CHAPTER (2)

LITERATURE REVIEW

2.1 Introduction

Composite materials have been successfully employed in many engineering applications, notably in the aerospace, marine, automotive parts, oil and gas industries and consumer goods. This is due to their attractive physical and mechanical properties, particularly their strength to weight ratio and resistance to fatigue and corrosion.

The important mechanical properties of a composite pipe are strength, stiffness and fatigue life, which make it imperative to determine leakage integrity and reliability of a piping system. During last decades, composite pipes have become the major challenges concerning research due to increasing use in variety of applications, including gas and oil transportation, seawater desalination, farmland irrigation, chemical plants, high pressure containers,…etc. Since the composite pipes are subjected to combinations of internal pressure and fatigue loading, during past decades investigating fatigue performance and developing fatigue life prediction methodologies, have been the subjects of study for a large number of researchers.

The behavior of composite materials subjected to fatigue load is very complex due to non homogeneous and anisotropic properties, and it has been studied for a long time; however, composite materials design is still based on very long fatigue tests and high safety factors are used [15].

2.2 Fatigue Damage Model and Failure mechanisms of Composite pipes

Reifsnider et al [16] observed the fatigue failure mechanism, during the initial period of fatigue life to the end period of fatigue life. They found many non-interactive cracks occurred in matrix, they discussed this condition that when the matrix crack density reaches saturation, the fiber failure, interfacial debonding and delamination occurred in composites. Damage was rapidly developed and the material causes 'sudden death' at the end period of fatigue life.

One of the earliest studies of the failure behavior of fiber glass pipes was conducted by Hull et al [17]. In which pipes were internally pressurized to failure using the closed end and the unrestrained end. Leakage was observed to be the main failure mode for fiber glass reinforced pipes, and leakage modes were distinct for different ratios of axial load to internal pressure. They found in closed end type resin cracking produced a non-linear stress/strain response and at high pressures the pipes behaved as though complete resin/fiber decoupling had occurred, but in unrestrained end resin the shear was predominated.

Similar tests were managed by Soden et al [18] to investigate leakage and fracture strength in ±55° filament wound thin walled GFRE pipes subjected to various biaxial stress conditions from combinations of internal pressure and axial loading. They found that the initial failure for all loading conditions was usually leakage at a pressure considerably lower than the final failure pressure. They concluded that the fracture strength was very much depending on the ratio between hoop and axial stress applied.

Broutman and Sahu [19], investigated the initial formation of transverse cracks. Extensive experimental works have also been carried out in other works [20, 21] to observe matrix cracks. It was found that the cracks formed in the transverse direction of the fibers and crack density increased with increasing applied stress until reaching saturation at which failure occurred. The researchers then went on to revise the multiple fracture theory in studying the effect of ply thickness on predictions of crack spacing in unidirectional composite laminates. It was concluded that the threshold strain for transverse cracking is highly dependent on the thickness of the plies around which cracking occurs.

Harrison and Barder [22] tested a simple [0°/90°/0°], [±45°] and quasi-isotropic carbon fiber reinforced epoxy laminates in fatigue and uniaxial tension. They found that the failure mode in quasi-isotropic laminates depend on the ply stacking sequence. In fatigue test, they found the transverse ply cracking strain of [0°/90°/0°] specimens were lower than that of similar specimens tested in uniaxial tension. They suggested that, crack density at saturation depends to the extent on the applied strain levels, rather than just laminate geometry, especially during fatigue loading.

Nairn et al. [23, 24] carried out a series of experiments on crack density as a function of applied stress. They found that no cracks were observed until the limit stress was reached. However, once initiated, the crack density often increased very rapidly.

Katerelos et al. [25, 26] investigated the elastic modulus degradation and the residual strain development in cross-ply and angle-ply glass fiber/epoxy laminates, predictally using the equivalent constraint model (ECM) and experimentally using a Raman spectroscopic technique. They observed that, the predicted approach showed good agreement with the experimental results obtained by microscopic strain measurement using the laser Raman spectroscopy technique. They concluded that, for both cross-ply and angle-ply the elastic modulus of the damaged laminate and the residual strains depend on the same local parameters related to the crack: the normalized composite average composite opening (COD) and normalized average composite sliding (CSD) displacement of the crack surface.

A finite element model was proposed by Tao and Sun [27, 28] they investigated the effects of matrix cracking on the stiffness degradation of laminates. The predicted normalized transverse and shear modulus was plotted against the exponential function of the normalized crack density of a cracked lamina. They found that, the normalized crack density (thickness of the cracked layer/crack spacing) is a more critical parameter to characterize matrix cracking damage, location of the cracked layer in a laminate has negligible effect on its effective modulus; and orientation of the constraining sublaminate has considerable influence on the effective modulus of the cracked layer.

Jones [29] examined the morphology of transverse matrix cracks present in GFRE pipe loaded up to final failure, using a standard microscopic technique. According to their observations, white striations parallel to the fibers appeared during pressurization which increased progressively as weepage pressure was approached. The formation of streaks was also accompanied by acoustic emission indicating matrix cracking that took place within the laminates. From micrograph image observations, they found that matrix cracks tended to be initiated at a region with higher fiber content. They subsequently classified these cracks as transverse, parallel or interlaminar and oblique transverse cracks.

Similar observations were made by Bailey and Parvisi [30] in their work on the debonding effects in cross ply laminates of glass fiber composites. They inferred that, the

whitening effect seen were, in fact, associated with fiber-matrix debonding. Micrograph images suggested that the transverse cracks then formed as a result of the coalescence and growth of this debonding in the laminates. Recently, Gemi et al. [31] looked at the fatigue behavior of filament wound GFRE pipes under pure internal pressure. Structural observations with a scanning electron microscope (SEM) showed matrix cracking coalescing with voids within the matrix phase, hence precipitating the damage progression process.

Frost [32, 33] studied the influence of loading frequency in predicting the long term fatigue behavior of a GFRE pipe. They concluded that the prime failure mechanism observed for short and long term fatigue were leakage as a result of matrix cracking. As mentioned earlier. Although transverse matrix cracking may not cause abrupt structural damage in pipeline applications, it is highly detrimental since it leads to weepage failure which, if not treated, can trigger the development of other, more deleterious forms of damage such as fiber breakage or bursting.

