SHF, R	Disruption of the thermal molding condition
Disruption of the filament orientation and ratio	Polarization, US, SHF, R	Errors in reinforcement placement
Unbonded Layers, delamination	IR, US, SHF	Malfunctions of the technological equipment
Disruption of the geometry, inhmogeneity of properties, porosity	US, IR,SHF	Variation of applied pressing force
Cracks, increased moisture content	US, SHF, E, R	Nonobservance of operating conditions

Table-2-4 : Measurable parameters of polymer composite by suitable NDT Methods

Method	Inspection parameter	Measurable parameters of polymer composite
US	Rate and coefficient of damping of various types	Elastic moduli, dimensions, strength, degree of polymerization, stressed state, frost resistance, grain size of structure, hardness, degree of crystallization, delamination, reinforcement coefficient, porosity, density
Vibration (resonance)	Natural frequencies and degree of damping of various modes	Ditto
Impedance	Mechanical impedance	Density, elastic moduli, geometric dimension, delamination, filler content, porosity, hardness of the materials
Acoustic Emission	Number, intensity, and amplitude and energy distribution of acoustic pulses	Build-up of damage incurred during trial loading, crack formation, failure of structural elements and adhesive bonds of materials
Thermal	Temperature diffusivity, thermal conductivity coefficient, thermal activity, specific heat conductivity	Density, porosity, moisture content, reinforcement coefficient, delamination
Electric	Electrical conductivity, dielectric constant, loss factor	Composition and structure, reinforcement coefficient, polymerization, crystallinity, aging, moisture absorption, geometric dimensions, density, radiotransparency
Electro-magnetic	Electrical conductivity, magnetic permeability	Density, reinforcement coefficient, porosity, build-up of damage
Radio-frequency	Reflection and transmission coefficient, refractive index, polarization factor, conversion coefficient	Geometric dimensions, moisture content, disruption of the continuity of the materials, amplitudes of vibration
X-Ray	X-Raying	Internal discontinuities, density, geometric dimensions, crystal lattice constants, orientation of structures, internal stresses
Optical	Transmissivity, reflectance	External defects, degree of damage to

		reinforcement, reinforcement coefficient, build-up of fatigue cracks
Holographic	Linear displacement	Internal(subsurface) defects, strained state

Acoustic NDT equipment employs ultrasound of the frequency range from 50 Hz to 50 MHz. Acoustic methods include ultrasonic, acoustic impedance, collision (free oscillations), resonance, velocimetric, reverberation, and acoustic emission methods [38].

Among these methods details of Acoustic Emission Technique is described in the latter section.

2.7.1 Acoustic Emission Technique

2.7.1.1 Introduction to the Acoustic Emission Technique

Acoustic emission (AE) in simple terms is defined as a transient elastic wave generated as an outcome of a material deformation. This stress wave propagates through the solid due to the energy released during the deformation process. The amount of acoustic energy released depends primarily on the size and the speed of the local deformation process. Acoustic activity may be observed both in highly elastic as well as brittle materials. The classical sources of acoustic emissions are defect-related deformational processes such as crack nucleation/growth and plastic deformation. Its unique ability to passively record events at their moment of occurrence is definitely the main reason for this technique to come in to the forefront of structural monitoring. This advantageous quality permits monitoring during loading.

The technique can also be characterized as dynamic and volumetric since it is well adapted for remote monitoring of active defects on varied structures.

The advantages of the AE technique may be summarized as:

- The only non-destructive method that enables passive and global monitoring of active defects.
- Use of multiple sensors can aid in locating the source of acoustic emissions.
- Measurements can be done in real time.

- Detailed analysis of the signals allows for differentiation between genuine damage associated signals and background noise.

AE is unlike most other nondestructive testing (NDT) techniques in two regards. The first difference pertains to the origin of the signal. Instead of supplying energy to the object under examination, AET simply listens for the energy released by the object. AE tests are often performed on structures while in operation, as this provides adequate loading for propagating defects and triggering acoustic emissions.

The second difference is that AET deals with dynamic processes, or changes, in a material. This is particularly meaningful because only active features (e.g. crack growth) are highlighted. The ability to discern between developing and stagnant defects is significant. However, it is possible for flaws to go undetected altogether if the loading is not high enough to cause an acoustic event. Furthermore, AE testing usually provides an immediate indication relating to the strength or risk of failure of a component. Other advantages of AET include fast and complete volumetric inspection using multiple sensors, permanent sensor mounting for process control, and no need to disassemble and clean a specimen.

Unfortunately, AE systems can only qualitatively gauge how much damage is contained in a structure. In order to obtain quantitative results about size, depth, and overall acceptability of a part, other NDT methods (often ultrasonic testing) are necessary. Another drawback of AE stems from loud service environments which contribute extraneous noise to the signals. For successful applications, signal discrimination and noise reduction are crucial [39].

2.7.1.2 Concept of Acoustic Wave Propagation

Inelastic material deformation leads to the release of elastic energy absorbed within the material. The mechanical waves thus produced radiate from a defect source and get detected by the transducers that are located on the surface of such a material, as shown in Figure.2-10). The amplitude (and consequently, the energy) of the stress pulse generated at a defect source can vary drastically depending on the nature of the defect and the dynamics of the source process.

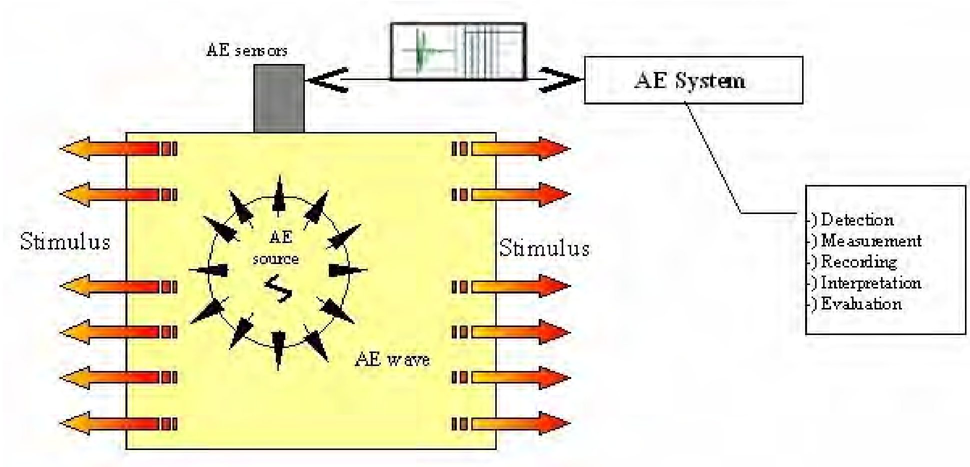


Figure 2-10: Principle of acoustic emission

Basically, an AE signal can be classified into:

1. Transient signal (bursts): these signals have definite start and end points deviating clearly from background noise (Figure 2-11). They are characteristically associated with crack propag

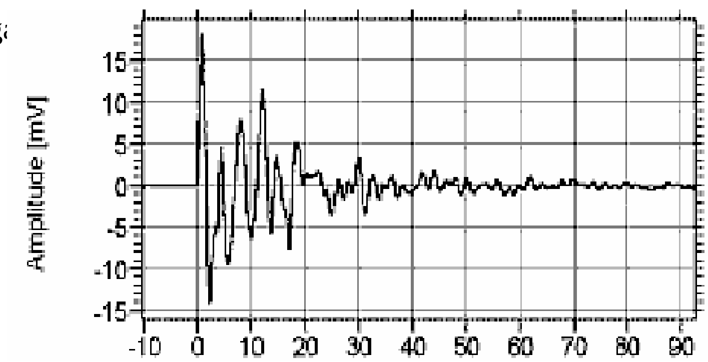


Figure 2-11 Transient signal (Vallen 2002)

2. Continuous signal: As the name implies, these are continuous waves who have varying amplitudes and frequencies but never end. Figure 2-12 represents a typical continuous signal pattern.

They are usually the AE response for movements or dislocations.

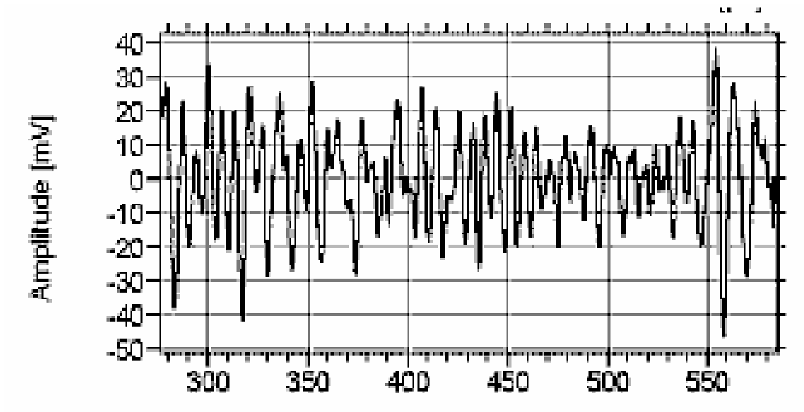


Figure 2-12 Continuous signal (Vallen 2002)

2.7.1.3 Acoustic Signal Parameters

Understanding an acoustic signal requires the knowledge of certain basic terminology which is essential to analyze and interpret these signals.

A typical signal is represented below in Figure 2-13.

1. Arrival time: Absolute time when a burst signal first crosses the detection threshold. .

2. Peak Amplitude: Maximum absolute amplitude within the duration of the burst signal. The amplitude is directly related to the magnitude of the source event.

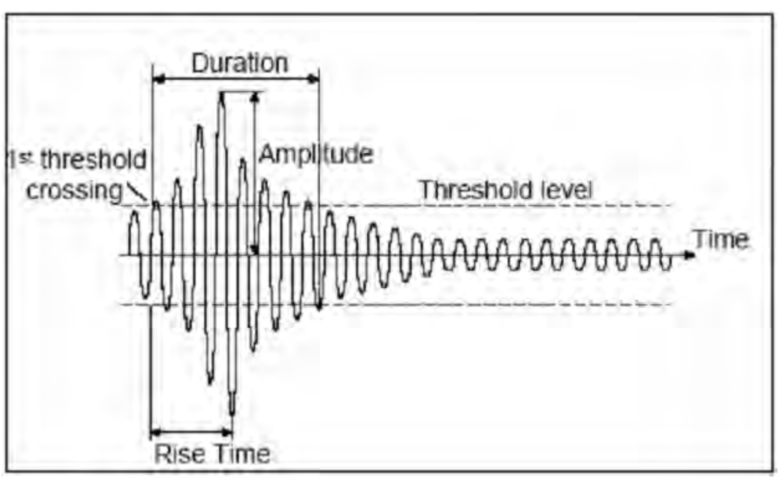


Figure 2-13 A typical AE signal

3. Rise Time: Time interval between the first threshold crossing and the maximum peak amplitude of the burst signal involving time in ms. This parameter is often useful in problem dependent processes such as dynamic loading or vibration of structures.

4. Signal Duration: Interval between the first and the last time the detection threshold was exceeded by a burst signal. Analogous to counts, this parameter measures the source magnitude. It is particularly useful for noise filtering and other kinds of signal qualification.

The attainable accuracy of data collected using the acquisition equipment is governed by several signal properties. Wave velocity, geometry and material properties are all factors that vary the amount of acoustic activity generated. Even the kind of stress and rate of loading applied to the material generates a different AE signature. High acoustic emissivity may be directly associated with: damage of materials, crack propagation, low-temperature deformation, brittle fracture, anisotropy, heterogeneity, high strength and high strain-rate.

The advent of new signal processing techniques has simplified removal of unwanted segments during the post- processing stage.

2.7.1.4 Equipment Used in AE Monitoring

The process of AE monitoring is made possible by using an array of instruments. Each component has a unique role to play and is essential to ensure proper monitoring. A brief description of each component is detailed in this section.

Sensors: They are the key instrument that detect the mechanical transient elastic waves generated from within a structure and convert them into electrical AE signals. Usually piezoelectric resonant sensors are used for AE testing. The Figure 2-14 shows various kinds of sensors available in today’s market.

Figure 2-14: Sensors

Couplants and holders: Sensors are affixed to the surface of the material to be tested using various couplants. These are mainly used to aid in easy and complete conduction of acoustic waves generated from the source. Commonly used, couplants are oil, glue, high vacuum grease, etc. Along with the use of couplants, most field tests require additional holders to hold the sensors in place.

Pre-Amplifiers: The main purpose of this device is to provide gain to boost signals to a less vulnerable level and effectively filter and reject noise from areas outside the sensor operating range.

Data acquisition system: Modern AE systems (Figure 2-15) use computers and appropriate software providing a menu -driven parameter input and system control. All the signals received at the sensor end are acquired and stored in the acquisition system. The new generation systems also enable extensive post-processing possibilities. Acquisition systems have also been well adapted for continuous monitoring of structures using wireless technology and web-based remote monitoring

Figure2-15 Data Acquisition system(pacndt.com)

2.7.1.5 The AE Process Chain [Vallen]

As can be seen in **figure 2-16** mechanical stress has to be produced within the test object, which is usually done by applying external forces. The behavior of the material properties and the starting point of the release of elastic energy, e.g. by crack formation are influenced by the material properties and the environmental conditions. The elastic wave propagating through the material is detected and converted into the electrical AE signal by the AE sensors. The AE system processes the AE signal, converts the detected burst into feature data sets, determines the source locations, calculates statistics, and displays them graphically and numerically in real time. So-called parametric channels measures the environmental conditions as well as the external load as reference parameters for the detected AE [40].

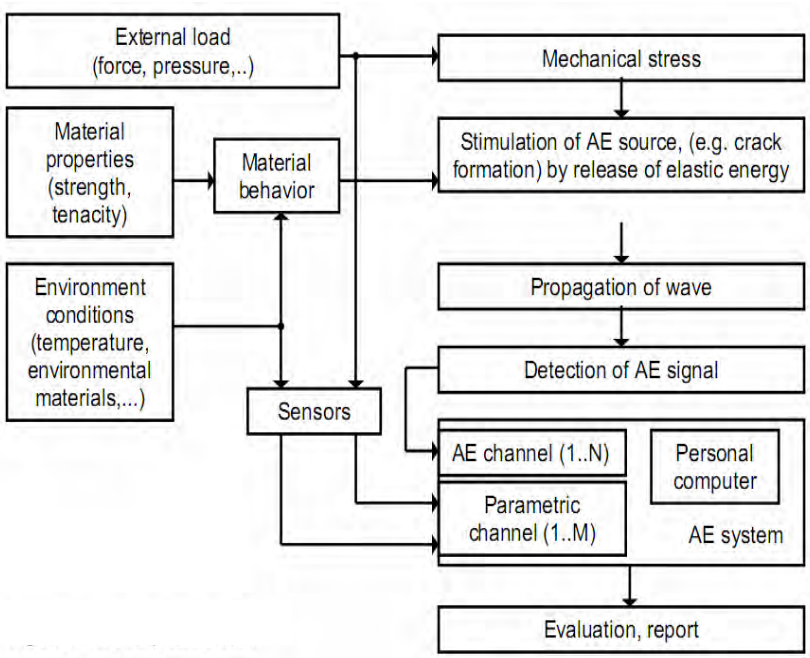


Figure 2-16: The AE Process

2.7.1.6 The AE Measurement Chain[Vallen]

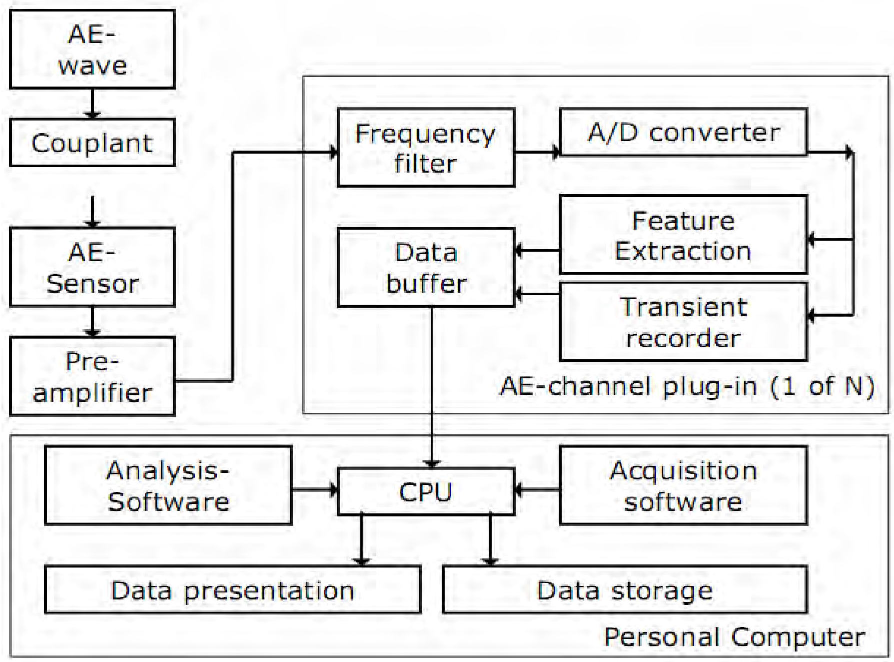


Figure 2-17: The AE Measurement chain

The diagram in Figure 2-17 shows the schematic of an AE measurement chain from the couplant to the PC.

Piezo-electric sensors have proved to be most appropriate for all types of AE testing. They are robust and extremely sensitive. The optimal frequency range to be chosen depends on the expected kind of AE sources and the conditions of wave propagation, wave attenuation and distances. When testing metal vessels for integrity, the frequency range 100 to 300 kHz is usually selected. Testing concrete and plastic materials requires often the selection of lower frequencies. If disturbing noise can not be eliminated by other means, and the source mechanism is appropriately wide band, the selection of higher frequencies may improve the signal to noise ratio, on costs of shorter detection distance. The selected frequency range is defined by the sensor, the frequency filters in the preamplifier and in the AE channel plug-in board [40].

Chapter-3: Methodology and Experimental Setup

3.0 Introduction:

Among different NDT methods Acoustic Emission is used for defect detection and material characterization. The main objective of this investigation was to study the tensile failure behavior of Natural Single Fibre (NSF) and Single Fibre Composites (SFC) by Acoustic Emission (AE) technique. At first the tensile failure behavior of natural single fibre using AE technique was studied and then the behavior of SFC was investigated. A mini tensile testing machine and an AE equipment has been used.

The present research work may be divided into two parts:

I. Development of the methodology for AE analysis during tensile test on natural single fibre specially for bamboo and
II. Preparation of SFC and analysis of failure behavior of SFC during tensile test by AE method

3.1 Development of the methodology for AE analysis during tensile test on natural single fibre

3.1.1 Preparation of Sample holder

Special type of sample holder has been designed (**Figure-3-1 and 3-2)** to ensure the gripping of single fiber in the mini tensile machine and to attach the AE sensor on the single fibre.

Aluminium foil was used to make thissample holder . Also two thick Al strips (20 X 12 X 1 mm) were used, because it is little bit difficult to set probe on Al-foil frame.