Another commonly observed failure mode for GFRE pipes is delamination, which is also referred to interlaminar cracks between composite layers. Jones and Hull [34] carried out microscopic observations of the delamination failures of GFRE pipes under biaxial loading. They observed that, for pure hoop loading, the pipe buckled and delamination took place on the compressive side of the bent pipes. This was later followed by catastrophic failure involving fiber breakage, which appeared to start in the regions of delamination. Local weepage or small jets of fluid spraying from local sites could be observed if delamination took place along the outermost interlaminar plane, since fluid could escape along the crack length. This was observed by Meijer and Ellyin [35] when GFRE pipes were tested at 4:1, 4.5:1 and 5:1 hoop to axial stress states. It was noted that the appearance of the tested pipes changed, becoming opaque over the entire surface due to coarse striations parallel to the reinforcement. This characteristic suggested delamination damage.

Ellyin et al [36] studied the behavior of multidirectional filament wound GFRE pipes subjected to biaxial loads with different loading rates. They concluded that, due to the combinations of fiber winding angles in the plies and matrix micro cracks cause great

differences in stiffness in neighbouring layers, creating high interlaminar stress and hence resulting in delamination damage.

O'Brien [37] was the first to develop an analytical model for predicting matrix crack induced delamination. The model estimates the energy release rate as a function of the modulus of the undamaged laminates and the modulus of the delaminated region. He observed that, in regions adjacent to delaminations, the 90∘ plies are assumed to carry no load and thus the uncracked plies carry proportionately increased loads, in regions where there is no delamination, the stresses in all plies are identical to the stresses in the undamaged state.

Wang et al. [38] carried out a 3D finite element analysis to determine the rate of energy release as delamination grows. Two types of delamination were investigated: one initiating from the intersection of transverse cracks and free edges of the laminates and the other from the intersection of transverse cracks only. Both case studies showed reasonable agreement with the experimental results.

Hashin [39] established the Three-dimensional fatigue failure criteria for unidirectional fiber cross ply composites under states of cyclic stress in terms of the transversely isotropic invariants of the cyclic stress. He modeled two separately distinct fatigue failure modes, fiber mode, and matrix mode. Later, Nairn and Hu [23] and Nagendra and Talreja. [40] extended the variational analysis of a transverse matrix cracking proposed by Hashin [39] to model the delamination damage induced at the crack tip. They found that, the variational mechanics analysis for delamination initiating at microcrack tips predicts that microcracking will continue until the microcrack density reaches some critical crack density for delamination. This critical crack density is determined by material properties, laminate structure, the fracture toughness for delamination, growth of critical delamination, and the fracture toughness for microcracking, growth of critical microcracking. Finally, they concluded that no cracks were observed until the limit stress was reached. However, once initiated, the crack density often increased very rapidly.

Takeda and Ogihara [41] used a simple one dimensional shear lag analysis to model laminates containing delamination originating from the crack tips and hence predicted the associated decline in modulus properties. However, this study was only concerned with

reductions in the axial stiffness, while the effects of delamination on shear modulus and Poisson's ratio remained unexamined.

Kashtalyan and Soutis [42] investigated a new theoretical approach to evaluate stiffness degradation due to delaminations growing at the 0º/90º interface from the tips of transverse cracks in the 90º plies and splits in the 0º plies of cross-ply laminates. They inferred that, crack induced delamination caused a significant total reduction in shear modulus and Poisson's ratio which in fact, exceeded that caused by transverse cracking.

More recently, Noh and Whitcom [43] conducted a very interesting study on the effects of various shapes of cracks induced delamination towards property degradation. It was claimed that the crack opening is closely related to the decline in stiffness of the damaged middle lamina.

The last common failure mechanism in composite pipe is the Weepage failure, where a slow leakage from the wall of the pipe can be observed visually from the uniform formation of fluid droplets on the outside surface of the pipe. This can develop either from the effect of long term static pressure (static fatigue), repeated pressure (cyclic fatigue) or a combination of both. This damage mode normally occurs at load levels considerably lower than that of structural bursting or collapse failures [44].

Majid et al [44] observed that the weepage in the 0.5:1, 1:1 and 2:1 hoop to axial loading conditions was due to transverse matrix cracking. This can be clearly seen from the uniform formation of water droplets on the outer surface of the pipe. As the internal pressure increased, the numbers of water droplets increased and, after a significant build-up, the surface of the pipe became covered with water which could be seen to be dripping out of the test set-up. All weepage failures were observed long after the Ultimate elastic wall stress (UEWS) point had been reached. Fiber breakage is the final sequence of the damage mode in GFRE pipes. When it occurs the specimen is considered to have lost its structural integrity before progressing quickly to total failure. This type of failure is also sometimes referred to as total structural failure since load can no longer be borne.

Pabiot et al. [45] studied the effect of the fiber/matrix interface on the weepage of filament-wound composite pipes. They demonstrated a relationship which shows that weepage failure in GFRE pipes subjected to internal pressure loading is very much

influenced by the interface in terms of crack initiation and propagation through the wall thickness.

Mieras [46] studied the effect of matrix properties on the failure of filament wound GFRE pipes. He suggested that weepage failure is very much dependent on the failure strain of the matrix system.

Legg and Hull [47] explored the effects of resin flexibility on weepage strength, and found that the weepage strength of ±55° filament wound GRP tested at hoop stress twice of axial stress ($\sigma_H = 2\sigma_A$) increased with resin flexibility due to changes in failure strains and the initiation and propagation of micro-cracks.

Tanigushi et al. [48] continued these investigations and looked into the influence of the mechanical properties of the matrix system in the GFRE pipes with respect to weepage failure. Weepage pressure was observed to be almost proportional to the failure strain of the matrix.

A recent study by Meijer and Ellyin [35] investigated first failure modes of GFRE pipes subjected to fourteen stress ratios ranging from pure axial loading (0:1 hoop to axial) to pure axial compression (0:-1 hoop to axial). Weepage/leakage was observed for all loading conditions from pure axial to 5:1 hoop to axial loading, except for high hoop dominating loadings and axially compressive loadings where the specimens demonstrated catastrophic failure with sudden bursting and leaving fibers pulled out, which were no longer constrained by the matrix. They suggested that, the non-linearity of the stress-strain response is a result of changes in transverse stiffness as crack concentration increases leading to weepage failure.

An assessment by Orifici et al. [49] on the failure of composite laminates implied that, failure of fiber in tension is caused by the accumulation of the failures of individual fiber in the plies. This eventually becomes critical when not enough intact fibers remain to bear the load. Failure of fiber in compression loading, on the other hand, was found to occur due to micro buckling.

Spencer and Hull [50] tested GFRE pipes to failure under a 2:1 hoop to axial stress ratio at various winding angles. They found no significant fiber rotation prior to weepage failure. However, after weepage was observed, the matrix cracks became very extensive and the pipes developed a large axial elongation and obvious circumferential contractions

where the fibers rotated towards an optimum angle of ±55º. Pipes then burst abruptly due to successive and continuous fiber breakage. This can normally be seen from massive macro cracks parallel to the fiber orientation in which the minimum necessary amount of energy has been dissipated for the fibers to pull out and fracture.

2.3 Biaxial loading of Composite pipes

Parnas and Katırc [51] developed an analytical procedure to design and predict the behavior of fiber reinforced composite pressure vessels. They considered the internal pressure throughout the vessel body to obtain the optimum winding angle under this load. They found that the optimum winding angle for the thick-wall and thin-wall pressure vessel analysis with the pure internal pressure loading case is obtained as ranging between 52.1 and 54.1 degrees depending on the material type.

Onder [8] investigated the optimal angle-ply orientations of symmetric and antisymmetric $[\theta, -\theta]_s$ pressure vessels designed for maximum burst pressure. Glass reinforced plastic (GRP) pipes are made of E-glass epoxy with fiber orientations $[45^\circ, -45^\circ]_s$, $[55^\circ, -55^\circ]_s$, $[60^\circ, -60^\circ]_s$, $[75^\circ, -75^\circ]_s$ and $[88^\circ, -88^\circ]_s$ and tested closed-end condition. He studied the finite element method and experimental approaches to verify optimum winding angles based on the Tsai-Wu failure criteria. He concluded that the optimum winding angle for the composite pressure vessel analysis with the internal pressure loading case is obtained as $[55^\circ\ ]$ for laminates and as $[90^\circ]$ for a lamina.

Dogan [52] investigated the resistances of the composite pressure vessels under internal pressure. He developed an elastic solution procedure in order to predict the first-ply failure of the pressure vessels made from an epoxy-carbon fiber composite layer. The layers were oriented symmetrically and antisymmetrically for $[30^\circ, -30^\circ]_{2s}$, $[45^\circ, -45^\circ]_{2s}$, $[55^\circ, -55^\circ]_{2s}$, $[60^\circ, -60^\circ]_{2s}$, $[75^\circ, -75^\circ]_{2s}$ and $[90^\circ, -90^\circ]_{2s}$ orientations. He applied the Tsai-Wu failure criterion for the checking the first-ply failure of layers in a simple form. In addition, the von-Mises criterion was used in order to find the failure of the plastic liner. He compared some analytical solutions with the finite element solutions to verify optimum winding angles. He obtained that the optimum winding angle for the composite pressure vessel analysis with the internal pressure loading case is obtained as $[54^\circ]$ for laminates and as $[90^\circ]$ for a lamina.

Sinha and Pandit [53] demonstrated a study on cylindrical section of carbon fiber reinforced polymer (CFRP) composite pressure vessel having four layers. They designed and modeled the pressure vessel using the finite element software ANSYS 11.The modeling is performed for both hoop and helical windings of the fibers in pressure vessel. For helical windings the layers were oriented symmetrically for [+25°/-25°]$_s$, [+35°/-35°]$_s$, [+45°/-45°]$_s$, [+55°/-55°]$_s$, [+65°/-65°]$_s$, and [+75°/-75°]$_s$. They predicted the burst pressure for each of the fiber orientations based on the Tsai-Wu failure criteria. They obtained that the ± 45° fiber orientation angle is the optimum fiber orientation angle for the composite pressure vessel subjected to high internal pressure loading and the slope decreases from ± 45° to ± 75° fiber orientations.

Martins et al [54] conducted a numerical/experimental study to investigate the failure pressure of filament wound composite tubes subjected to internal pressure. They tested four thin-walled E-glass fiber epoxy tubes with wind angles [±45°], [±55°], [±60°] and [±75°] for the closed-end loading condition. They showed a good correlation for all fiber wound orientations by comparing the numerical and experimental results. They found that the optimum winding angle for the composite tubes under internal pressure loading is [±55°] using different failure criterion.

Sodden et al. [18] carried out an experimental work on bi-directional, ±55 filament wound GRE pipes under a variety of biaxial stress states by applying combinations of internal pressure and axial tensile and compressive loads. Special attention was paid to the end gripping and pressure sealing problem by adding material reinforcement to the end of the pipe to minimize the stress concentration. They concluded that, the fracture strength of the pipes material and stress/strain response are dependent on mainly the ratio between applied circumferential and axial stresses. Also they observed that, at most stress ratios, unlined tubes failed by leaking at stresses which were considerably lower than those at which lined tubes fractured.

Hale et al. [55] designed a biaxial test model suitable for conducting a test on filament wound composite pipe at elevated temperatures. They tested two materials systems in common use in offshore piping applications, fiber e-glass in a phenolic (GFP) and an epoxy resin matrix (GFE). In this test model, the pipe was thermally regulated by a cartridge heater installed inside the test spool and loading was achieved by the

pressurization of the test medium. A ram was installed inside the pipe to create two compartments which could be separately pressurized to produce various hoop to axial stress ratios. Their conclusions may be summarized as follows:

1. The strength of the (GFE) pipes reduced significantly, particularly at high temperatures and when the matrix was subjected to pure hoop and pure axial loading.
2. The (GFP) pipes were unaffected by temperature throughout the loading envelope.
3. Comparison of the strength of the two materials as a function of temperature is highly dependent on the fiber orientation.
4. At high temperatures above about 140ºC the (GFP) pipes is stronger than the (GFE) pipes under all loading configurations. At lower temperatures below 140ºC the (GFE) pipes system becomes stronger in loading cases where hoop load predominates. In loading cases from pure axial to approximately 1:1 hoop to axial loading, the (GFP) pipes is stronger above about 100ºC, below which temperature the (GFE) pipes and (GFP) pipes systems are of approximately equal strength.