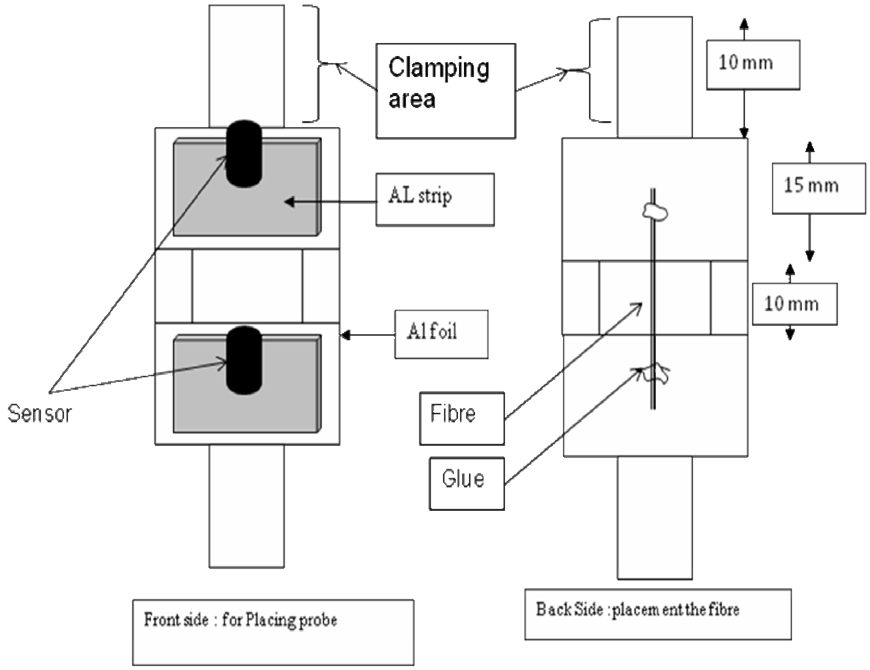


Figure-3-1 : Schematic diagram of sample holder

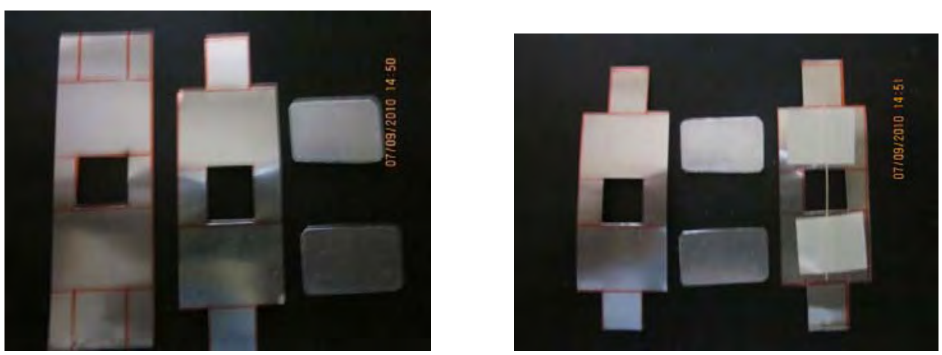


Figure- 3-2: original sample holder

3.1.2 Collection of Bamboo Fibre

The bamboo fibre as shown in figure 3-3 was extracted from Bamboo culms of Bamboo (Family: **Poaceae** (poh-AY-see-ee) Genus: ***Guadua*** (GWA-doo-uh) Species: ***angustifolia*** (an-gus-tee-FOH-lee-uh), ie. *Guadua angustifolia*) using a purely mechanical process (neither chemicals nor high temperature were used during the extraction) developed in the department of Metallurgy and Materials Engineering, Katholieke Universitiet Leuven [36]. The origin of the bamboo is Colombia. The diameter range for these fibres was between 90 and 250 μm;

a b c

Figure: 3-3: (a) Bamboo culm (b) Bamboo (technical) fibres after mechanical extraction from culm (c) Kink Test of bamboo fibre

The fibres that did not have any kink band (F**igure 3-3c)** and tearing portion and was uniform in diameter through out the length were selected for this study.

3.1.3 Fibre Placement on the sample holder:

The cross sectional area of each individual fibre was determined using apparent density, weight and the length of the fibre. The apparent density of the fibre was 1.44 gm/cm^3 and the fibre length was 40 mm. The fibre was weighed using a 5 digit weight machine.

The fibre was set on the sample holder using super glue and sticky paper and it was done one day before the test. Every care was taken to set the fibre parallel to the loading axis of the sample holder (Figure 3-4).

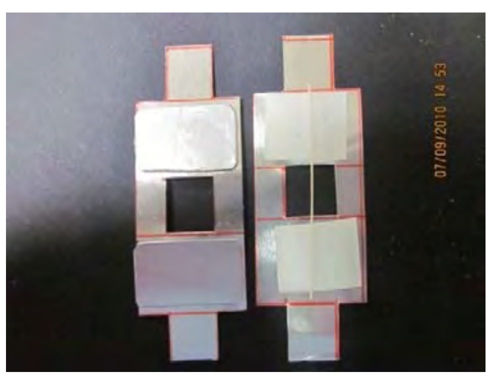
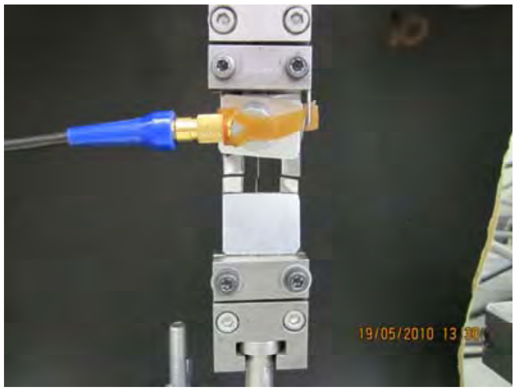


Figure 3-4: Placement of fibre on sample holder

3.1.4 Placement of Sample holder in the mini tensile machine:

The Aluminium sample holder /frame was attached and gripped in the machine using top and bottom screwed clamp (Figure 3-5).



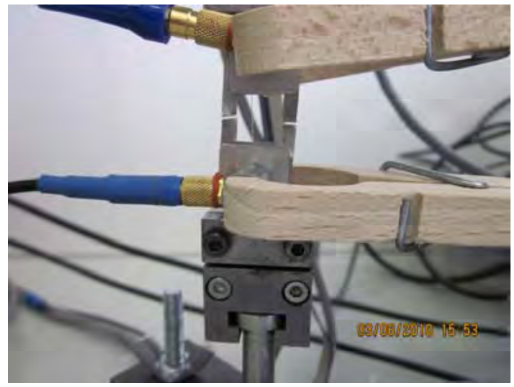


Figure 3-5: Placement of sample holder in the mini tensile machine

Then two sensors were placed over the strip using a wooden clamp. Then the Al foil was cut carefully in the middle zone of sample holder before starting the test. The whole process was time consuming and painstaking.

3.1.5 Equipment Used in Experiment: Mini Tensile Testing Machine & Acoustic Emission Instrument

Tensile test of Bamboo fibers were done using the mini tensile testing machine (F**igure 3-6)** that was developed in the department of Metallurgy and Materials Engineering, Katholieke Universitiet Leuven.

For Bamboo fibre a 200 N Load Cell with screwed clamps was used.

Load used	:	200 N
The speed for this tensile test chosen	:	0.1 mm/min.
Sampling Mode	:	smart
Sample Freq	:	2 point/sec

Figure 3-6: Mini Tensile Testing Machine

A Micro processor based 4 channels AE system (Vallen AMSY 5 system (Figure-3-7)) was used to monitor the AE signals during the tensile test as shown in. The system used included integrated transient recorders (Vallen TR) which record the waveform of the AE signal. This waveform could be used for comparison of AE data with failure mechanism.

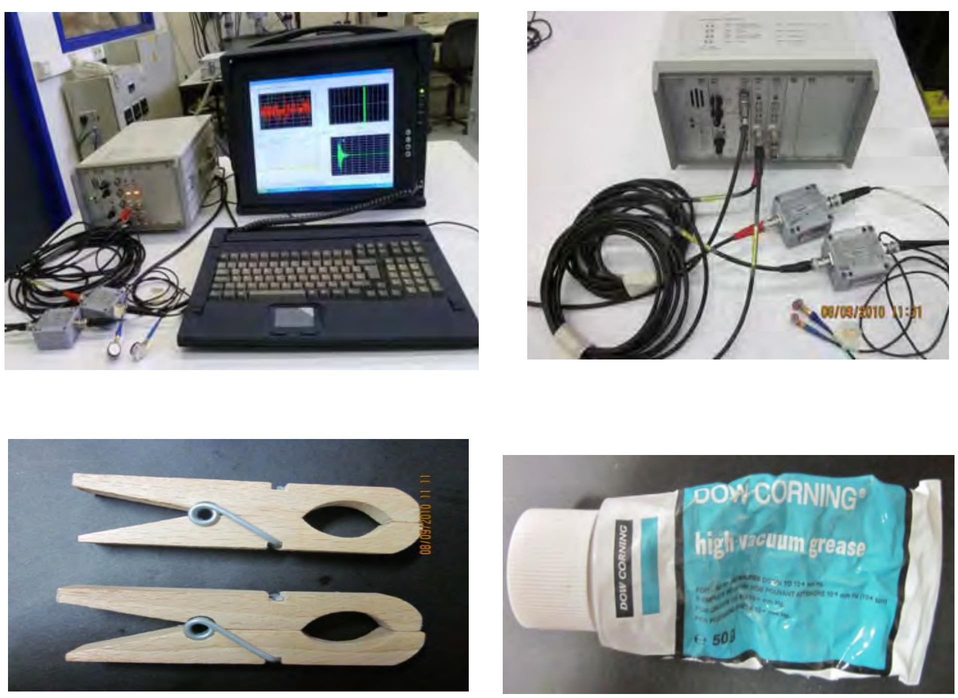


Figure-3-7: Vallen AMSY-5 system with accessories

Vallen AMSY-5 system	
Channels	4 (2x ASIP-2 board)
Parametric inputs	4
Processing speed	>100 000 hits/s
Preamplifier	AEP4 : 34dB
ASIP-2A: Dual Channel AE-Signal Processor	
Sampling rate	40 MHz
Resolution	18 bit
Bandwidth	1.6kHz to 2.4MHz
Input ranges	2.5Vpp, 5 Vpp,10 Vpp
Transient recorder	256MB/channel
AE sensors	
Digital wave B-1025	Broadband , 9mm
VS375,SE375	375 kHz , 20.5mm
VS30-V	30kHz , 20.5mm
AE105A	450-1150 kHz , 8mm
AE204A	100-800 kHz , 8mm

Nominal AE instrument settings parameters were:

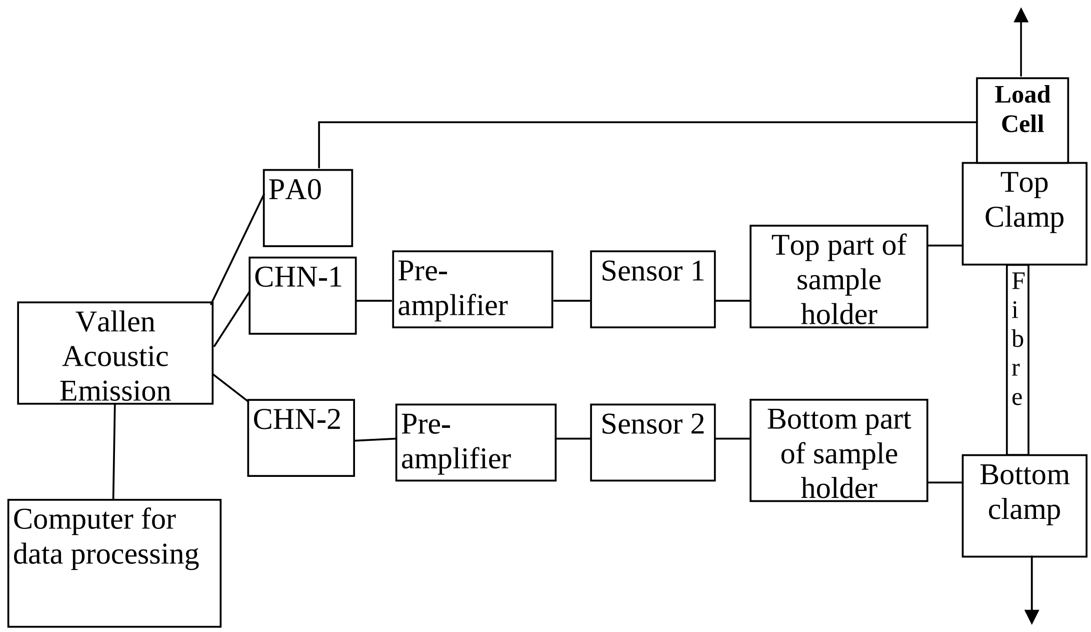
Sample rate for AE Data: 10 MHz
For TR Data: 5 MHz
Sample per set : 8192
Preamplifier gain : 34 dB
Pre-trigger sample : 1000
Sensors frequency : 0.1 to 3 MHz
Filter : 25 - 1600 kHz
Rearm time : 0.0992 µ Sec
Duration Discrimination Time: 99 µsec

Two AE sensors used with a wide range of frequency 100 KHz to 3 MHz [Model B1025 manufacturer: Digital Wave Corporation, USA]. A constant force wooden clamp was used to hold the sensors in place. Vacuum grease was used as the AE couplant for all tests.

AE signals detected by two sensors were counted and amplified by the preamplifier, passed through a filter of 25 kHz- 1600 kHz. The threshold voltage was set at 40 dB for sensor 1 and 27.9 dB for sensor 2. AE signals were analyzed by a 16 bit personal computer, and the AE parameters, such as the number of events, True energy (1 energy unit(eu)=1E-14V^2S), rise time, duration time and amplitude distribution, were obtained.
The Mini Tensile Testing machine was connected to the Vallen AE system by analog parameter inputs of load [N] and time [s]

3.1.6 Experimental Procedure:

Tensile testing of natural bamboo fiber was made with the above sample holder shown in figure: 3-1. Experimental setup (Figure 3-8) was done as shown in the chart below:



Flow chart for Experimental arrangement

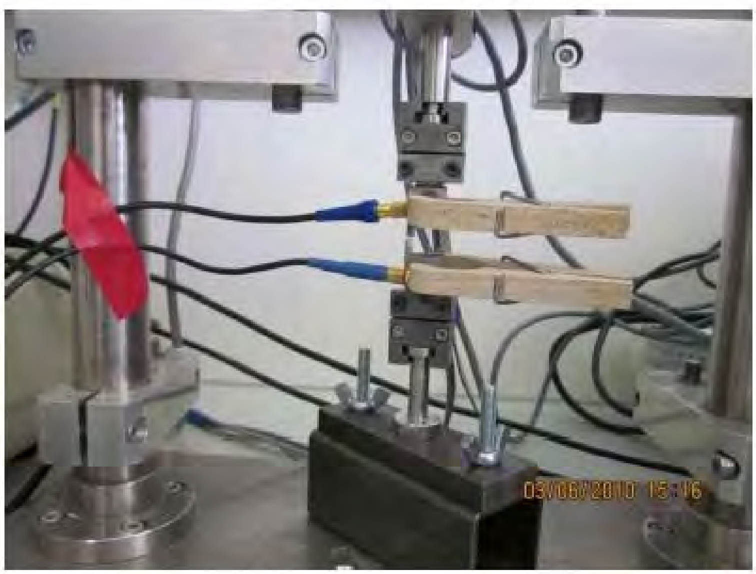


Figure 3-8: Experimental setup

During operation of both Mini Tensile and AE Equipment, it is needed to start the test simultaneously at the same time after setting required parameter.

At this moment tensile test were made on one span length (open area of sample holder), 10 mm. Depending on the clamping of Sample holder the span length is = 40 mm. But depending on glued area apparently it was seen that the free span length varies from 10 to 15 mm.

For this test setup 30 – 40 fibres were tested and only good ones are taken into account. Samples that broke near the edge of the clamps and the AE signal not received by both sensor at the same time were excluded from the analysis.

3.1.7 Experiment on Group Fibre:

Same sample holder and same set up was used for group (three) fibre (Figure 3-9) to understand AE signal from failure of individual fibre during tensile test.

Figure 3-9: Sample holder with three fibre

3.2 Preparation of SFC and analysis of failure behavior of SFC during tensile test by AE method

The researchers usually termed the Single Fibre Composite test as the fragmentation test. The present experimental work was intended to understand the failure of individual behaviour of fibre and matrix using AE Technique during tensile test.

For this experiment the following steps were done:

- Preparation of dog bone shape sample
- Arrangement of experimental setup for tensile test
- Observation of failure surface of SFC by scanning electron microscope

3.2.1 Preparation of dog bone shape sample

Specimen Materials

The matrix materials must have a sufficiently high strain-to-failure to ensure that the fiber completes its fragmentation process before the matrix fails.

Natural fibre : The fibers used in this experiment were bamboo single fibre extracted from bamboo culms (*Guadua angustifolia*) using a purely mechanical process (neither chemicals nor high temperature were used during the extraction). The diameter range for these fibres was between 90 and 250 µm;

Matrix : The resin used in these experiments was EPIKOTE resin 828 LVEL of Hexion, German, which was a medium viscosity epoxy resin.

Curing agents : The curing agent Dytek DCH-99 (Diaminocyclohexene) INVISTA, UK was used.

The failure strains of cured epoxy resin and fibre used in this research were 2.0% and 1.9% respectively.

Though the failure strain rate of fibre is approximately equal to matrix, Epikote resin was used as the polymer matrix, because from few previous experiment done at the lab of MTM, KU Leuven by other student, it was noted that EPIKOTE Resin 828 is more compatible for Bamboo fibers.

MOULD preparation for Dogbone Shape Specimen

Specimen moulds are necessary to make single fiber composite specimen. Moulds were made from silicone rubber compound (SILASTIC 3481 base and SILASTIC 81 curing agents), and a dogbone shaped iron plate was used for making dogbone shaped dents in the mould. The dogbone iron plate as shown in the following Figure 3-10 was attached to an aluminium sheet frame with double-sided tape.

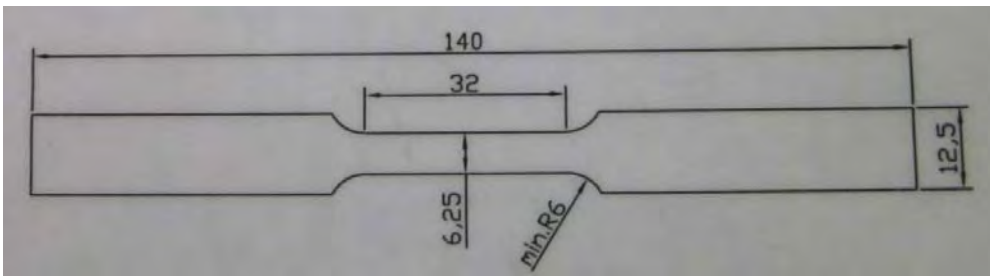


Figure 3-10: Schematic diagram of Dog bone shape specimen

Silicone was mixed with the curing agent (100:5 by weight) according to the product instructions. The mixing was done in a disposable plastic container. Thorough mixing of silicone and its curing agent was ensured. The mixed silicone was poured in the aluminium sheet frame template as shown in **Figure-3-11**. This process was done in room temperature for about 24 hrs. Then the silicone moulds were removed from the template and trimmed as needed.

Figure-3-11: Mould Preparation

Dogbone Shape Specimen preparation

Epoxy resin was mixed with the curing agent diaminocyclohexene at a ratio of 100:15.2 under vigorous stirring. As soon as the resin was mixed, the mixture was put inside a vacuum oven to ensure removal of gaseous matter from the resin and hardener mixture.

A single fibre was embedded in the center of a specimen mould. After the fiber was fixed on the mould, the mixture was poured cautiously using a syringe into the silicone mould, which had a fibre installed.

Some excess resin was required to prevent shrinkage away from the sides of the mould. In this research oven curing was done at 70^0 C for 1 h and then at 135^0 C for 1 h. Then the mould with sample was placed on a table at room temperature as shown in Figure-3-12.

Figure-3-12: Sample with Mold

A completed Single Fiber Composite (SFC) specimen is shown in Figure 3-13.

Figure 3-13: Dogbone shape SFC

3.2.2 Experimental setup for SFC:

The most common testing machine used in tensile testing is the universal testing machine model Instron 4467. This type of machine has two crossheads; one is adjusted for the length of the specimen and the other is driven to apply tension to the test specimen.

Dog bone shape sample was prepared in this way that after gripping both ends of sample, two probes could be placed. Specimens were tested in an Instron-4467. Acoustic emission monitoring was carried continuously using a Vallen AMSY-5 AE system by Vallen System GmbH.