Frost [33] analyzed the stress-strain response of GFRE pipes under static and cyclic fatigue internal pressure loading. He reported that, the crack density increased with increasing load, which resulted in more pronounced non-linearity in the stress-strain response. He suggested that, as the crack density increased, the delamination then took place which allows for ply rotation. This rotation hence caused a more noticeable non linearity response in the axial strain.

Sun and Tao [28] predicted The failure envelopes for unidirectional composites and multi-layered composite laminates by linear laminate theory . They used in the prediction the ply-by-ply discount method with parallel spring stiffness reduction model. They then modeled stress-strain behavior using simplified shear-lag and finite element analysis, considering the materials non-linearity and progressive matrix cracking. They found that, the non-linear response of laminated fiber reinforced composites as primarily resulting from three main sources: material non-linearity, progressive failure in the laminates, and geometric non-linearity.

Caroll et al [56] experimentally investigated the effects of the rate and stress ratio of biaxial loading on the stress-strain behavior of GFRE pipes. They found that elastic

behavior of the pipe was present at low stress levels. They went on to formulate a relationship between the stress-strain responses to accumulating damage.

Ellyin et al [36] analysed the stress-strain response for multidirectional filament wound GFRE pipes under biaxial loading. Confirming findings of Caroll et al [56], they noted that the elastic behavior of the tested pipes was not just present at low stress levels but also showed time dependent properties.

Roberts et al [57] examined the effects of micro cracks on the stress-strain relationship in GFRE pipes. They developed a crack density model for predicting the stress-strain response in which a relationship between crack density and applied stress was established. Good conformity between modeled and experimental results was attained. The non-linearity was also observed to become more pronounced at higher temperatures approaching the resin glass transition temperature, T_g.

Recently, Meijer and Ellyin [35] conducted a test on ±60° GFRE pipes under different stress ratios between hoop and axial stress. They observed that the stress strain response for hoop dominated loading tended to be relatively linear compared to the response in the axial direction which is dominated by the polymer matrix.

An investigation by Soden et al [58, 59] described the failure envelopes for ±45°, ±55° and ±75° wound tubes under a variety of biaxial stresses. It was concluded that the strength of the tubes varied greatly according to the ratio of axial to hoop stresses. It was also noticed that the shape of the failure envelope was highly dependent on the orientation of the fibers.

 Carroll et al [56] conducted an experimental investigation into the behavior of GFRE pipes subjected to monotonic biaxial loading of various hoop to axial stress ratios. A somewhat different failure envelope was constructed with failure stresses in compression loading considerably higher than those seen in Soden's [58, 59] failure envelope.

Sun and Tao [28] constructed failure envelopes for unidirectional composite laminates from linear laminate theory. They used a ply by ply discount method with a parallel spring stiffness model for modeling the envelopes. They then compared their model based failure envelope to the test results used in the World wide failure exercise (WWFE) study. Their findings showed good conformity with the final failure strength where failures were largely

dominated by fiber tensile strength. Conversely, the result yielded poor agreement with the experimental failure strains dominated by transverse and shear matrix cracking.

Hale et al. [55] investigated experimentally the effects of high temperature and wetting conditions on two different matrix based GFRE pipes, IPD epoxy and PSX phenolic, under biaxial loading. They noted that the plot for the envelope tends to be skewed towards the origin of the axes as temperature increased.

Meijer and Ellyin [35] recently carried out multiaxial stress tests on filament wound GFRE pipes under different loading conditions where stress and strain failure envelopes were produced. The maximum strain failure criterion was then fitted to the experimental strain failure envelope. The criterion was found to over-predict strength at stress ratios where failure occurred by local leakage and during axial compressive loading.

2.4 Fatigue behavior of GFRE Composite pipes

The behavior of composite materials subjected to fatigue loading is very complex due to non homogeneous and anisotropic properties, and it has been studied for a long time; however, composite materials design is still based on very long fatigue tests and high safety factors are used.

One of the earliest works on the fatigue mechanism was done by Dharan [60], who elucidated the roles of the fibers, the matrix and their interface in causing composite fatigue. He came out with a conceptual framework of explaining fatigue damage known as the fatigue life diagram, as shown in Figure 2.1.

The fatigue behavior of composite tubes was studied by Owen and Griffiths [61]. They conducted a series of fatigue tests of thin walled glass/polyester tubes under a combination of axial loading and internal pressure, both for static and fatigue loading. They observed that, the behaviour of tubular specimens is strongly influenced by the presence of joints in the reinforcements. Then for fatigue behaviour they found that, when the stress ratio between the hoop and axial stress increases the fatigue strength decreases.

Bredemo [62] studied the uniaxial fatigue of filament wound GFRE pipes, focusing on the initiation and progression of damage mechanisms. He found that, damage progressed sequentially from the initiation of matrix cracks to local delamination before failure due to fiber fracture. Matrix cracks were observed to initiate perpendicular to fiber direction

within a single ply. Increases in crack density subsequently initiate local delaminations in the fiber-matrix interface where the matrix cracks ended in the ply. These then coalesce with matrix cracks in the next ply and eventually create a pathway for fluids to pass through the pipe wall thickness. Fiber fractures take place once the tensile stress in the fibers exceeds the limiting strength of the glass, whereupon the structure fails completely.
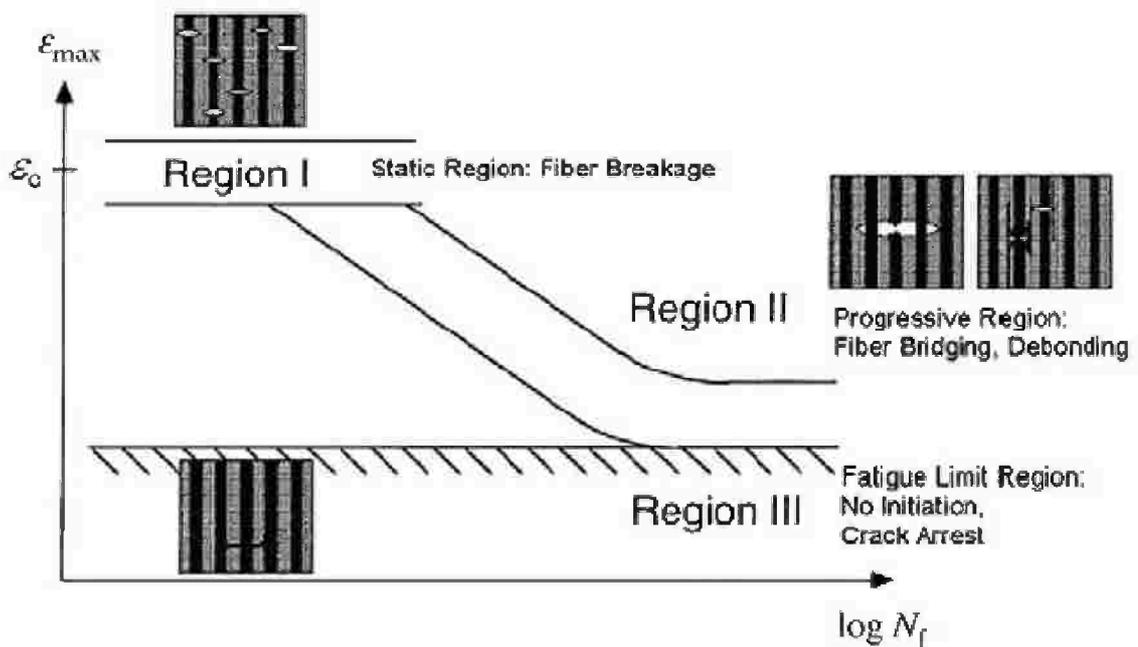

Figure 2.1 Fatigue life diagram for unidirectional composites for axial tension–tension loading [60].

Frost [32, 33] investigated the short and long term performance of GFRE pipes under static and cyclic internal pressurization. He concluded that, matrix crack propagation in these types of loading, controls failure through a combination of transverse matrix cracking and ply delamination at the fiber-matrix interface. The ply stresses were controlling of transverse and shear stress failure.

Carroll [56] conducted extensive experiments to investigate the effects of load rate and ratio on the fracture behavior of ±55° filament wound pipes under biaxial loading. It was observed that the failure mode is very much dependent on the stress ratio and the rate of loading.

Comprehensive work on filament wound glass/epoxy pipes was also conducted by Perreux and Joseph [63], they studied the fatigue behavior of [+55°,-55°] filament wound

GFRE pipes under uniaxial cyclic loading, working on the development of a damage model from cumulative damage law and eventually predicting lifetime. They found that, the fatigue life declines with an increase in stress levels.

Rousseau et al [64] characterized the influence of the degree of weaving on the damage behavior of filament wound GFRE closed-ended pipes under internal pressure loadings. They showed that, this influence is negligible as far as off-axis loadings are concerned. But the damage growth is shown to be increased by the degree of interweaving of the pipes only for closed-ended internal-pressure loading, thus increasing damage growth and the possibility of leaking in high interweaving structures (undulating regions). They suggested that, the degree of interweaving should therefore be minimized for filament wound pipes and pressure vessels subjected to closed-ended internal pressure loadings.

Keynak and Mat [65] carried out an investigation to determine the fatigue life of ±55° wound GFRE pipes tested at stress levels between 60%, 70% and 80% of their ultimate strength, applying three different frequencies; 0.1, 1, 10 HZ for each stress level for the constant amplitude sinusoidal loading with a stress ratio of R= 0.1. They found that, fatigue lives of the specimens decreased with an increase in the stress level, while they were generally increased by increasing the frequency.

Gemi et al [31] and Tarakcioglu et al [66] similarly studied the fatigue failure behavior of ±55° and ±75° filament wound pipe under alternating internal pressure, testing at load levels ranging from 30% to 70% of ultimate strength. Whitening was observed before leakage and final rupture. Both studies concluded that failure is controlled by fiber breakage at high loads while at low loads it is controlled by matrix cracking.

2.5 Factors Affecting the Fatigue Behavior of Composite Materials

Several factors are affecting the fatigue behavior of composite materials. These factors must be taken into consideration and can be arranged these factors according to influence in this work:

1. Effect of type of loading,
2. Effect of loading frequency,
3. Effect of volume fraction,

4. Effect of fiber orientation,

5. Effect of mean stress and stress ratio,

6. Effect of environmental factors,

7. Effect of size and stress gradient,

8. Effect of surface finish,

9. Effect of stress concentration.

2.5.1 Effect of Type of Loading

In practice, three major types of loading are encountered, namely bending, axial and torsional loadings. Since most fatigue test data for metals is obtained under conditions of rotating bending, it has been suggested that the type of loading can be conventionally accounted for by the use of a load correction factor. This correction factor is used to correct the value of the endurance limit of the metal to the required type of loading [67]. For composites, the matter differs greatly, as for composites, the important thing is: how are the fibers, matrix and their interface loaded. So, we always have a complex loading condition regardless the global loading type, and it depends on many factors. Therefore, each type of loading must be studied separately.

Since in most structural applications, composite material are subjected to cyclic loading conditions, the effect of fiber/matrix interfacial strength on their fatigue behavior has been studied for many years. Kim and Ebert [68] found that there are sudden drop in the stiffness of unidirectional fiber glass/epoxy composites during cyclic loading, which can be attributed to debonding of the fiber/matrix interface.