15 SFC specimens were tested. The experimental setup is shown in the **figure-3-14.**

The parameters of Instron 4467 used during testing were as follows:

Load cell	:	5 kN
Cross head speed	:	0.85 mm/min
Sample rate	:	5 pts/s
Specimen gauge length	:	32 mm
Grip distance	:	90 mm

The AE acquisition settings used throughout the test were as follows:

Threshold	:	28.7 dB,
Rearm Time	:	0.0992 μ Sec,
Duration discrimination time	:	99 μsec
Preamplifier gain	:	34 dB.
AE sensors frequency	:	0.1 to 3 MHz

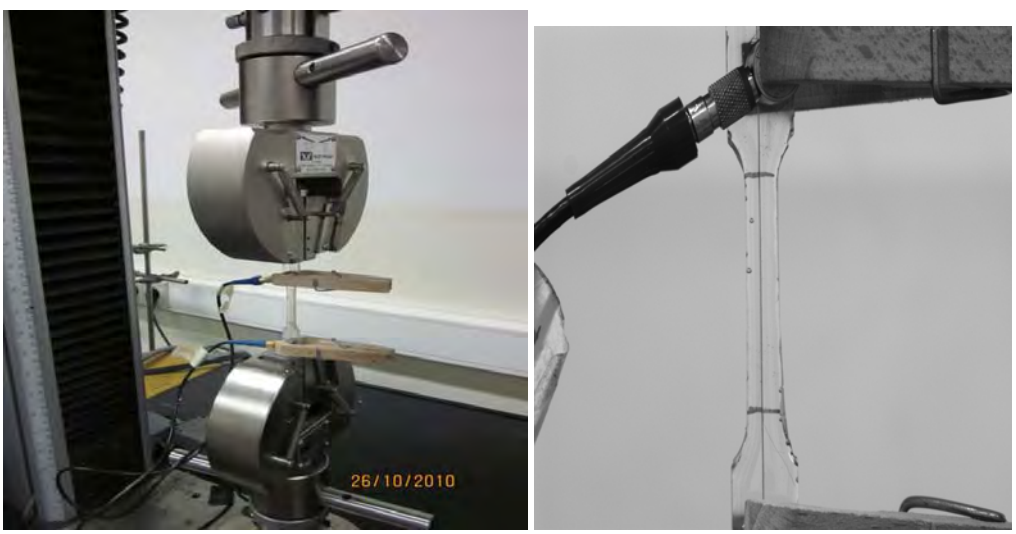


Figure-3-14: Experimental Setup for Dog bone shape sample at Tensile machine with AE Technique

Chapter-4: Result and Discussion

4.1 For Single Fibre Test

4.1.1 General:

From the mini tensile machine, the data time in sec, position in mm and force in Newton were **found** as a **.dat** format file along with the plotted graph as shown in figure 4-1.

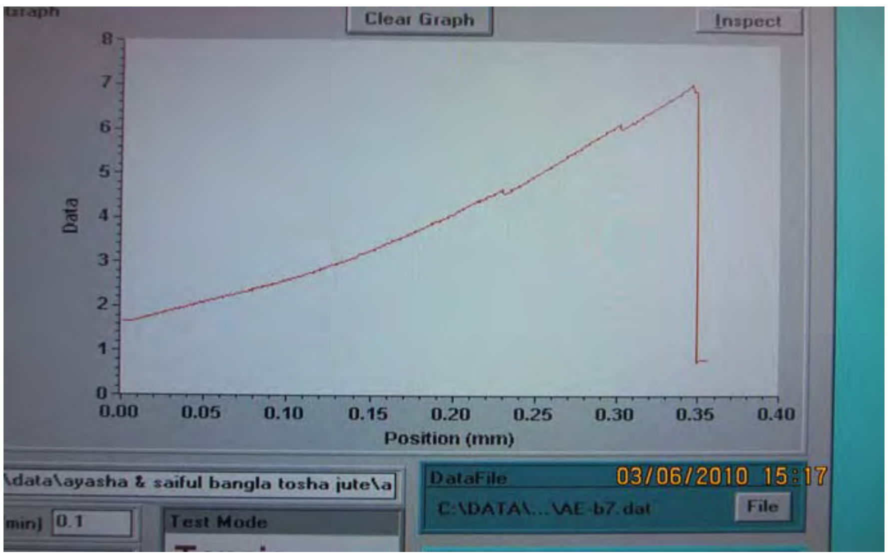


Figure 4-1:-Position Vs Load or Data graph

These data are transferred into Excel format. A Time Vs Load and strain Vs load graph can be drawn. These graphs are corrected according to the procedure mentioned in the paper [41] and the corrected Stress-Strain curve found.

From the AE equipment the following information for the tensile test found:

- Time Vs Hit Vs Load graph
- Time Vs load Vs Loc Event graph
- Time Vs Amp graph
- Amp Vs hit graph
- Time Vs Energy graph,
- Energy Vs Load graph

- Data set which include Counts, Rising time, Duration, Energy, Amplitude, Threshold Value, RMS value of AE signal etc.
- Wave form in the Time Vs Amp format, Spectrum in the form of Amp Vs Frequency Format
- The graph can be saved as .jpg/.bmp format or as a **.dat** format. For analyzing the data these graphs are saved as **.dat** format and then these data are transferred to excel format. From this excel sheet, the curves can be redrawn.

4.1.2. Justification of uses of Aluminium (Al) foil:

Usually researchers use a paper frame for single fibre tensile test. Since the purpose of the experiment is to use AE sensor to understand the failure behaviour, it is difficult to attach the sensor on the paper frame. Also it is difficult to use couplant on paper to attach the sensor and if sound passes through the paper most sound will be attenuated due to rough surface of paper. Moreover, during setting the sample holder with the sensor in the mini tensile machine most of the time the fibres had been broken before test. For this reason Al-foil was used as sample holder. Hence an Al strip was used to place the probe on the sample holder without tilting.

4.1.3. Analysis of AE Outcomes:

Tensile failure modes were observed directly by SEM whereas AE signals were monitored using a piezoelectric transducer placed on the sample holder. It could be very useful to combine the optical and nondestructive AE methods for evaluating the failure mechanisms of the natural fibre, since information obtained on microfailure could help interpretation of the results from the other techniques.

4.1.3.1 Co-relation between different parameter of experimental data

One of the primary goals of the single fibre test was to determine whether or if some characteristics of the AE from the fibre break could be correlated with the fracture load. It was observed from the Time Vs Load graph (**figure 4-2)** that there are a few load drops.

Moreover, it was observed from Time Vs Amplitude graph (**figure 4-3)** that there are few high peak signals among other amplitude signals.

In the Table 4-1 load, amplitude, duration, rising time, energy, location Event for different load drop of typical single fibre sample given:

Table 4-1: AE data for single fibre tensile test of typical sample

Sample No. b23	**Amp in dB**	**Stress in Mpa**	**No. Of Loc. Event**	**Rise time in µsec**	**Duration in µsec**	**Count**	**Energy in eu**
Load drop 1	82.5	517.51	1	61	3600	162	1.20E+05
Load drop / Final Breaking	99.9	623.76	4, 7	5	5825.6	532	1.60E+07

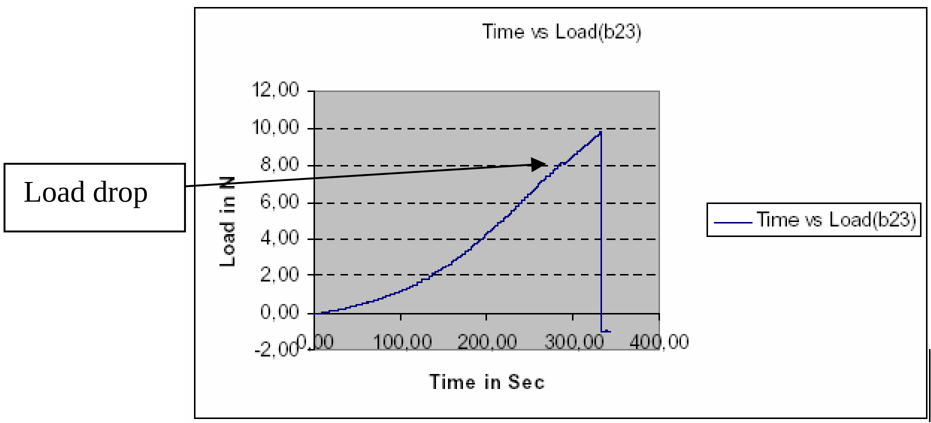


Figure 4-2: Time Vs Load

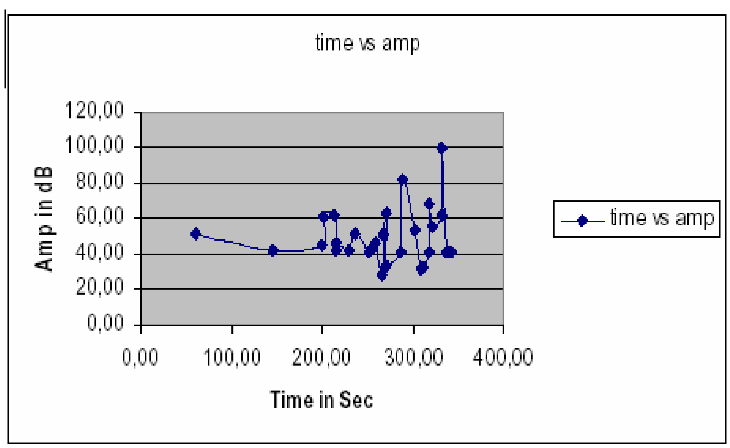


Figure 4-3:Time Vs Amplitude

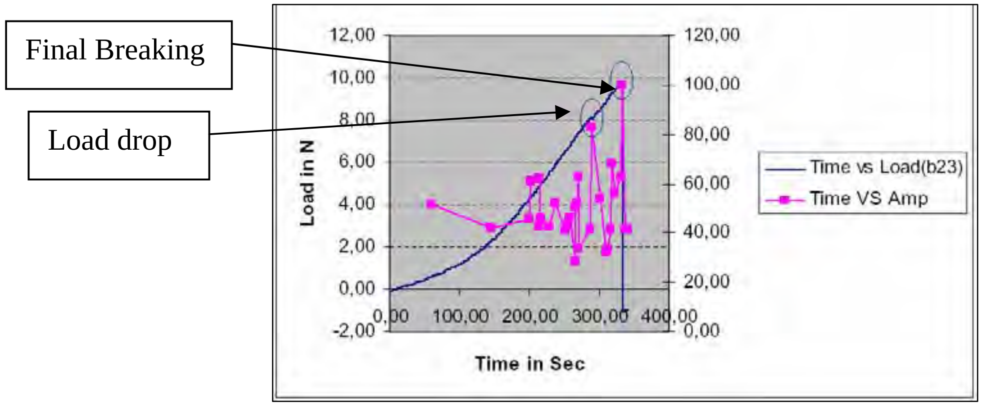


Figure 4-4: Relation between Time Vs load Vs Amplitude

When these two graphs were drawn side by side (**figure 4-4)** i.e. when load in primary y-axis and amplitude in secondary y-axis and time in x-axis it was observed that the high peak amplitude signal coincides with the load drop.

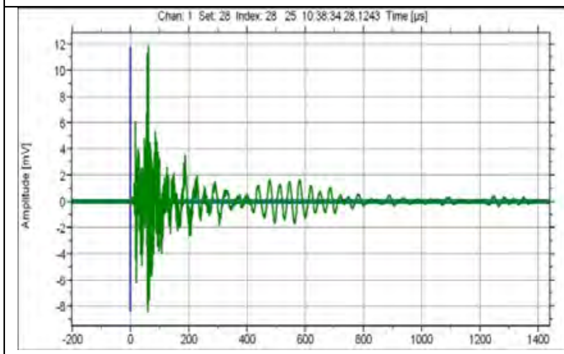
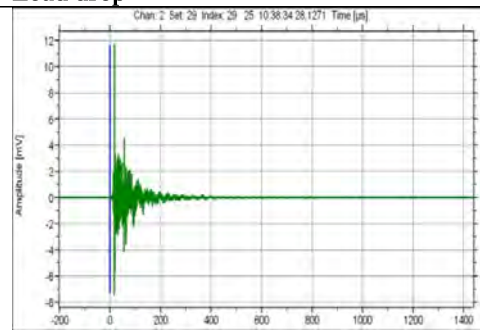
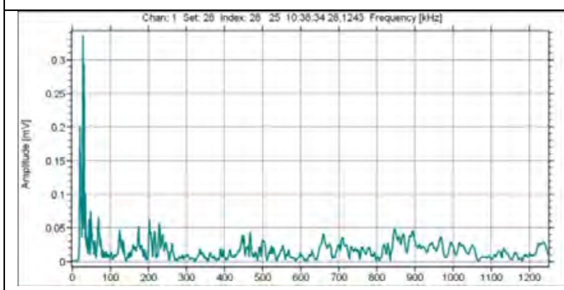
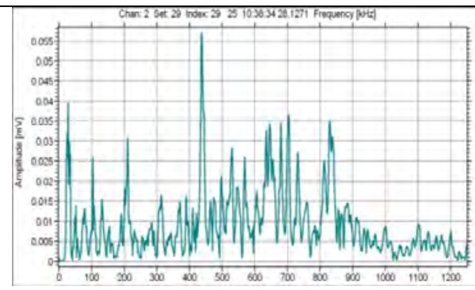
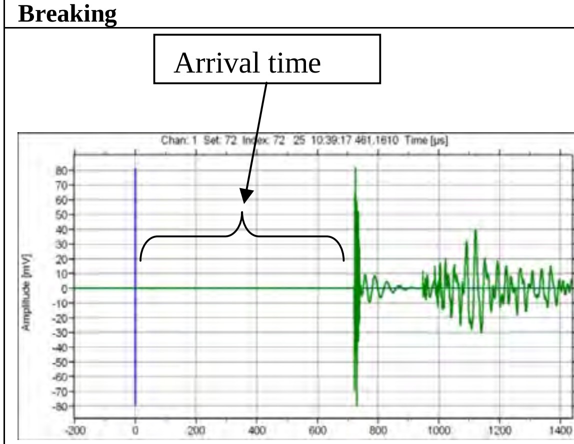
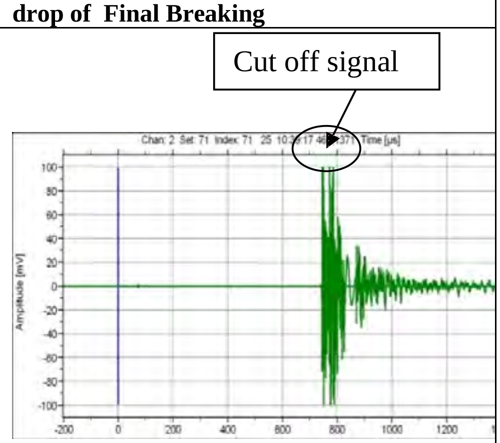
For other tested samples same coincidence of load drop and high energy or count or duration were observed when same type of graphs were drawn as time Vs load and time Vs energy or time Vs counts or time Vs duration of AE signal **(Please see the Appendix)**.

4.1.3.2 Wave form and Frequency Spectrum of AE signal:

For every sample wave form signals were recorded. Among these signal the waveform of different load drop and final breaking were extracted and summarized in the following figure **4-5** for a typical sample. The distances between two channels i.e. two sensors were approximately 20 mm. Depending on the distance of sensor from the breaking zone of fibre the wave form is little bit different in different channel. It was observed that the wave form for final breaking was totally different. For breaking case the wave starts after some time, which is called arrival time. The amplitude value was higher than 99.9 dB. In this case cut off signal was found. The gain of preamplifier that was used for the experiment was 34 dB. It has some limitation. It is saturated at 100 dB. For this reason it was not possible to find the exact energy and amplitude value during final breaking.

From frequency spectrum it seemed that higher resonance frequency was found for Initial or second load drop zone. And for final breaking the resonance frequency was lower.

In near future more analysis can be done using wave form or frequency analysis**.**

<table>
<tr><td>Chn-1 Wave form and Frequency Spectrum for typical sample (B23) at 1st Load drop</td><td>Chn-2 Wave form and Frequency Spectrum for typical sample (B23) at 1st Load drop</td></tr>
<tr><td></td><td></td></tr>
<tr><td></td><td></td></tr>
<tr><td>Chn-1 Wave form and Frequency Spectrum for typical sample (B23) at Load drop of Final Breaking</td><td>Chn-2 Wave form and Frequency Spectrum for typical sample (B23) at Load drop of Final Breaking</td></tr>
<tr><td>
</td><td>
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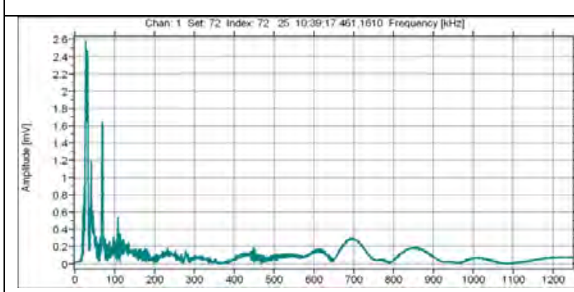
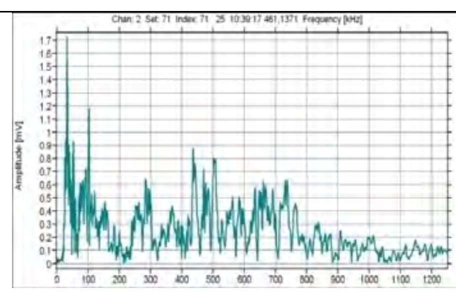
<tr><td></td><td></td></tr>
</table>

Figure-4-5: Wave form and Frequency Spectrum for typical sample

4.1.4 Observation of Fibre Failure surface by Scanning Electron Microscope (SEM):

After tensile test the fibre failure surface was observed by SEM. During SEM it was tried to observe the fibre breaking depending on load drop i.e. whether the no. of load drop zone was similar the no. of different failure area. From SEM image it was observed that the fibre breaking was brittle type. In the Following Figure 4-6 SEM of for typical sample shown:

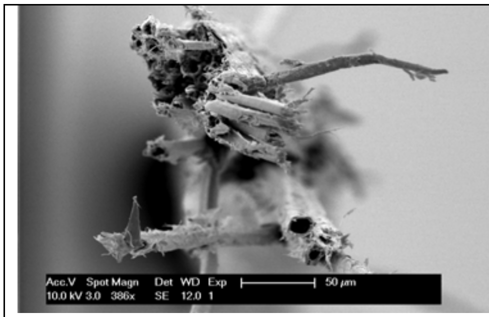
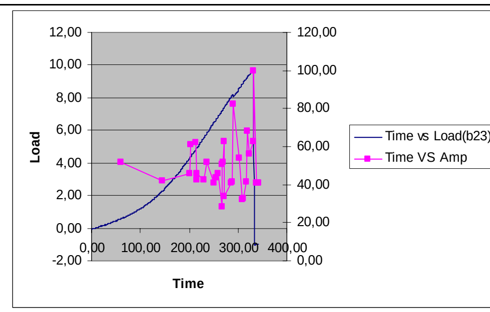
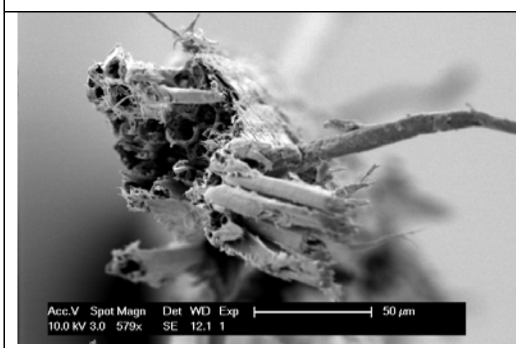
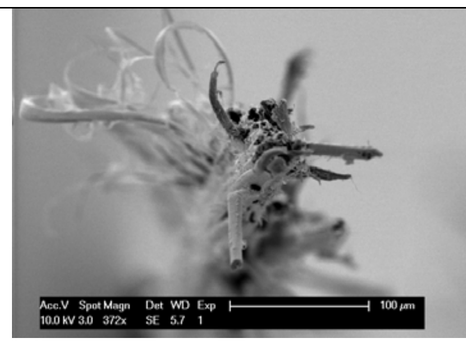
 SEM Image for Sample No b23	 Graph for Sample No b23
 SEM Image for Sample No b23	 SEM Image for Sample No b23

Figure 4-6 SEM imgae for typical sample

4.1.5 **Tensile Test of Group Fibre:**

To understand the AE signal from individual fibre breaking during tensile test, same type of sample holder was used for a bundle of fibre (i.e. three technical fibres). From graph (**figure-4-6),** it was observed that each fibre broken at saturated amplitude value i.e. 99.9 dB. For first two fibres it was also observed that one or two load drop present before final breaking.

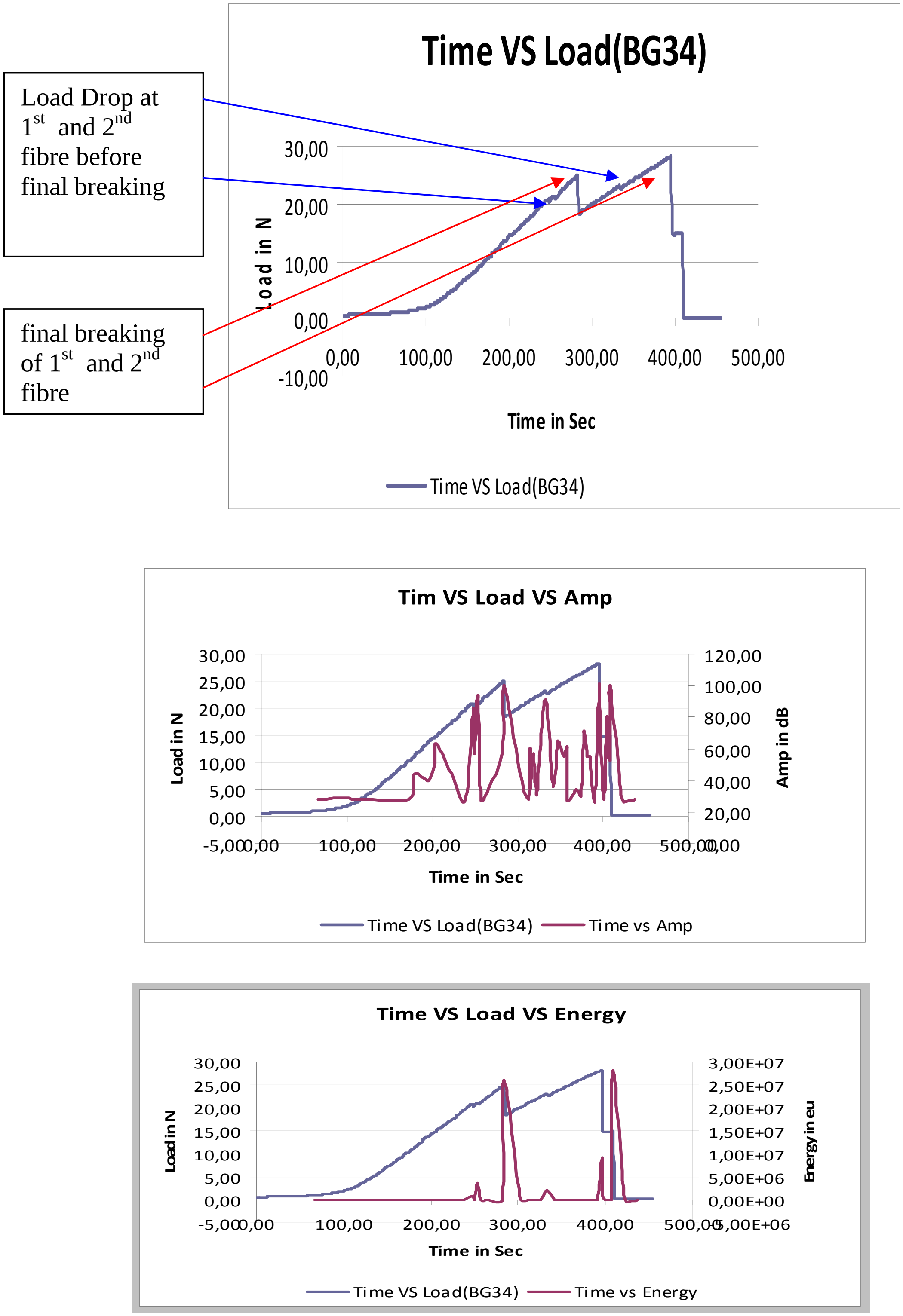


Figure-4-7: Relation between Time Vs load Vs Amplitude for Group Fibre

In the following Table 4-2 load, amplitude, duration, rising time, energy, location Event for different load drop of typical group fibre sample given:

Table 4-2 AE data for Group fibre tensile test of typical sample

Sample No. BG34	**Amp in dB**	**Load in N**	**No. Of Loc. Event**	**Rise time in µsec**	**Duration in µsec**	**Count**	**Energy in eu**
Fibre-1 : Load drop 1	62.93		2	1035.6	3339.2	140	1.95E+04
Fibre-1 : Load drop 2	93.79		2	43.0	3619.2	116	3.47E+06
Fibre-1 : Load drop/ Final breaking	99.9	24.88	2	4116.8	10672.0	829	1.66E+07
Fibre-2 : Load drop 1	91.16		1	202.6	2702.4	85	2.00E+06
Fibre-2: Load drop/ Final breaking	99.9	28.19	16	239.4	5384.0	273	4.36E+06
Fibre-3: Load drop/ Final breaking	99.9	14.89	2	33.0	6188.8	226	2.09E+07

From this data it is observed that breaking of individual fibre could be identified by AE method.

4.1.6. Discussion on Experimental Result

Assumption-1:

As we know from basic theory of AE that when a material starts breaking, it starts making sound. Depending on area or part of breaking the amplitude of the sound is varying. And during final breaking it produces high sound. From **figure 4-4** it is observed that initially in the first load drop the amplitude is lower than the other successive load drop.

In Table 4-1 load, amplitude, duration, rising time, energy, location Event for different load drop of typical sample given.

From this data it was seen that during final breaking the amplitude of the signal crosses the threshold value as the value (at saturation) of the pre-amplifier is 100 dB.

It is possible that the initial load drop for transverse cracking of a single elementary fibre could be initiated from some surface defects and the successive other high peak signals for debonding between two elementary fibre and final breaking of group of elementary fibre. Though in the Time Vs Amplitude curve there are more low amplitude signal, it seemed that the other signals could come for some micro cracking or fibril splitting.

Assumption 2:

The structure of natural technical fibre composed of several highly oriented elementary fibres made of cellulose and hemicelluloses as shown in the **figure-4-8**. They are bonded together by other materials such as lignin, hemicelluloses, water and extractives. The cellulose is defined as a linear, crystalline polymer composed of 1-4 linked Beta-D glucopyranose and can respond to high stress, where as hemicelluloses can respond to lower tensile stress due to their less oriented and inhomogeneous properties. Thus it seemed that the initial load drop in the time Vs load curve could come for failure of hemicellulose part and yields little bit lower distinct amplitude signal and the final breaking is due to failure of cellulose part and yields distinct higher amplitude signal.

Assumption-3:

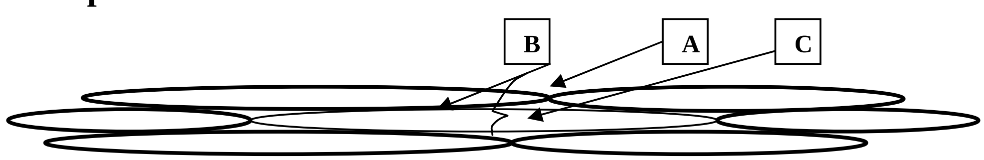


Figure-4-8: Morphological structure of Natural fibre(Bamboo)

Also depending on the position of external joint between two elementary fibres, the fibre failure could be started transversely (position-A) as shown **in figure-4-8**. The lower amplitude signal could be from this type failure of joint. Then debonding starts between adjacent elementary fibre (Position–B) and the distinct higher amplitude signal can be from this type of debonding failure (in the load drop). Then the final breaking happened at elementary fibre zone (Position C).

Assumption-4:

The experimental results for jute and Hemp fibre showed that the amplitude and the energy of AE signals emitted by the fracture process of high strength fibers are significantly higher than those of low strength fibres. It may be because the micro failure process of the high portion could occur through the crystal areas; where as one of the low portion occurred through the amorphous areas.

It could be assumed that at the initial load drop the fracture starts from amorphous zone and gives lower amplitude signal. Final fracture zone could occur at crystal areas of bamboo fibre and gives higher amplitude signal.

Assumption-5:

In the SEM picture different probable transverse breaking zone of elementary group fibre observed. From the SEM picture it seemed that different detectable lower amplitude value yields from some failure of elementary fibre or micro fibril or debonding of different part of fibre through the length.

4.2 For Single Fibre Composite (SFC) Test

From the Time Vs Load graph as shown in figure 4-10, gradual transition from elastic to plastic behaviour of SFC sample observed. The sample was broken during tensile test shows the brittle nature with little plasticity.

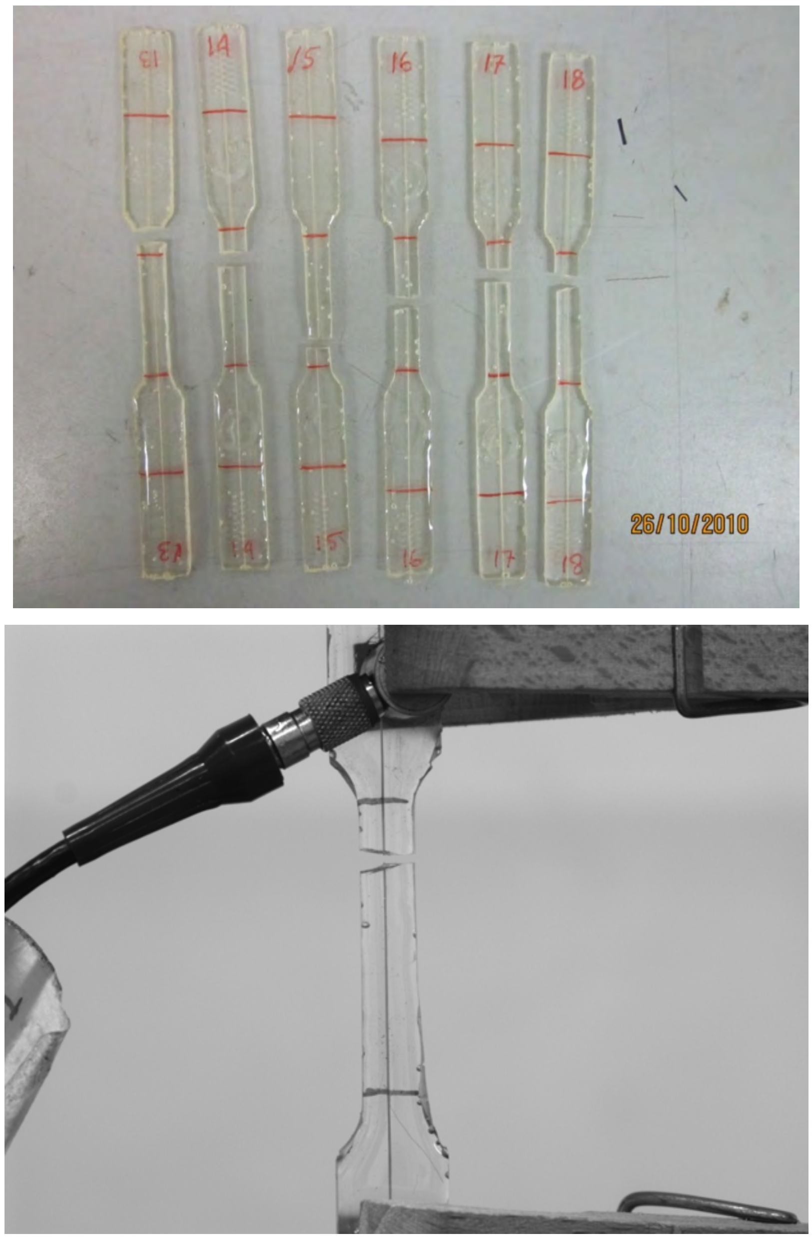


Figure-4-9: Failure SFC sample after Tensile Test

In the following Table 4-3 load, amplitude, duration, rising time, energy for final breaking of typical sample given:

Table 4-3: AE data for tensile test of typical sample of single fibre composite

Sample No.	Amp in dB	Load in kN	Rise time in μsec	Duration in μsec	Count	Energy in eu
Sample No. SFC 8						
Load drop / Final Breaking	99.9	3.72	313.8	867.2	35	9.89E+07

(For other samples Please see Appendix-B)

4.2.1 Analysis of AE Outcomes:

From the following graphs for different sample it was observed that fibre and matrix failure happened approximately at the same time.

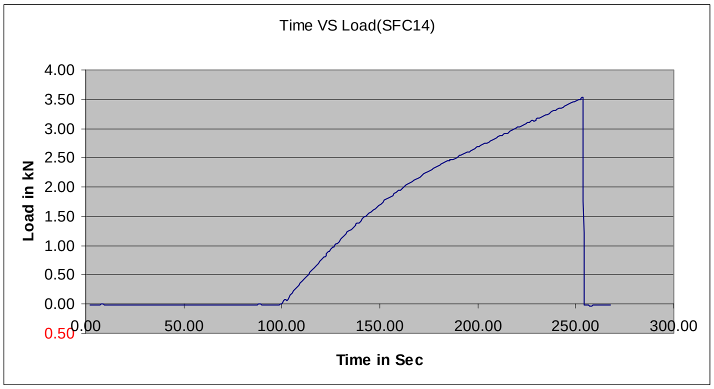


Figure 4-10: Time Vs Load graph for typical SFC sample

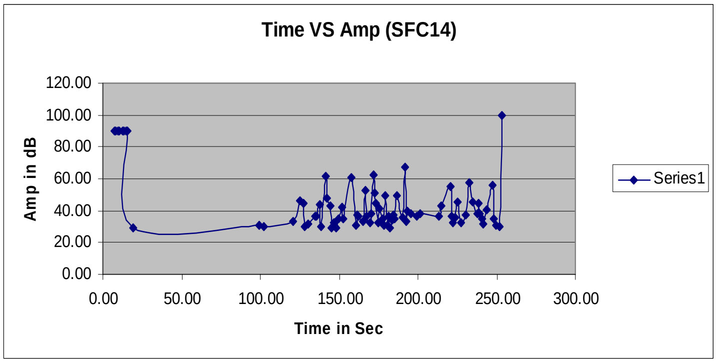


Figure 4-11 Time Vs Amplitude graph for typical SFC sample

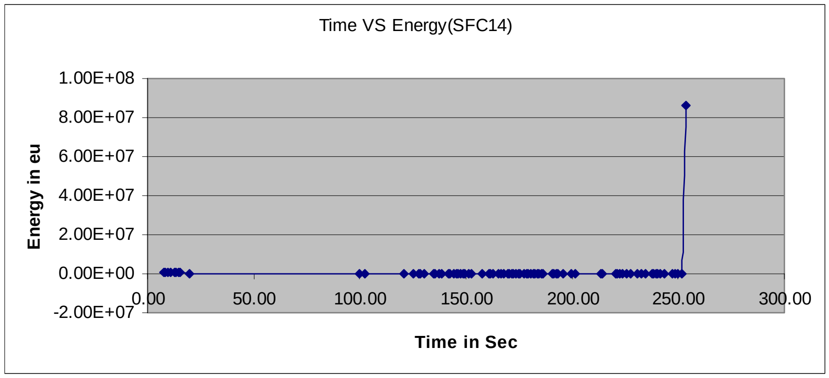


Figure 4-12: Time Vs Energy graph for typical SFC sample

For every cases Amplitude exceed the threshold level (99.9 dB) of pre-amplifier. So it was not possible to measure the exact amplitude for failure of fibre-matrix. Before final failure of SFC it was observed that few signals are found within the amplitude range 31-60 dB. It could be for the multiple cracking of matrix.

For other tested samples same coincidence of final failure with high amplitude and high energy were observed when same type of graphs were drawn as time Vs load and time Vs energy and time vs Amp **(Please see the Appendix)**.

4.2.2 Wave Spectrum for final Breaking

From the following spectrum it was observed that for every sample Chan -1 and Chan-2 received different type of signal.

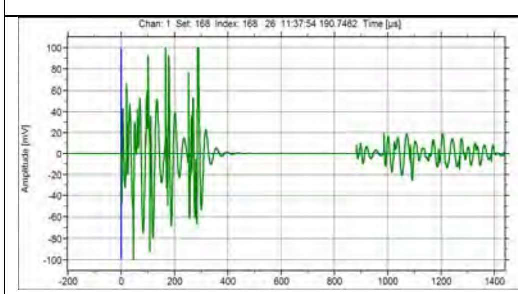
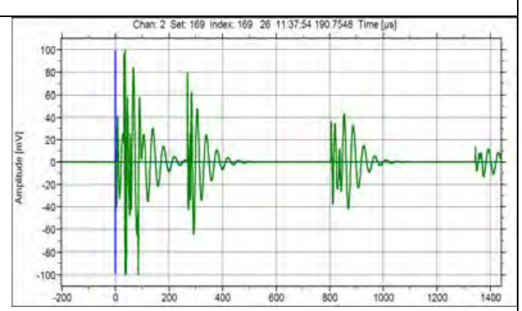
Spectrum for final Breaking for SFC14 Chan-1	Spectrum for final Breaking for SFC 14 Chan-2
	

Figure 4-13 ***Wave Spectrum for final Breaking of typical sample***

4.2.3 Observation of Failure surface of SFC by SEM:

After tensile test the failure surface of SFC was observed by SEM. In the Following Table- SEM of few samples are shown:

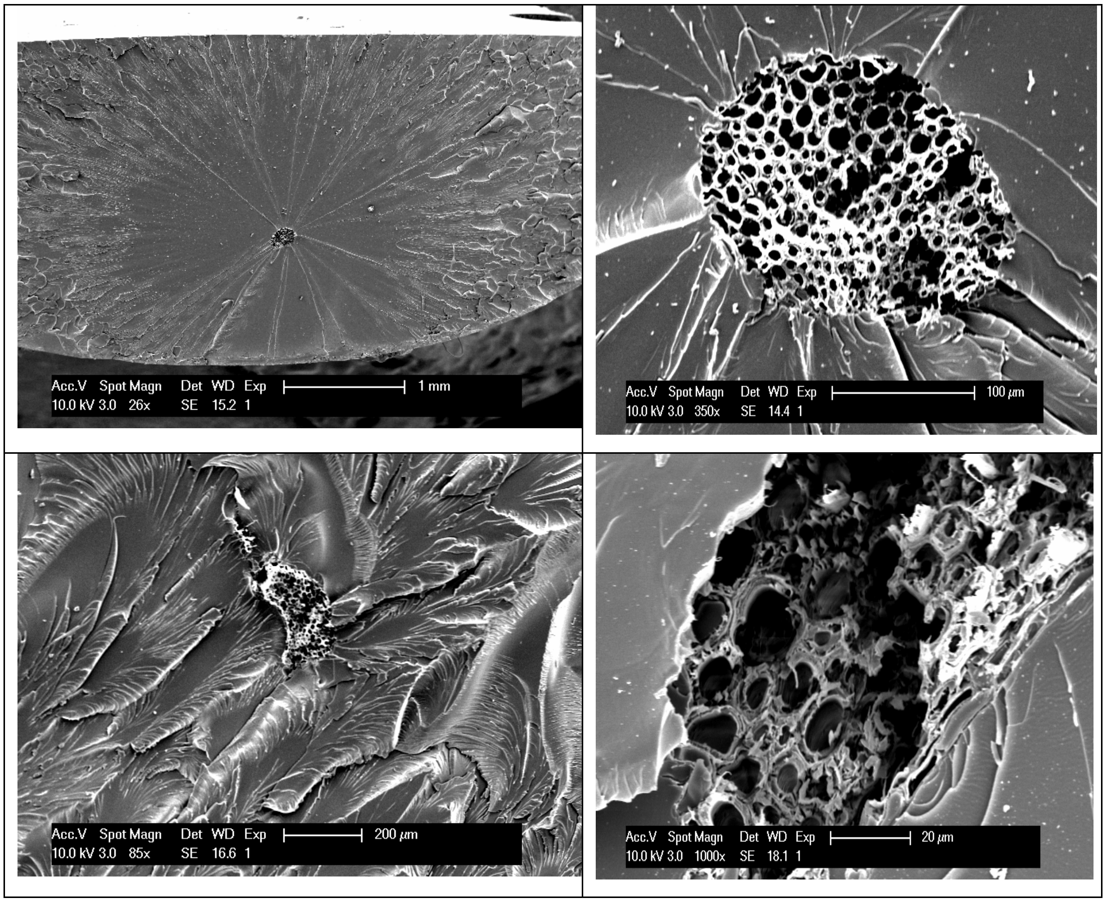


Figure 4-14: SEM image of Failure SFC sample after Tensile Test

From SEM image it was noticed that the fibre-matrix breaking was brittle type and no evidence of fiber-matrix debonding was observed.