Wang et al [69] examined the tensile and torsional fatigue behavior of (American Society for Testing and Materials) ASTM G-10 GFRP at cryogenic temperatures in a liquid nitrogen environment. They used two fiber orientations, $[0,90^o]$ and $[\pm\ 45^o]$. For the $[0,90^o]$ specimens under uniaxial tension, failure was perpendicular to the loading direction and brittle fiber pull-out was observed, accompanied by cracks normal to the loading direction that dominated the failure. Debonding of fibers from the matrix was evident in almost every interface region, some of the interface cracks extended into the matrix; and delamination was not quite evident in the uniaxial tensile fatigue. The fracture surface of a tubular specimen failed in pure torsional fatigue differed completely from that in the tensile case. Fracture generally followed a spiral path with delamination and subsequent buckling of fiber layers, and was accompanied by extensive fiber-matrix interface

debonding, matrix cracking, and micro buckling of fibers. Their conclusions may be summarized as follows:

1. The fatigue resistance of composites in shear is lower than that in a tensile mode in general.

2. Fatigue resistance degradation of composite laminates at cryogenic temperatures may be related to the change of material stiffness.

3. Fatigue damage mechanisms can be related to the loading mode and material microstructure. In $[0,90^o]$ laminates under tensile fatigue, damage is controlled by fracture of load-bearing fiber bundles, first at cross-overs and then elsewhere. For $[\pm45^o]$ laminates under tensile fatigue, and $[0,90^o]$ laminates under pure torsional fatigue, matrix dominated damage by interface debonding, matrix cracking, and fiber and fabric buckling prevails throughout the composite.

Yang et.al [70] tested the bending, compression, and shear behavior of woven glass fiber-epoxy composites, and they found that:

1. Under bending test the outer layer fracture along the beam axis led to the final failure. A closer observation of the specimen showed that there was some visible damage on the compressive side. As loading progressed, cracking first developed in outer ply on the tensile side. Microcraking initiated when the stress exceeded the local matrix pocket strength.

2. Compressive loading resulted in the formation of a shear band. There was no relative displacement of the fibers across the failure zone, i.e. transverse movement across the failure band.

3. Under shear test both the upper and lower surfaces underwent extensive damage. There was no indication of shear failure or crack initiation in the mid-plane. Furthermore, fibber unevenness deterred fabric plane slippage, and additional through-the-thickness stitching practically eliminated the possibility of inter-plane slippage.

Mahfouz [71] studied the response of resin transfer moulded (RTM) composites under reversed tension-compression cyclic loading. He defined the endurance limit, as it was defined for metals, on the basis of 10^6 cycles to failure. Fiber breakage has not been observed during static compression tests, indicating that the tensile part of the cyclic load has caused such failure. This fiber breakage was also accompanied by filament debonding within the fiber bundle; this debonding was the result of the nucleation of the interfacial

failures because of the repetitive and reverse nature of the load. Although the fiber fracture has taken place in the tensile mode, it is believed that fiber buckling during compression did not cause fiber fracture but contributed significantly to delamination.

Amijima et al [72] investigated the non-linear behavior in stress-strain curves of plain woven GFRP under repeated biaxial tension/torsion loading. They found that; under shear stress loading, the stress –strain relation during loading period become linear just before final failure, while the unloading stress-strain curve kept its non-linear relation. They attributed the non-linear behavior to the preferential cracks due to the shear stress component.

Krempl et al [73] tested graphite / epoxy thin-walled tubes under uniaxial tension – compression and biaxial in-phase torsion and tension – compression fatigue loading. No features were identified that may be used to consistently distinguish static failure from fatigue failure. In other words, they found that it was impossible to distinguish between monotonic and fatigue fractures from the macroscopic fracture appearance in composite materials, while the microscopic failure mechanisms and failure initiation process should be quite different.

Abouelwafa et al [74] studied the biaxial fatigue of woven roving GFRP tubes subjected to in-phase and out-of-phase cyclic bending/torsional moments, their results indicated that, for the out-of-phase loading condition, as the stress level increases, the decrease in fatigue life is much higher than for the in-phase loading condition. For fatigue lives above 20000 cycles, the out-of-phase conditions give longer lives compared with the in-phase conditions.

Ahmed and Khashaba [75] concluded that, in their study of fatigue analysis of unidirectional GFRP composites under combined bending and torsional loads:

1. Unidirectional glass fiber reinforced polyester composites have poor torsional fatigue strength compared with the published results of pure bending fatigue strength.

2. Endurance limit values of GFRP specimens tested under combined torsion/bending loading equal 8.5 times the endurance limit of pure torsion. On the other hand the endurance limit of combined fatigue strength approximately half the endurance limit of pure bending fatigue strength.

Hashin [76] examined the behavior of unidirectional composites under compression – compression cyclic loading. He showed that, under static compression in the fiber

direction, the composite failed because of fiber buckling, and the compressive strength was proportional to the matrix shear strength. Under cyclic loading, fibers buckled at lower loads than that of static loading. This was because of the deterioration of the matrix shear strength due to cycling, and the opening of the longitudinal cracks at the fiber – matrix interface.

Francis [77] studied the fatigue behavior of notched composites under different loading conditions (tension, torsion, or combination of both) using thin-walled tubular specimens made of graphite / epoxy with fiber orientation [±45°] having an average diameter of 25.4 mm and a hole of 4.8 mm diameter at the middle. He found that the S-N curves for axial tension are nearly identical to those of torsion.

2.5.2 Effect of loading frequency

For composites containing thermosetting matrices, it is important to maintain the frequency low enough to avoid extensive heating that would affect the test results. Experimental results show that a two high frequency gives shorter fatigue lifetimes.

Ellyin and Kujawski [78] investigated the frequency effect on the tensile fatigue performance of glass fiber-reinforced $[\pm 45°]_{5s}$ laminates and concluded that there was a considerable influence of test loading frequency. Especially for matrix dominated laminates and loading conditions, frequency becomes important because of the general sensitivity of the matrix to the loading rate and because of the internal heat generation and associated temperature rise.

Kujawski and Ellyin [79] studied the effect of stress rate and frequency on the creep and relaxation behavior of glass reinforced composites during fatigue. They found that, at low stress levels, an increase in cyclic creep rate results as frequency decreases. Hence, the fatigue lives were found to decrease as frequency decreases, with more declines at higher load levels. Longer fatigue lives were reported when frequency increased at low stress levels. On the other hand, fatigue lives were found to decrease at high load levels and frequencies as local heating took place. Also, cyclic creep rates were found to increase at higher load levels and lower frequencies.