Chapter 5: Conclusion and Recommendation

5.1 For single fibre tensile test:

5.1.1 Conclusion:

Understanding the mechanical behavior of natural fibre and its polymer composite is essential to form a well suited composite. In the present days among the different non-destructive testing methods Acoustic Emission is a suitable tool for detecting and evaluating and for better understanding the damage mechanism and failure behavior in composites during mechanical loading. Hence it is necessary to study the fracture and failure behavior of the single fibres separately. To understand the failure behavior of single fibre is critical.

The present research deals with bamboo single fibre and bamboo single fibre composite. Methodology was developed for natural single fibre tensile test with Acoustic Emission (AE) to assess or monitor the tensile failure behaviour of natural fibre especially for Bamboo single fibre. Series of experiment performed with this methodology. One of the primary goals of the single fibre test is to determine whether or if some characteristics of the AE from the natural fibre break could be correlated with the fracture load.

- It is possible to detect the natural single fibre breaking or failure with the time of occurrence of each fibre using AE method and could be correlated with the fracture stress of a natural single fibre with some characteristics of the associated AE signal.
- From the graph Time Vs Load Vs Amplitude of experimental data clear correlation between few load drop (one or two) with corresponding high amplitude signal among other amplitude signals before the final breaking was observed. From the experimental data it was observed that for the load drop the value for load was not consistent. The value of load at first load drop for a particular sample is 8N (stress: 517.51 MPa)
- Final breaking of single fibre gives saturated value (since the saturated value for preamplifier is 99.9 dB) of high amplitude signal for all experiment. So it was not possible to get the actual value of AE signal amplitude for final breaking.

- The load drop before final failure of fibre could be initiation of failure of fibre.
- Multiple fibre (three fibre) test with the developed methodology give the clear indication to identify the load drop of single fibre failure by AE. Three fibres takes about the three times load of single fibre for final breaking (though the value was not consistent for all sample).
- From the SEM of fibre fracture surface and the graphs it is observed that the fibre fracture is brittle type.
- To understand the initiation of fibre breaking or failure clearly by AE technique more experiment is needed.
- The developed methodology can be used for understand the tensile failure behavior of other natural single fibre using AE technique.

5.1.2. Recommendations:

1:-

If it is possible to test the sample using preamplifier with lower gain dB than 34 dB, it may be possible to get the exact energy value and amplitude value for final breaking.

2:-

If it is possible to do the SEM during tensile test then the fibre characteristics may be clearly observed and correlated with Acoustic Emission data. The test could be done as follows:

After arranging the set up for SEM and tensile test, at first the fibre should be tested by SEM before starting tensile test. During tensile test when load drop observed in the graph, immediately stop the test and do the SEM again to understand the reason for load drop. In this way again start the test and do the SEM for other load drop and finally observe the fracture surface by SEM. In this way it could be possible to understand the initiation of fracture.

3:-

In future it could be possible to analyze the fibre failure using frequency spectrum and wave form of AE data**.**

4:-

To understand the initiation of fibre breaking or failure clearly by AE technique more experiment is needed.

5.2 For Single Fibre Composite (SFC) Test

5.2.1 Conclusion:

Tensile test of Single Fibre Composite is used to assess the fibre matrix debonding. Our aim was to discriminate fibre breaking and matrix breaking by acoustic emission during tensile test.

- It is observed that since the experiment done with about same strain rate type fibre (strain to failure for bamboo single fibre is 1.9%) and matrix (Strain to failure of Matrix ~ 2%) the fibre and matrix were broken approximately at the same time. Individual Fibre breaking and matrix breaking could not be observed.
- It was also observed from SEM image that fibre-matrix fracture surface was brittle type and no evidence of fiber-matrix debonding was observed. The Time vs load graph and AE data also gave the same indication of fibre-matrix failure.

5.2.2 Recommendations:

- If the matrix strain to failure rate is higher than fibre it could be possible to discriminate the breaking of fibre and matrix.

- To understand the fibre matrix debonding or identify the individual matrix breaking and fibre breaking or failure from tensile test of SFC by AE technique more experiment is needed.

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Chapter-7: Appendices

Appendix-A: Data for Single Fibre Test

Table 7-1: AE data for Single fibre tensile test of other samples

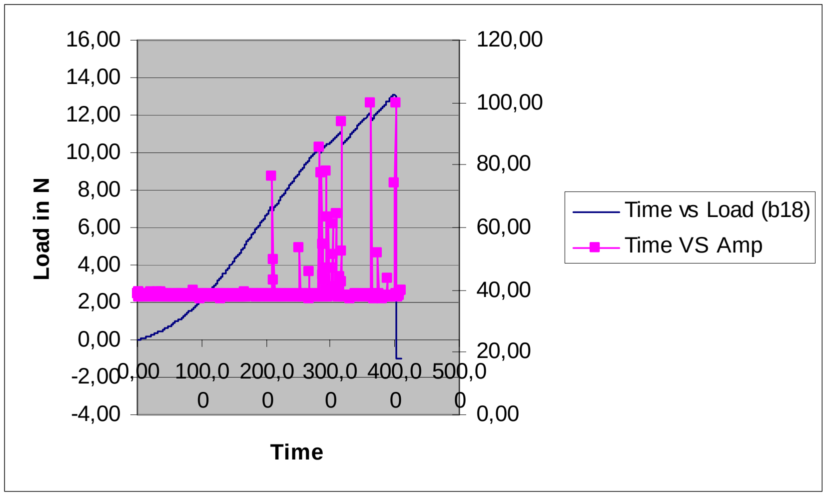
Sample No.	**Amp in dB**	**Stress in Mpa**	**No. Of Loc. Event**	**Rise time in µsec**	**Duration in µsec**	**Count**	**Energy in eu**	**Diameter (µm)**
B22								117.07
Load drop 1	89.27	426.11	1	9.2	1623.2	248	6.03E+05	
Final Breaking	99.9	602.5	6	1090.4	7843.2	746	1.99E+07	
B23								141.05
Load drop 1	82.5	517.51	1	61	3600	162	1.20E+05	
Load drop / Final Breaking	99.9	623.76	4, 7	5	5825.6	532	1.60E+07	
B24								127.03
Load drop 1	82.88	350.33	2	21.4	2304.8	94	1.16E+05	
Final Breaking	99.9	450.94	7	200.4	9712	597	3.08E+07	
B25								141.05
Load drop 1	67.45	556.13	1	93.4	1032	93	6.99E+03	
Load drop 2	85.51	670.97	2	19.2	1739.2	80	6.37E+05	
Load drop / Final Breaking	99.9	683.53	6	745.8	9961.6	572	4.29E+07	
B26								142.61
Load drop 1	65.94		1	16.4	680.6	131	3.79E+03	
Load drop 2	83.25	564.73	1	40	2588.8	206	8.55E+04	
Load drop / Final Breaking	99.9	735.76	4	902.8	6462.4	500	4.17E+07	
B 27								105.13
Load drop 1	96.8	498.36	1	194.4	4520	234	1.51E+07	
Load drop 2	86.64	551.82	1	457.4	2055.2	479	3.22E+05	
Load drop / Final Breaking	99.9	608.31	5	596.6	10659.2	1324	7.02E+07	
B28								135.45
Load drop 1	77.61	209	1	13.4	1666.4	107	8.06E+04	
Load drop / Final Breaking	99.9	468.34	12	245.6	10102.4	616	4.36E+07	
B 30								153.07
Load drop 1	99.9	477.96	1	48	6825.6	318	2.84E+07	
Load drop 2	85.89	690.86	2	53.4	3715.2	327	4.11E+05	
Load drop/Final breaking	99.9	733.93	3	5848	13888	1081	5.32E+07	

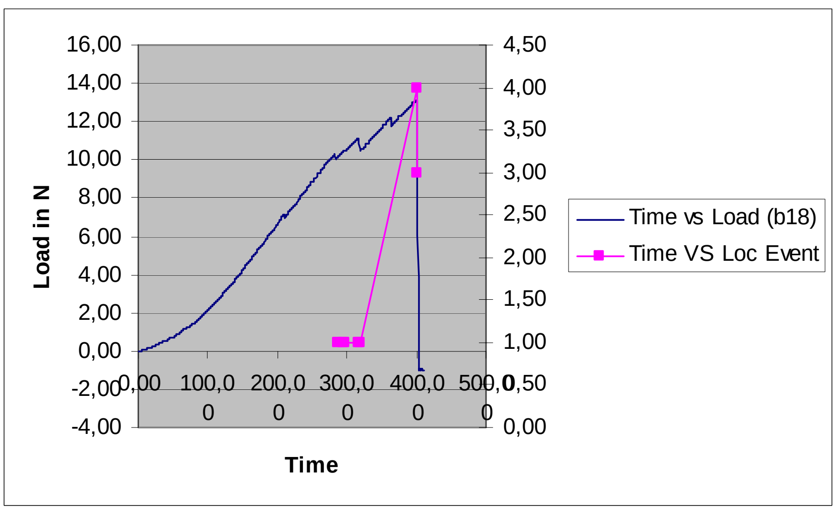
Sample No.	**Amp in dB**	**Stress in Mpa**	**No. Of Loc. Event**	**Rise time in µsec**	**Duration in µsec**	**Count**	**Energy in eu**	**Diameter (µm)**
B 31								181.48
Load drop 1	99.9	671.74	1	7.4	6752	379	2.80E+07	
Load drop 2	94.92	893.48	1	2.8	5121.6	392	3.06E+06	
Load drop / Final Breaking	99.9	865.24	6	503	8521.6	626	3.13E+07	

Graphs:

Time VS Load VS amplitude, Time VS Load VS Loc Event, Time VS Load VS energy graphs for single fibre test of others sample

Sample B18





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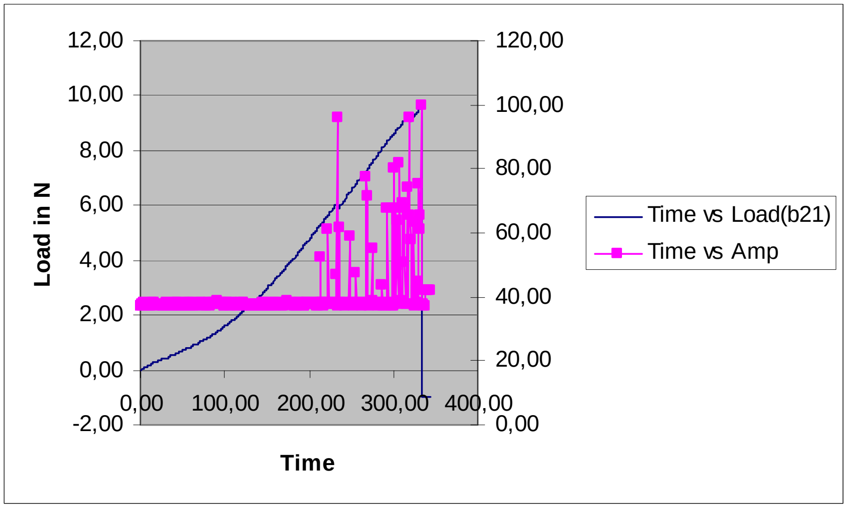
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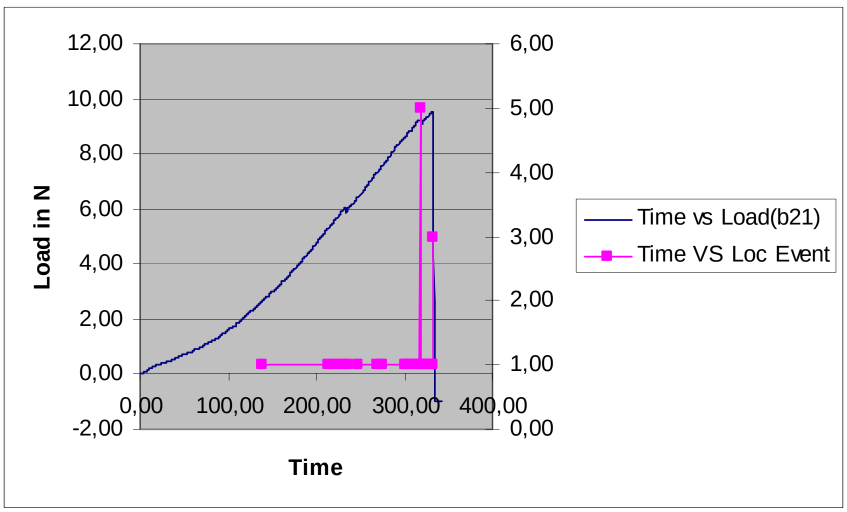
Time
Time vs Load(b21)
Time vs Amp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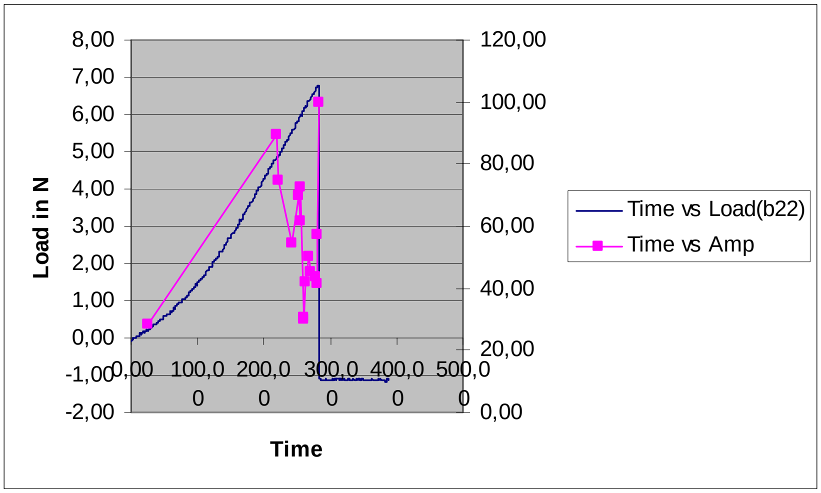
Time
Time vs Load(b21)
Time VS Loc Event

Sample B22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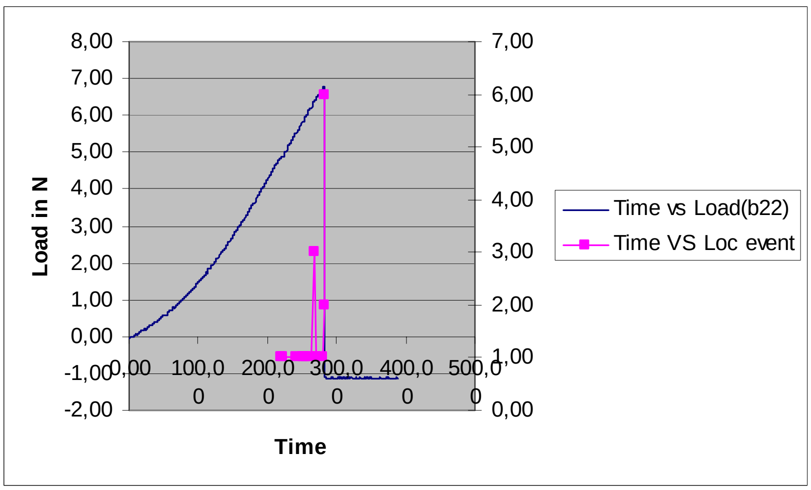
Time vs Load(b22)
Time vs Amp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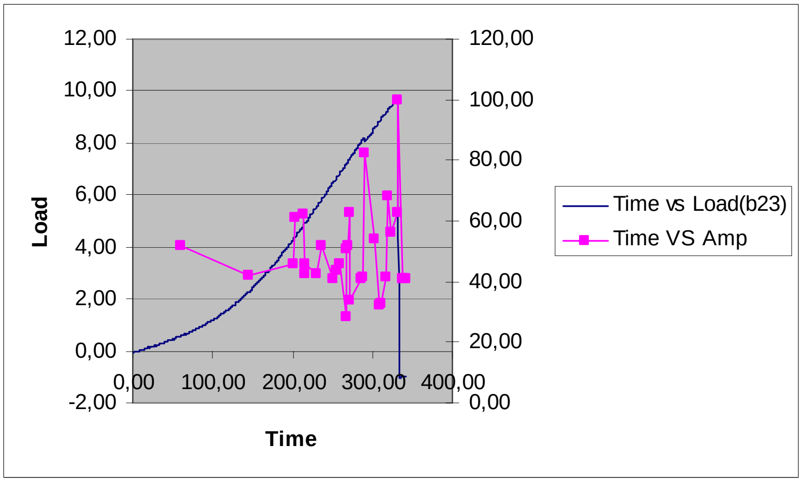
Time
Time vs Load(b22)
Time VS Loc event

Sample B23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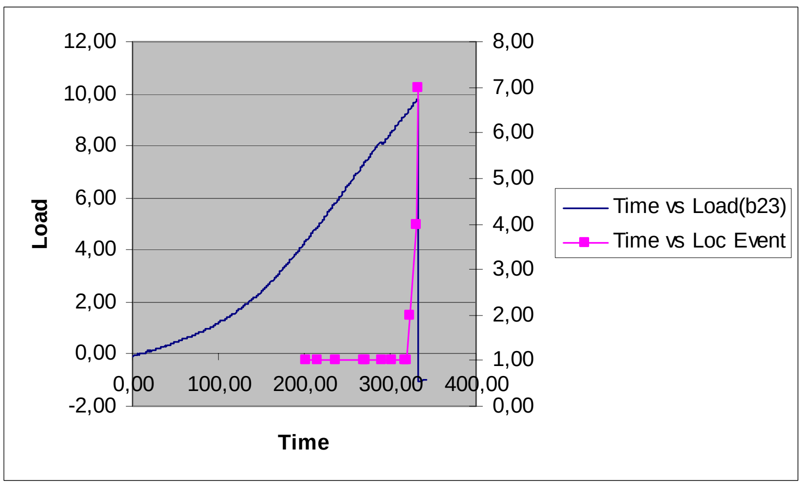
Time
Time vs Load(b23)
Time VS Amp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Time
Time vs Load(b23)
Time vs Loc Event