Lee and Liu [80] studied the effect of frequency on the fatigue resistance of nylon fiber-reinforced composites. They found that, the fatigue life of composite specimens at given stress amplitude was shorter under higher cyclic frequency, which also lowered the fatigue

endurance limit. They attributed this behavior to a greater rate of heat generation due to hysteretic loss of constituent materials.

The residual strength and fatigue life of composite laminates have been observed to decrease more rapidly when the loading sequence is repeatedly changed after only a few loading cycles [81]. This so-called 'cycle-mix effect' shows that laminates that experience small cycle blocks, have reduced average fatigue lives as compared to laminates that are subjected to large cycle blocks, although the total number of cycles they have been subjected to, is the same for both laminates at the end of the experiment, the frequency can have a major impact on the fatigue life.

2.5.3 Effect of volume fraction V_f

The fiber volume fraction V_f is a ratio between the volume of fiber and the total volume of the composites, the fiber volume fraction can be computed using the following equation:

$$V_f = \frac{W_f}{W_f + W_r},$$
(2.1)

Where:

W_f is weight of fiber,

W_r is weight of resin,

Chamis [82] studied the effect of the fiber volume fraction (V_f) on the mechanical properties of graphite / epoxy unidirectional laminates. Longitudinal and transverse tensile strengths were drawn as functions of (V_f) as shown in Figure 2.2, and he suggested that the optimum load transfer between fiber and matrix when the volume fraction varies between 0.55 & 0.65. and these values were found in many researches [83-89]. Accordingly, it is selected to be in range between 0.50 and 0.67 for present study.
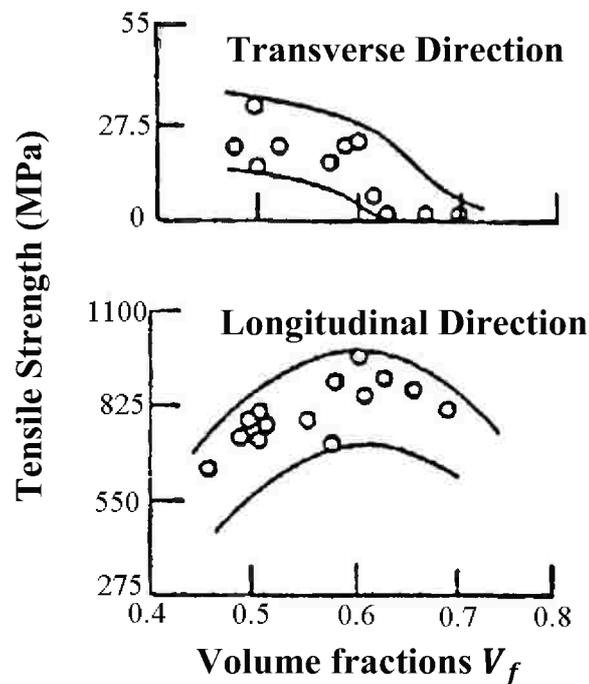
Figure 2.2 Tensile strength of Thornel-50 / epoxy unidirectional composite [82]

2.5.4 Effect of fiber orientation

El-Midany [83] studied the biaxial fatigue behavior of woven-roving GFRP subjected to in-phase and out-of-phase cyclic bending and torsion using thin-walled tubes with two fiber orientations $[\pm45^o]_{2s}$ and $[0,90^o]_{2s}$. He found that the $[0,90^o]_{2s}$ specimens are stronger than $[\pm45^o]_{2s}$ in pure bending and vice versa in pure torsion. For in-phase loading, as well as out-of-phase loading. It was found that for bending to torsion ratios less than 2; the $[\pm45^o]_{2s}$ specimens are much stronger than the $[0,90^o]_{2s}$ specimens. At bending to torsion ratio equals to 2, both types of specimens had nearly the same fatigue strength.

Nassr [84] studied the fatigue behavior of glass fiber-reinforced polyester under torsional loading, via testing thin-walled woven-roving specimens with two fiber orientations $[0,90^o]_{2s}$ and $[\pm45^o]_{2s}$ at negative stress ratios (R); R=-1, -0.75, -0.5, 0. He found that the $[\pm45^o]_{2s}$ specimens had higher torsional strength than the $[0,90^o]_{2s}$ specimens, at any negative stress ratio.

Sharara [85] studied the effect of stress ratio on the fatigue characteristics of glass fiber-reinforced polyester, under uniaxial bending loading using woven-roving tubular specimens with two fiber orientations $[0,90^o]_{2s}$ and $[\pm45^o]_{2s}$ at negative stress ratios (R) of;

-1, -0.75, -0.5, -0.25, 0. He found that the fatigue life of $[0,90^o]_{2s}$ was greater than the corresponding life of $[\pm45^o]_{2s}$ specimens for all applied stress ratios. He concluded that, the specimens with $[0,90^o]_{2s}$ orientation were more suitable for dynamic bending applications.

Elhadary [86, 87], conducted fatigue tests of woven-roving glass fiber-reinforced polyester specimens, with two fiber orientations $[0,90^o]_{2s}$ and $[\pm45^o]_{2s}$, under combined bending and torsional moments, in-phase and out-of-phase, with different Fluctuating stresses resulted in the following conclusions:

1. The $[\pm45^o]_{2s}$ woven-roving GFRP is more fatigue resistant in torsion than the $[0,90^o]_{2s}$.

2. The $[0,90^o]_{2s}$ woven-roving GFRP is more fatigue resistant in bending than the $[\pm45^o]_{2s}$.

Mohamed [88] investigated the fatigue tests of woven-roving glass fiber-reinforced polyester specimens, with fiber orientations $[30°,-60°]_{2s}$ $[\pm45°]_{2s}$, $[0,90°]_{2s}$ and $[-30°,60°]_{2s}$, under combined bending and torsional moments, in phase, with different negative or positive stress ratios resulted in the following conclusions:

1. The $[\pm45°]_{2s}$ woven-roving GFRP is more fatigue resistant in torsion than the $[0,90°]_{2s}$, $[30°,-60°]_{2s}$ and $[-30°,60°]_{2s}$. And the$[0,90°]_{2s}$ have the lowest value.