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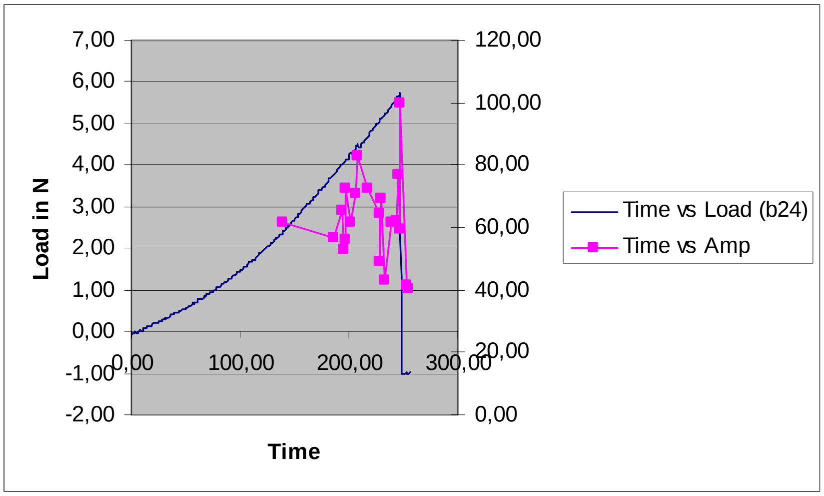
Sample B24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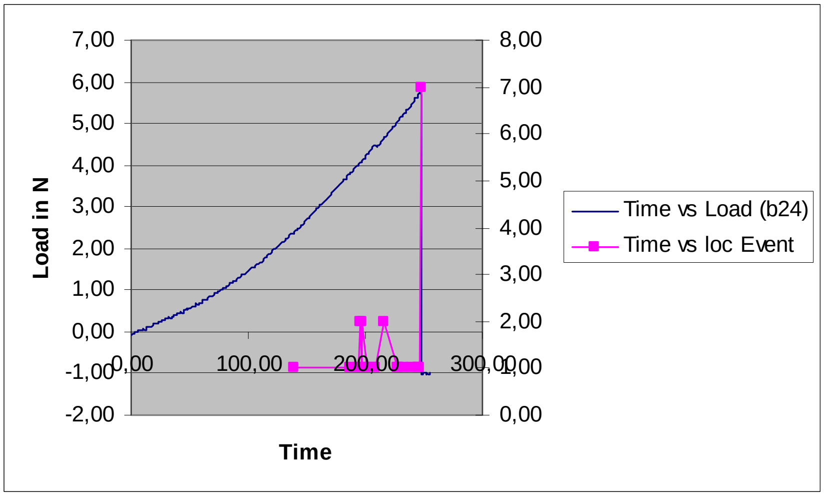
Time vs Load (b24)
Time vs Amp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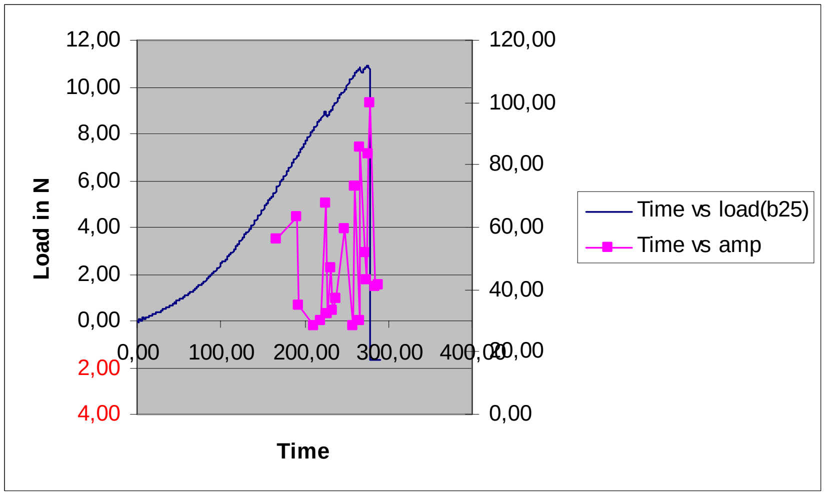
Time vs Load (b24)
Time vs loc Event

Sample B25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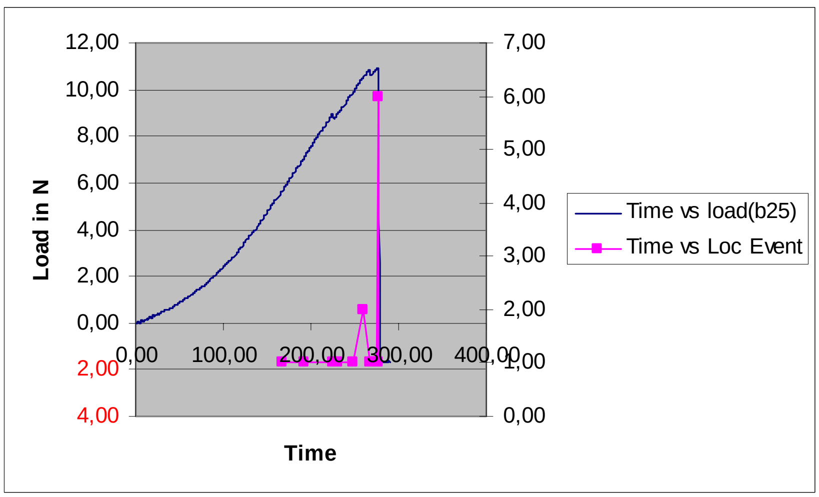
Time
Time vs load(b25)
Time vs amp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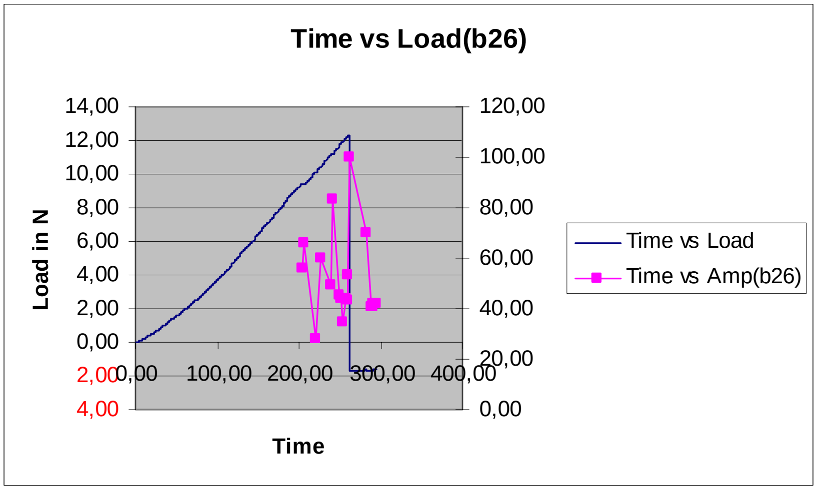
Time
Time vs load(b25)
Time vs Loc Event

Sample B26


Time vs Load(b26)
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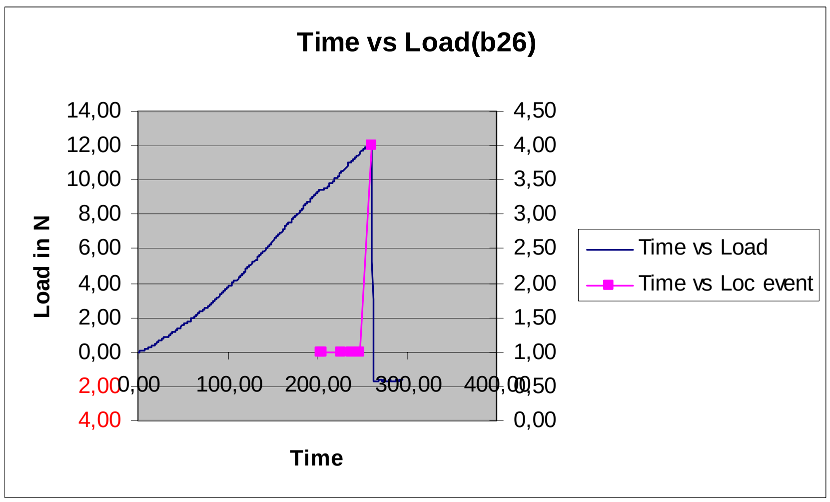
Time vs Load
Time vs Amp(b26)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400,00
Time
4,50
4,00
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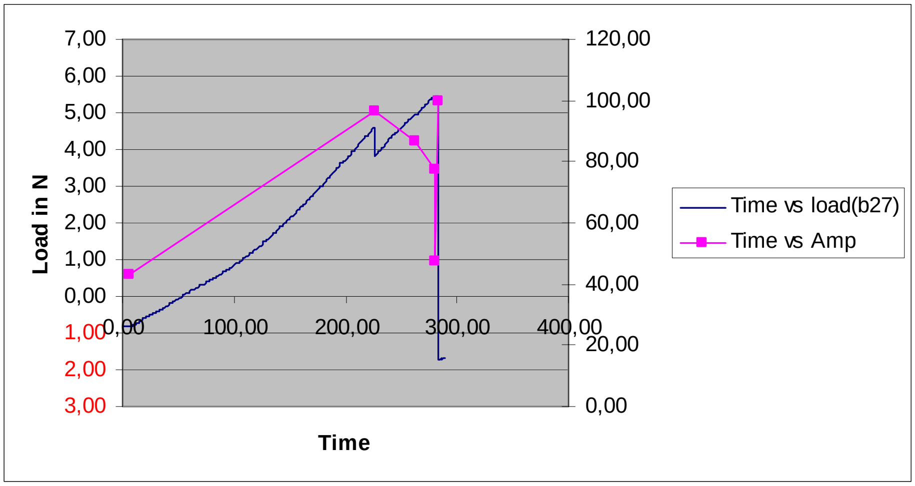
Time vs Load
Time vs Loc event

Sample B27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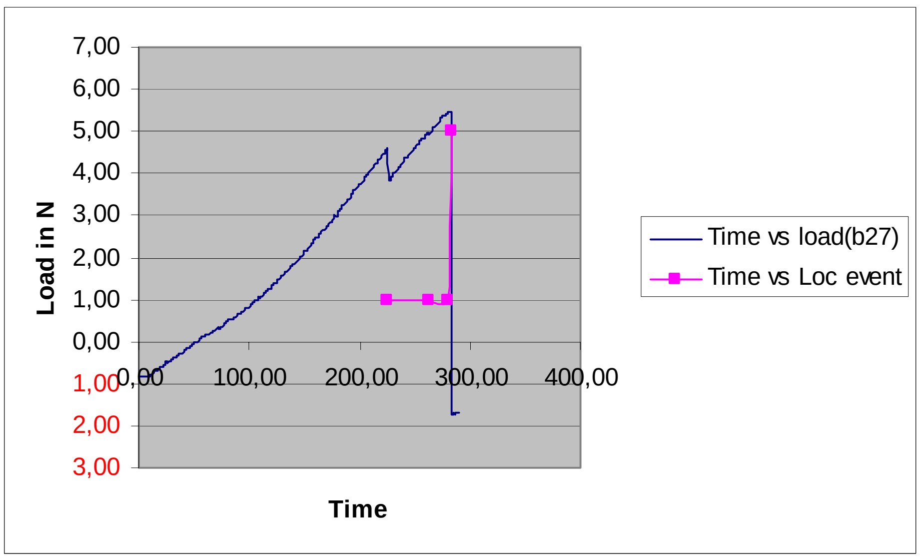
Time vs load(b27)
Time vs Amp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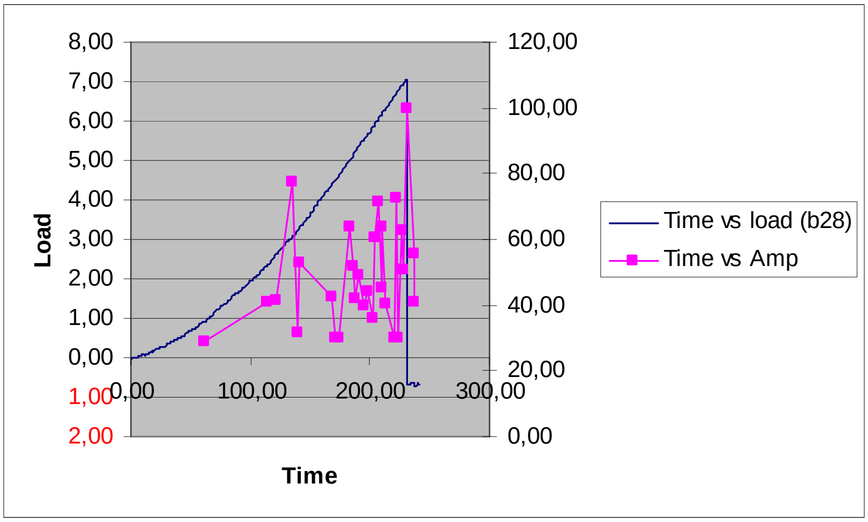
Time
Time vs load(b27)
Time vs Loc event

Sample B28


Load
Time
Time vs load (b28)
Time vs Amp
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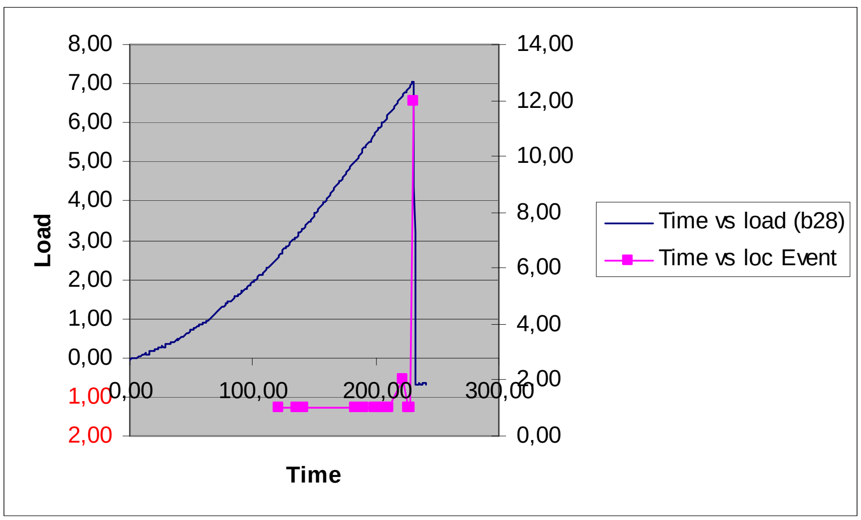
Load
Time
Time vs load (b28)
Time vs loc Event
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200,00
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12,00
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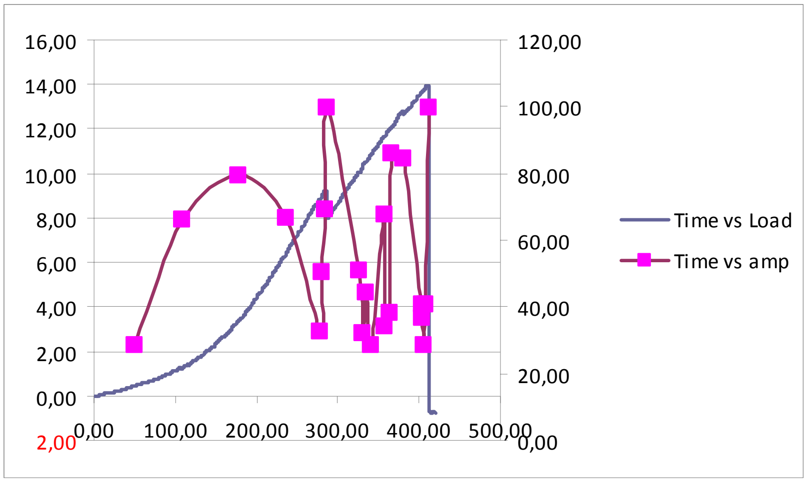
2,00
0,00

Sample B30



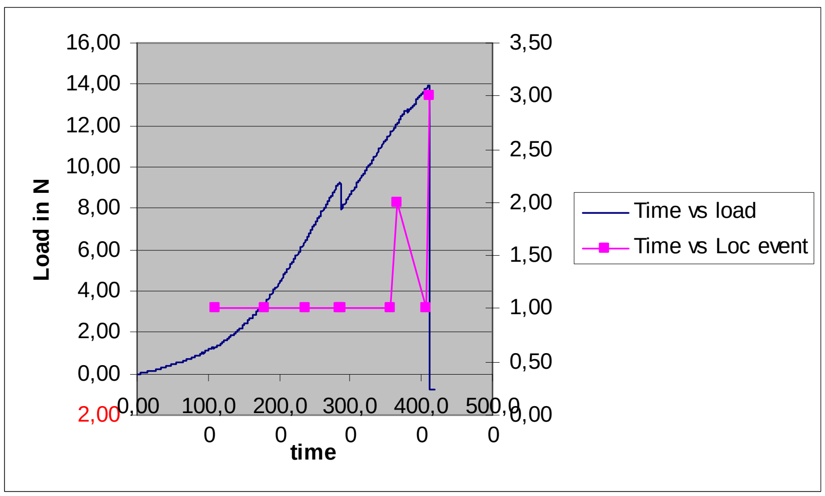


Figure: Time vs load / Time vs Amplitude / Time Vs Energy and their relation for other samples

Appendix-B: Data for Single Fibre Composite Test

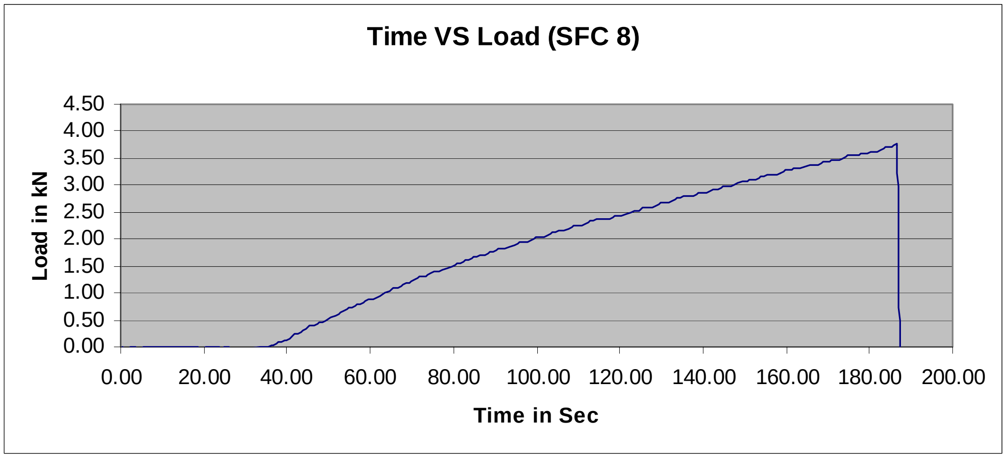
In the following Table load, amplitude, duration, rising time, energy for final breaking of SFC sample given:

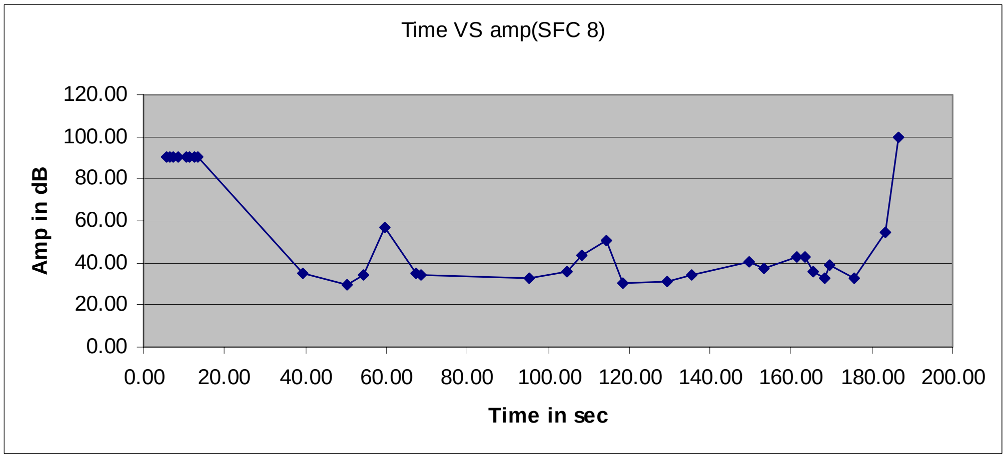
Table7-2: AE data for single fibre composite

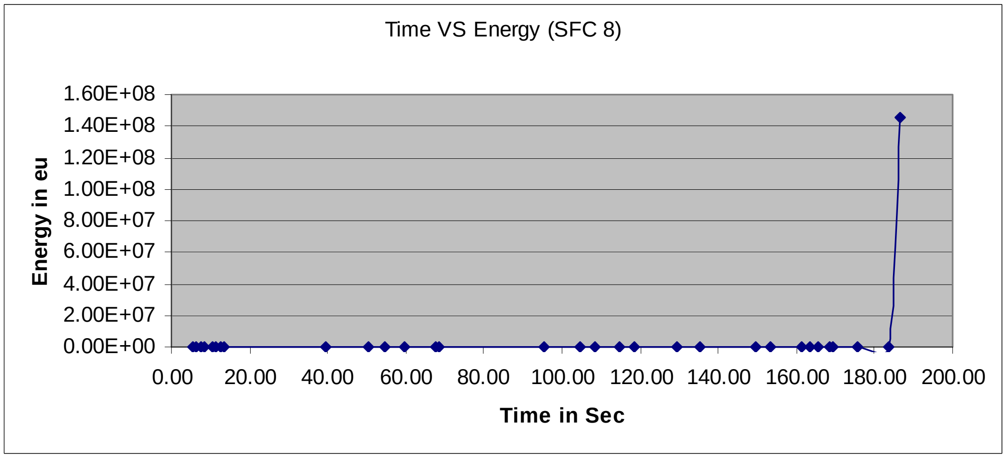
Sample No.	Amp in dB	Load in kN	Rise time in μsec	Duration in μsec	Count	Energy in eu
Sample No. SFC 8						
Load drop / Final Breaking	99.9	3.72	313.8	867.2	35	9.89E+07
Sample No. SFC14						
Load drop / Final Breaking	99.9	3.53	45.8	546	23	4.45E+07
Sample No. SFC15						
Load drop / Final Breaking	99.9	3.53	23.6	2636.8	115	1.12E+08
Sample No. SFC16						
Load drop / Final Breakin	99.9	3.56	232.0	10924.8	367	8.49E+07
Sample No. SFC20						
Load drop / Final Breaking	99.9	3.28	62	3072.8	121	5.55E+07
Sample No. SFC21						
Load drop / Final Breaking	99.9	3.22	30.4	1348.4	47	7.19E+07
Sample No. SFC22						
Load drop / Final Breaking	99.9	3.0	23.2	623.4	27	3.28E+07
Sample No. SFC 23						
Load drop / Final Breaking	99.9	2.84	42.0	1506.4	54	4.97E+07
Sample No. SFC24						
Load drop / Final Breaking	99.9	4.05	52.2	3061.6	125	6.49E+07

Graphs: Time VS Load, Time VS Amp and Time Vs Energy for other SFC Sample

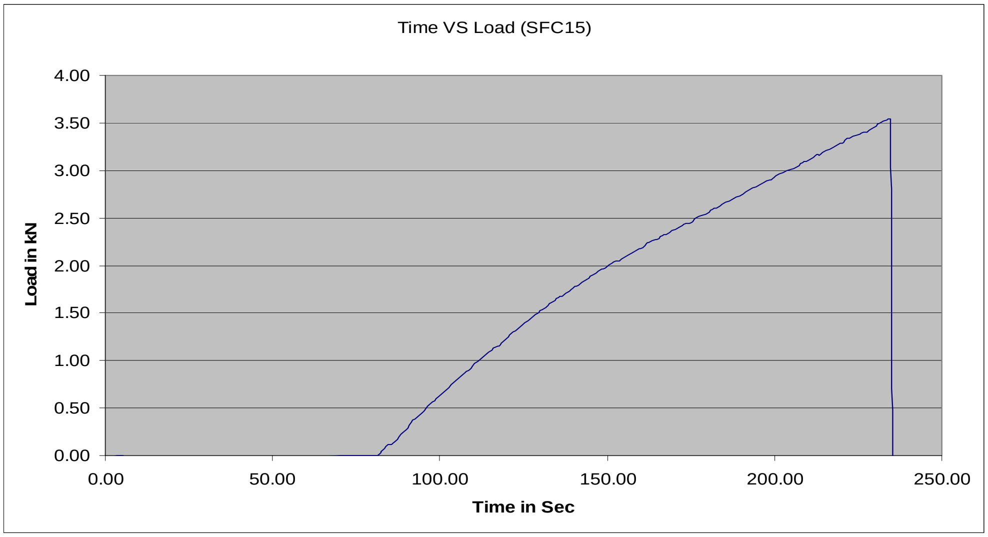
Sample No.: SFC8

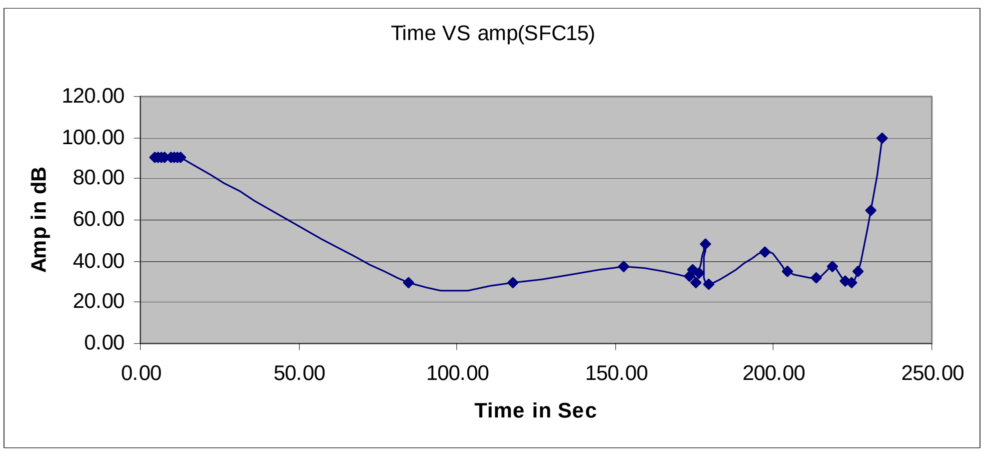


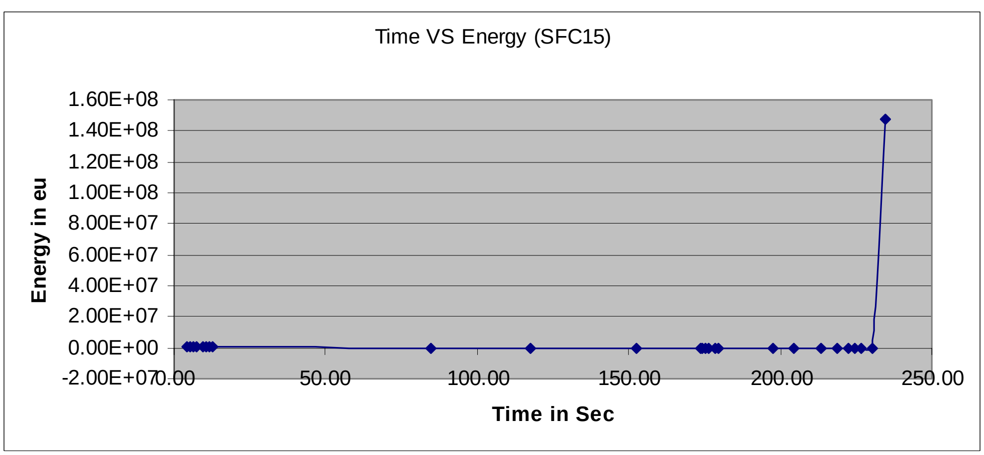




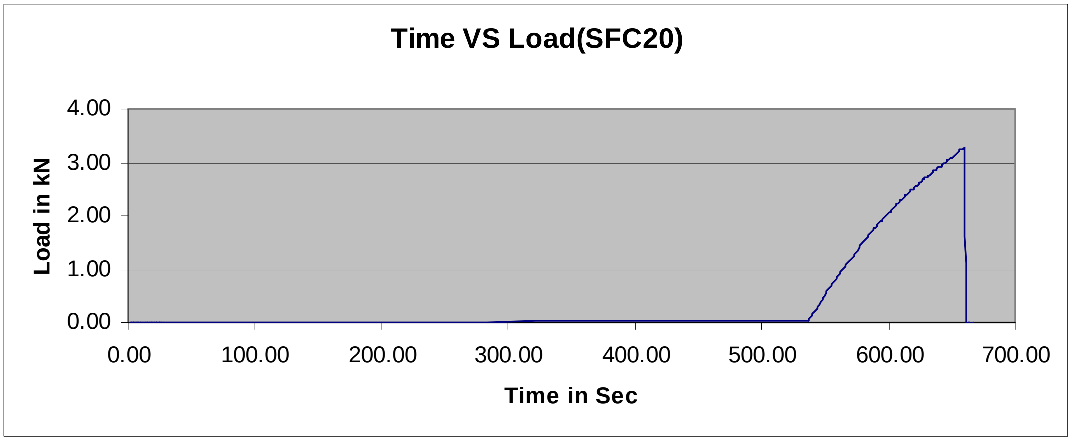
Sample No.: SFC15

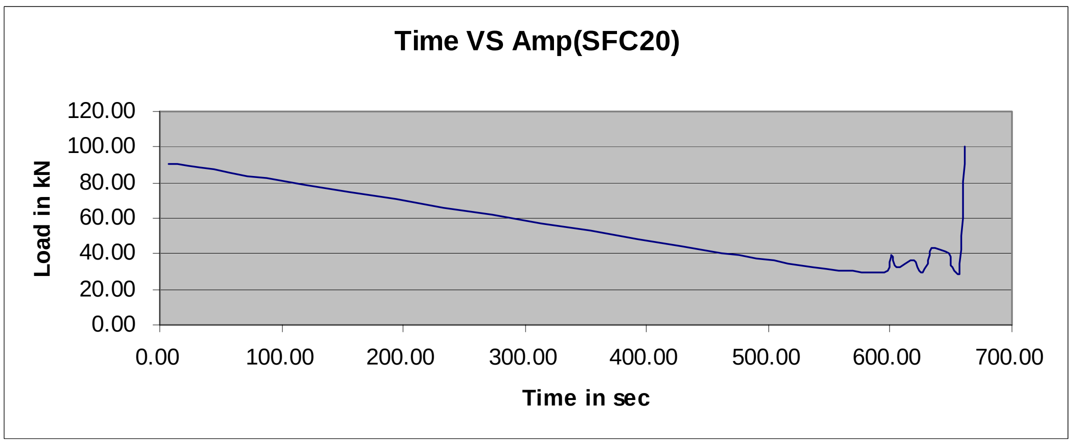


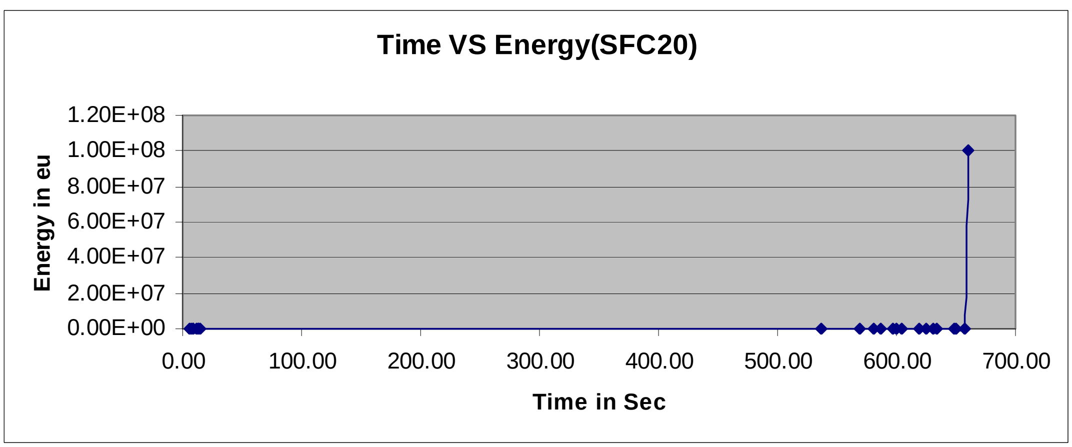




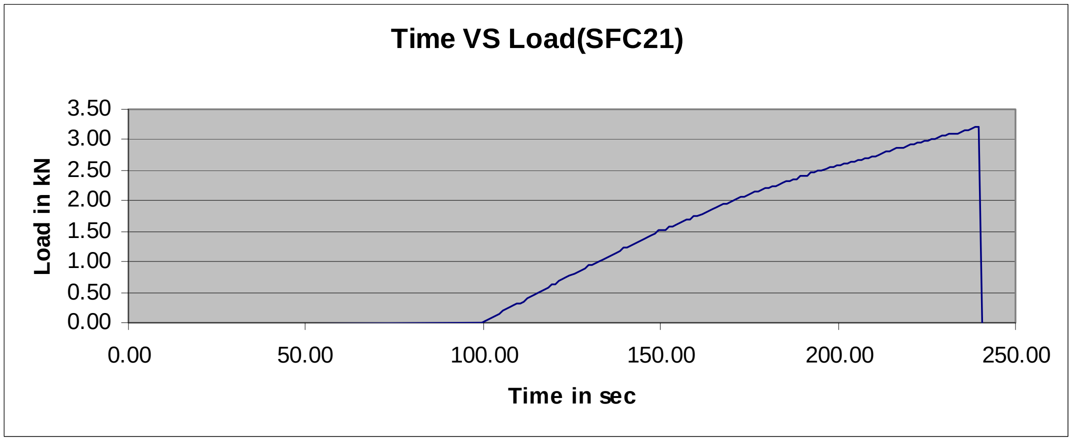
Sample No.: SFC20

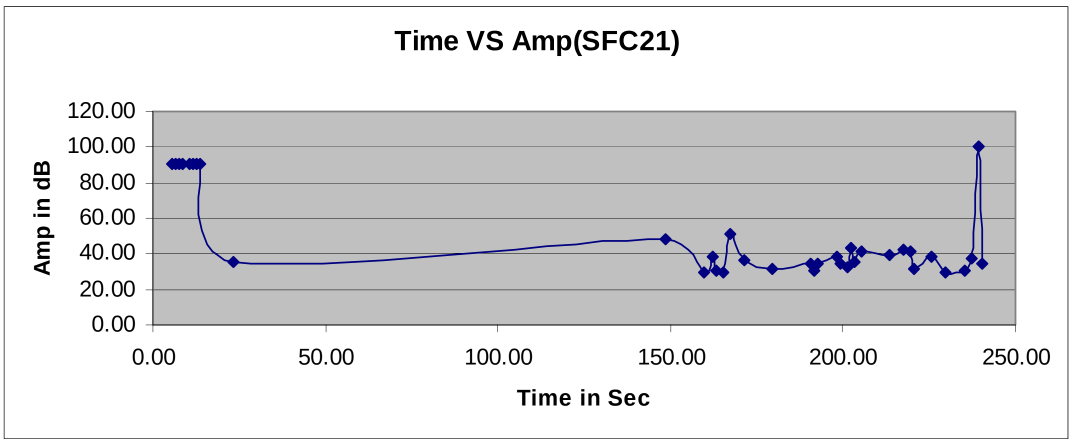


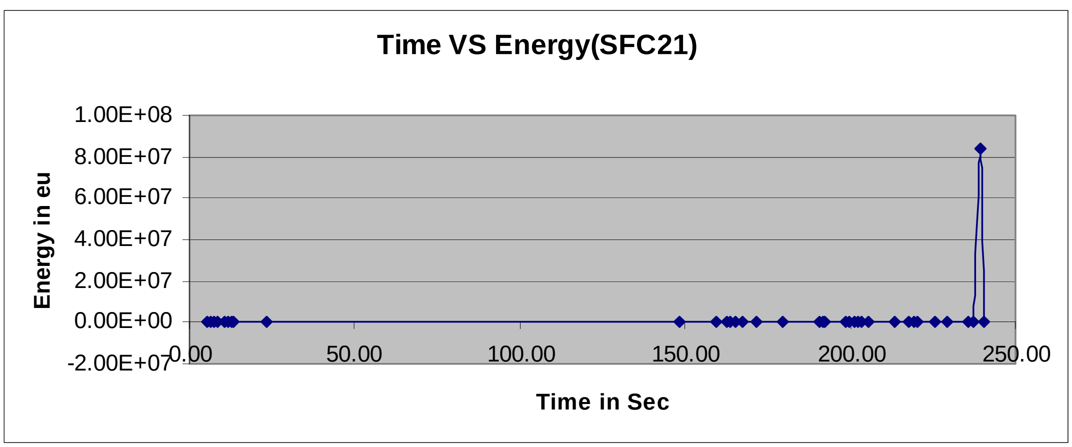




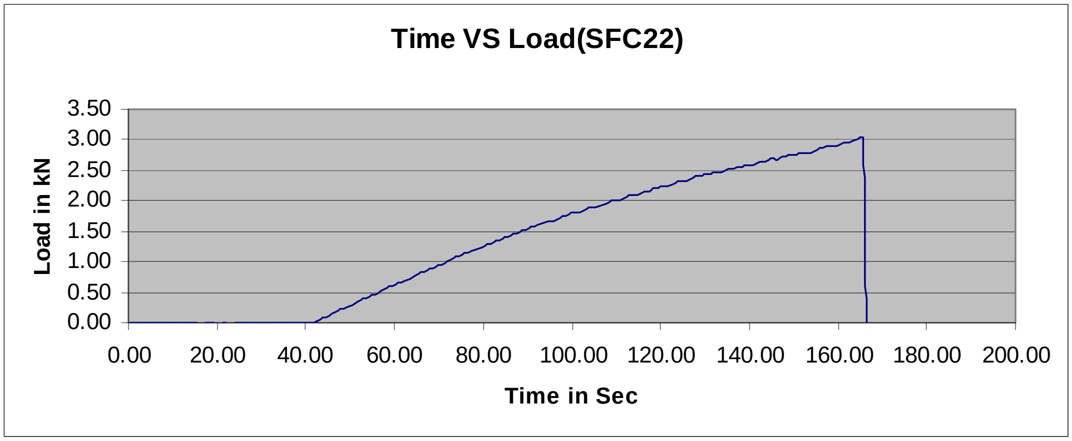
Sample No.: SFC21

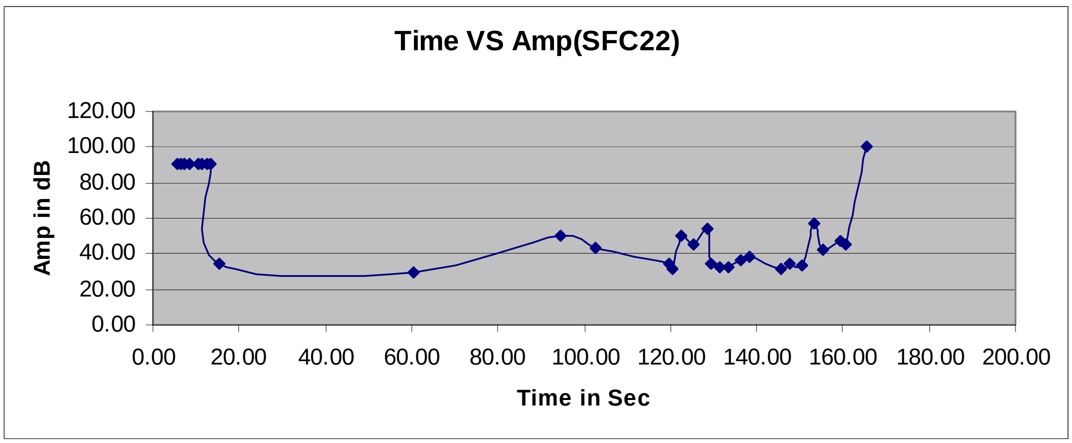


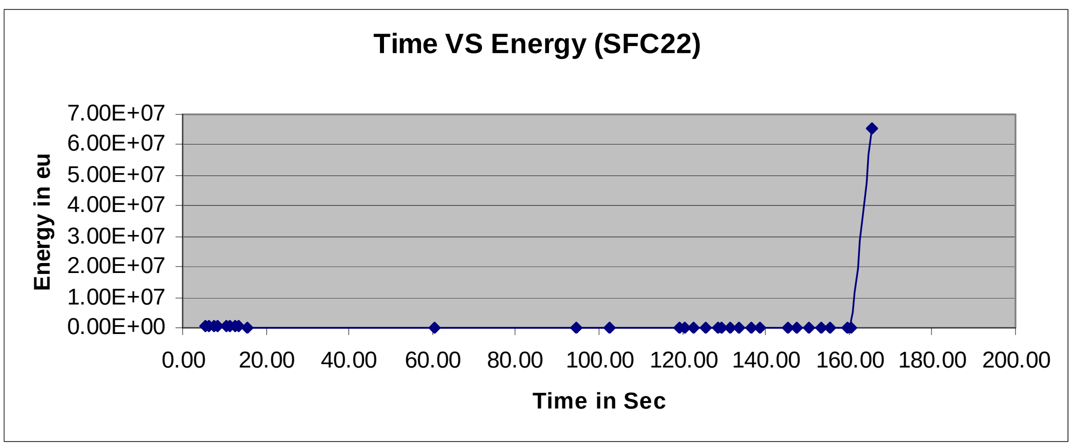




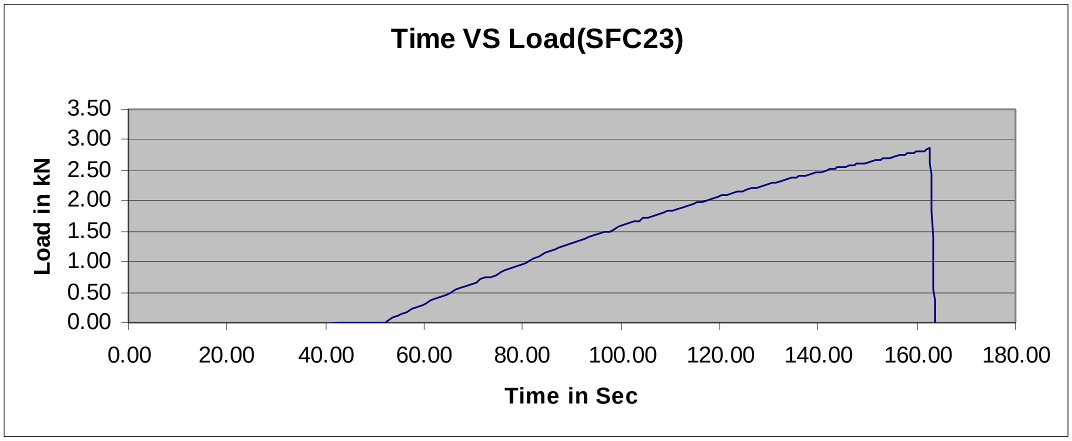
Sample No.: SFC22

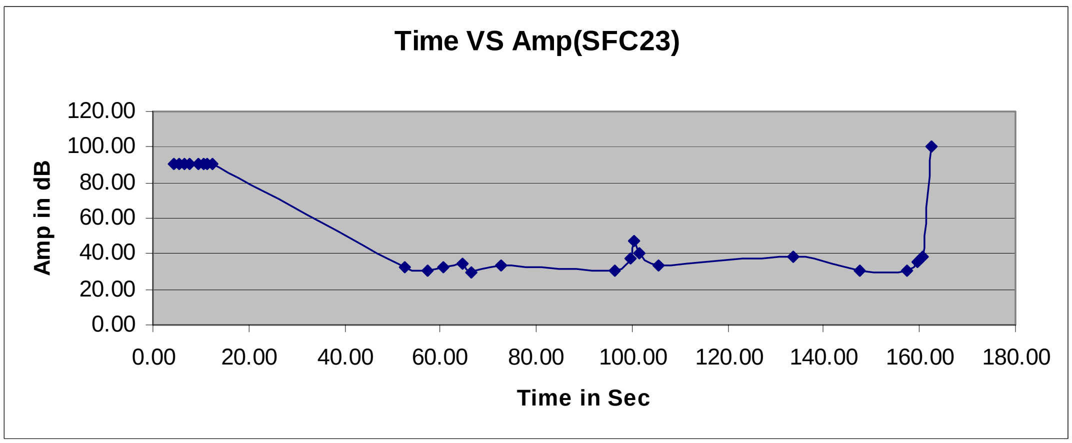


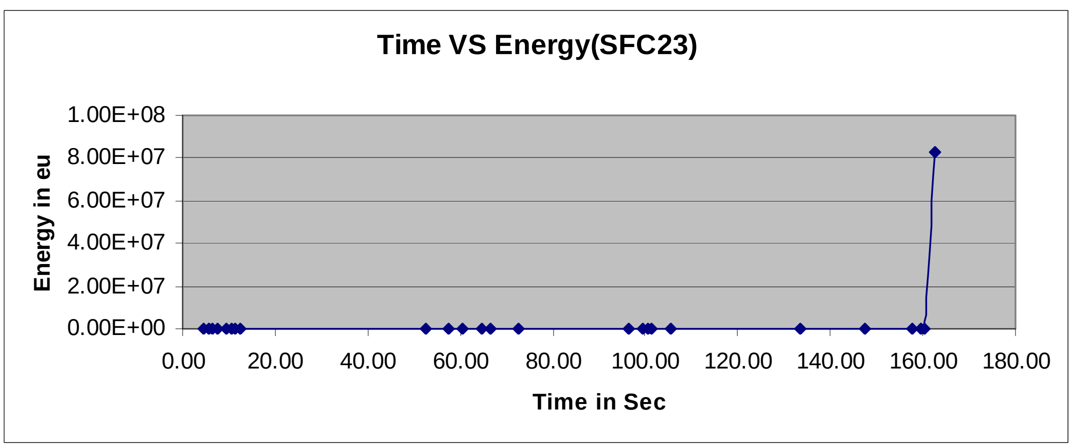




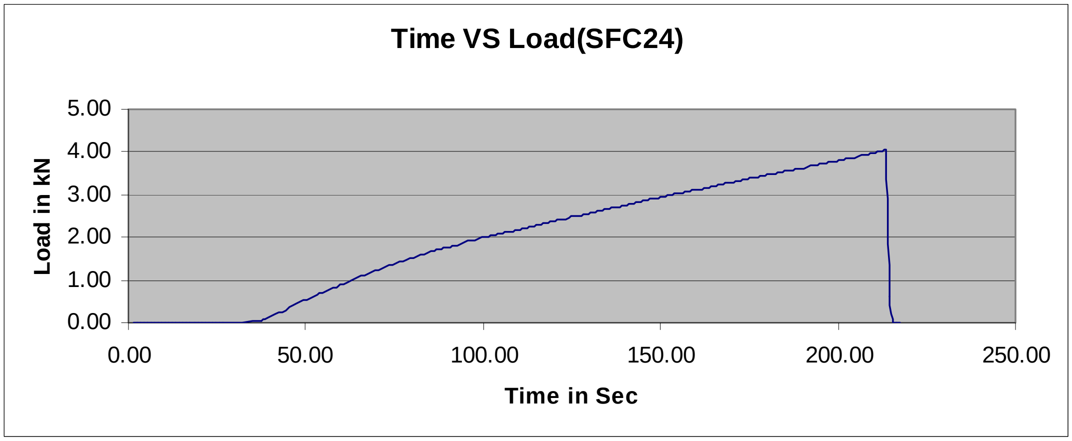
Sample No.: SFC23

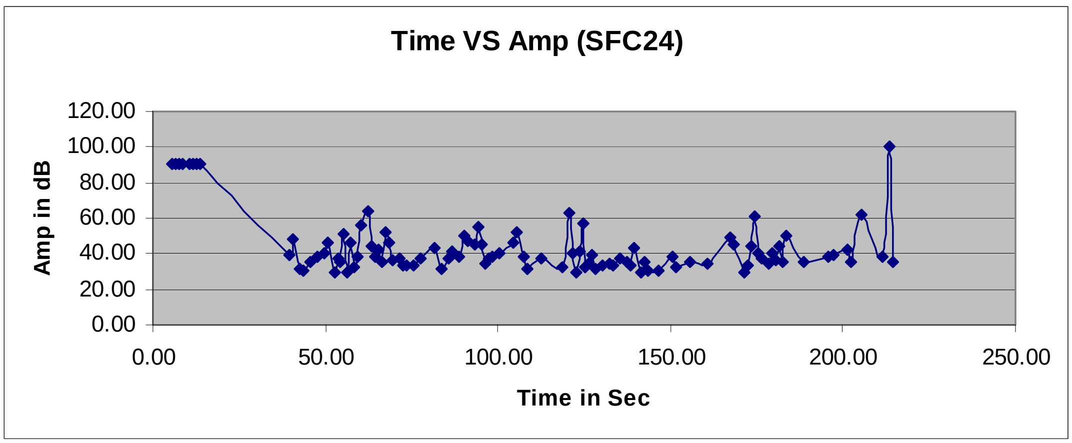


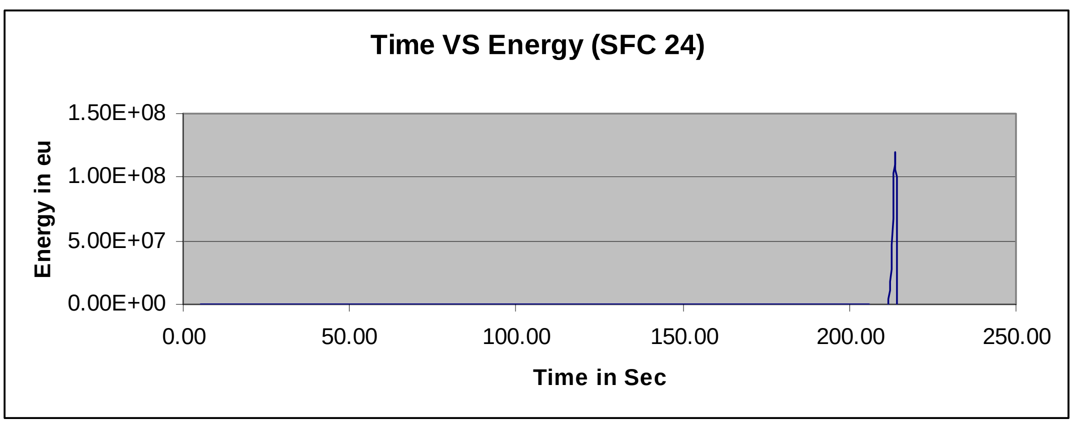




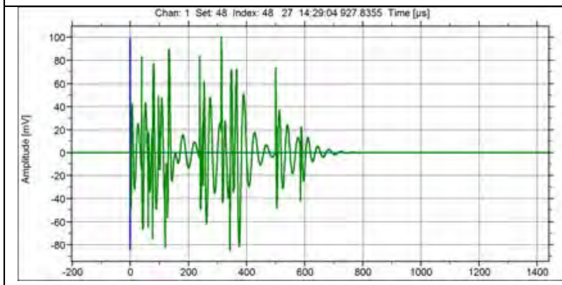
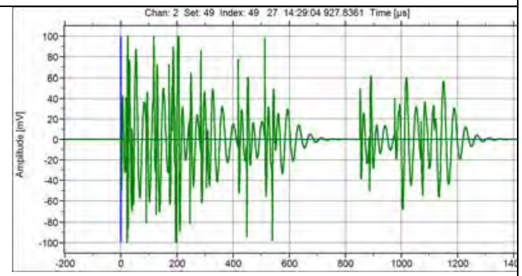
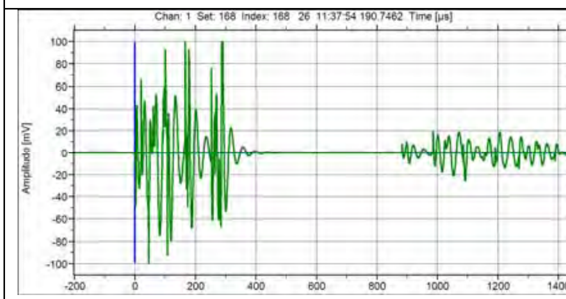
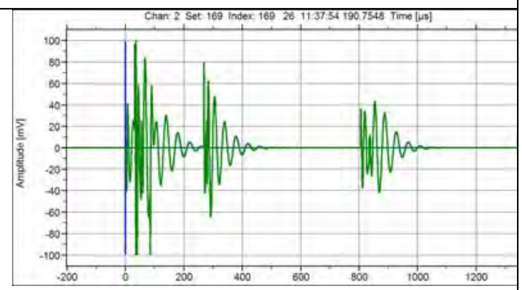
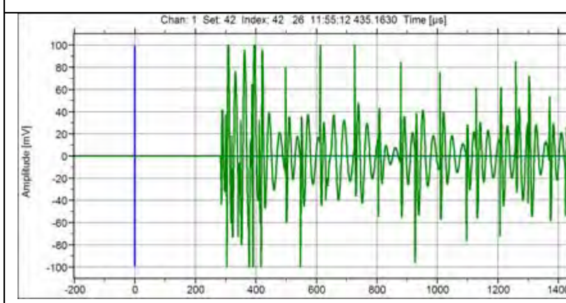
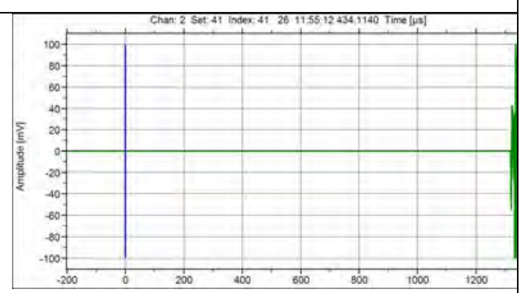
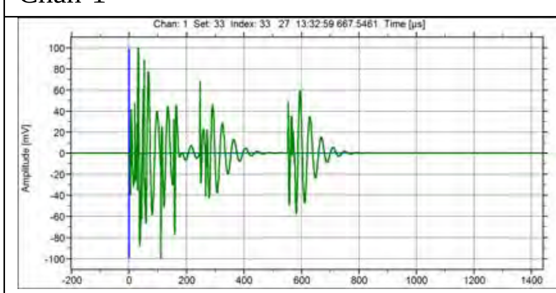
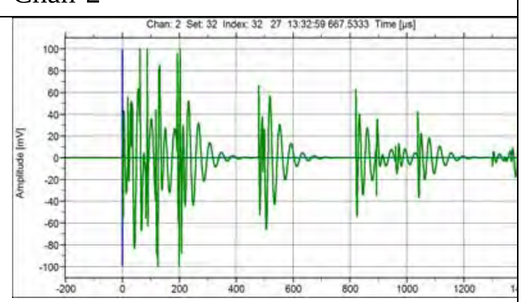
Sample No.: SFC24



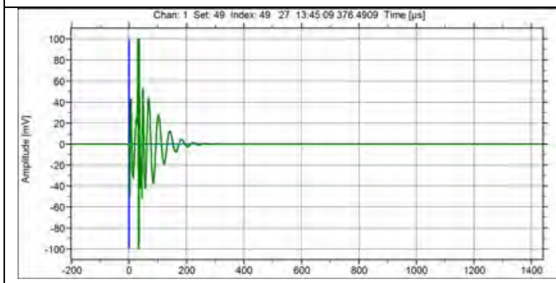




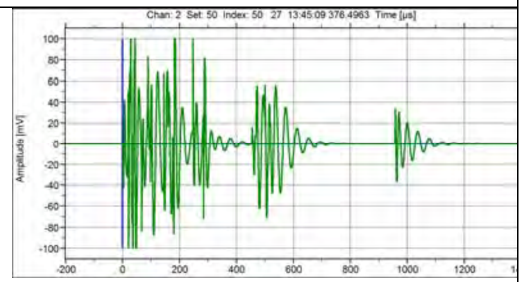
Wave Spectrum for final breaking of other SFC sample:

Spectrum for final Breaking for SFC8 Chan-1	Spectrum for final Breaking for SFC8 Chan-2
	
Spectrum for final Breaking for SFC14 Chan-1	Spectrum for final Breaking for SFC14 Chan-2
	
Spectrum for final Breaking for SFC15 Chan-1	Spectrum for final Breaking for SFC15 Chan-2
	
Spectrum for final Breaking for SFC20 Chan-1	Spectrum for final Breaking for SFC20 Chan-2
	

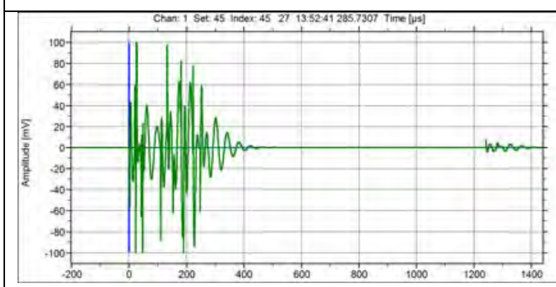
Spectrum for final Breaking for SFC 21 Chan-1



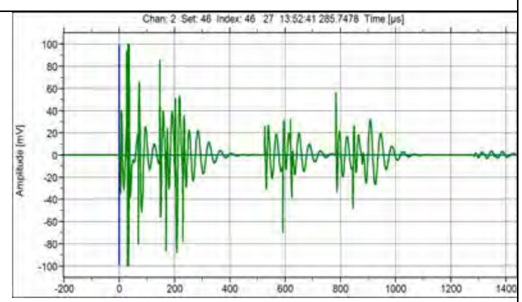
Spectrum for final Breaking for SFC 21 Chan-2



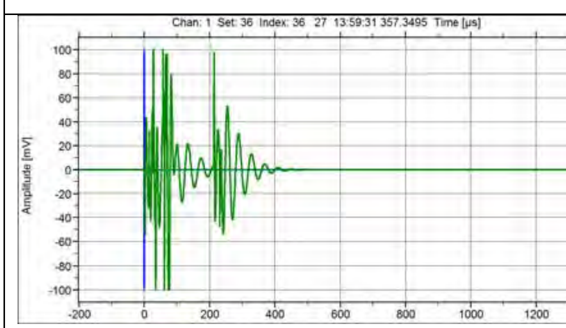
Spectrum for final Breaking for SFC22 Chan-1



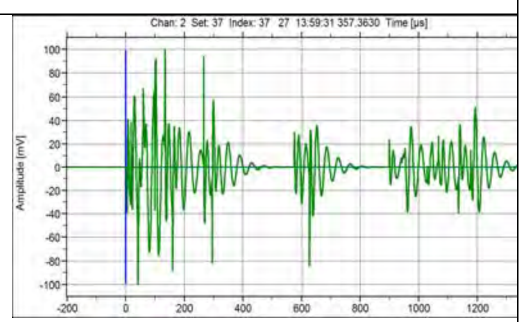
Spectrum for final Breaking for SFC22 Chan-2



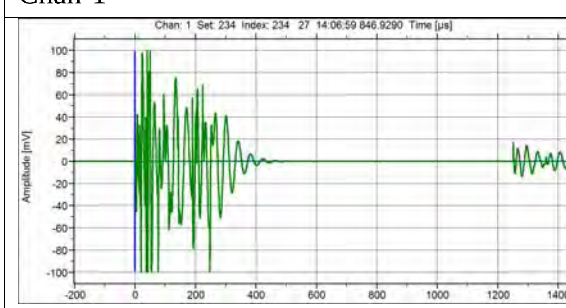
Spectrum for final Breaking for SFC23 Chan-1



Spectrum for final Breaking for SFC23 Chan-2



Spectrum for final Breaking for SFC24 Chan-1



Spectrum for final Breaking for SFC24 Chan-2