2. The $[0,90°]_{2s}$ woven-roving GFRP is more fatigue resistant in bending than the $[\pm45°]_{2s}$, $[30°,-60°]_{2s}$ and $[-30°,60°]_{2s}$. And the $[\pm45°]_{2s}$ have the lowest value.

3. The $[30°,-60°]_{2s}$ and $[-30°,60°]_{2s}$ woven-roving GFRP have approximately the same bending and torsional strength, and observation is similar to that found in pure torsion static tests.

The effect of varying of the winding angle on the strength performance of thick, filament wound E-glass fiber reinforced epoxy resin pipes under internal pressure and axial tension or compression was studied by Soden et al [89]. They concluded that the winding angle and stress ratio have a pronounced effect on the associated deformation and fracture strength of GFRE pipe. Three failure envelopes for ±45°, ±55° and ±75° wound pipes produced by Soden show that an increase in winding angle increases uniaxial tensile strength in the hoop direction but decreases tensile strength in the axial direction. Simple validation through netting analysis indicates that the maximum strengths for GFRE pipes with winding angles of ±45°, ±55° and ±75° are achieved when loaded at stress ratios between hoop and axial stress of 1:1, 2:1 and 14:1 respectively.

For the same winding angle of Soden et al [89], Spencer and Hull [50] concluded that, in their study of GFRE pipes to failure under a 2:1 hoop to axial stress ratio:

1. For all winding angles, leakage failures were seen at stress levels much lower than final fracture stresses.

2. For a wound GFRE pipe subjected to an internal pressure with a winding angle within a range of 35° to 55°, matrix cracking after initial plastic lengthening was found to dominate and formed throughout the pipe before weepage occurred. After weepage, extensive whitening developed and shortening of the pipe was clearly evident, accompanied by rotation of the fibers.

3. In pure hoop loading, bursting failure was always associated with fiber fracture in the vicinity where fiber bending was pronounced due to bulging and fiber cross-over. For pipes with higher winding angles, transverse matrix cracking is less significant since the stress generated transverse to the fibers is very relatively small.

Rosenow [90] used laminate theory to predict the stress strain response of GFRE thick pipes with winding angles varying from 15° to 85°, under biaxial pressure loading, hoop pressure loading and tensile loading, which he later compared with experimental results. He found that the optimum winding angle very much depends on stress ratio between hoop stress and tensile stress. The results suggest that the pipe should be wound at 54.7° for biaxial pressure loading, 75° for pure hoop loading and at the lowest possible angle for cases of pure axial loading.

Mistry [91] later continued the work of Rosenow [90] by studying the effect of the same varying winding angles but under combined external pressure and axial compression loads. He showed that failure may result from buckling and material failure, depending on winding angles and stress ratios. And he found that in the case of hydrostatic external pressure loading of the pipes, the optimum angle is close to 80° instead of 55° reported elsewhere for internal pressure loading. Similar failure modes were also observed by Moreno et al. [92] but their results suggested no strong influence of winding patterns on the buckling failure of wound GFRE pipe.

Previous studies have shown that ±θ° helical wound pipe is strong for an intended stress ratio but prone to transverse matrix crack damage when loaded outside the stress ratio. Recently, Mertiny et al [93] experimentally studied the effect of multiangle filament

winding on the strength of filament wound. Their results exhibited good overall performance against initial failure when subjected to various loading conditions, which could provide an advantage in performance over conventional angle ply laminates.

The benefits of multiangle wound GFRE pipes were also discussed by Lea and Yang [94] with regards to their improved tension and bending characteristics compared to the commonly used ±55° wound pipe. However, predicting the failure strength and modes from available failure criteria is complex and can be very cumbersome.

2.5.5 Effect of mean stress and stress ratio

The phenomenological fatigue life models extract information from the S-N curves and possibly propose a fatigue failure criterion. Thus, they do not take into account damage accumulation, but predict the number of cycles at which fatigue failure occurs under fixed loading conditions.

Under cyclic loading it is helpful to separate the loading into mean stress σ_m and stress amplitude σ_a components. In addition to the stress amplitude, the mean stress was found to have an effect on fatigue life and was first quantified by Gerber [95].

Gerber [95] developed an empirical relationship that is often visualized on a constant life curve. A tensile mean stress is harmful to fatigue life and, whilst compressive mean stress effects are usually neglected, an increase in fatigue resistance is sometimes found under those loadings.

Abouelwafa et al. [96] tested woven-roving GFRP specimens with $[0,90°]_{2s}$ and $[\pm45°]_{2s}$ fiber orientations under torsional fatigue loading with different mean stresses. They found out some important conclusions that may be summarized as follows:

1. The mean-stress component is ineffective for specimens under pure local shear stress, $[0,90°]_{2s}$ fiber orientation, to a certain ratio, then the mean stress component is found to have a detrimental effect on the amplitude component for the same life.

2. When specimens were subjected to tension-compression local stress components, $[\pm45°]_{2s}$ fiber orientation, the mean stress was found to have a detrimental effect for all negative stress ratios, and the classical Goodman's equation for normal stresses replaced by the corresponding shear stresses was found to govern the fatigue behavior of woven-roving GFRP.

El-Kadi and Ellyin [97] studied the effect of stress ratio, on the fatigue behavior of unidirectional laminate. They used glass-epoxy specimens subjected to off-axis tensile

loading with different stress ratios. Their results showed that for off-axis loading cases when the stress ratio increases the rate of fatigue strength degradation decreases.

Fatigue behavior of notched and un notched thin-walled woven GFRP tubes under tension/torsion biaxial loading has been investigated by Fujii et al [98] Five ratios of combined stress were used. Their results indicate that, the biaxial stress ratio slightly affects the slope of S-N curves. The slope of S-N curves decreases with an increase of its shear stress component.

Bradely [99] studied the fatigue behavior of unidirectional SiC/Ti-15-3 composite under both tension and compression with different mean stresses. He found that the tensile mean stresses were detrimental and that compressive mean stresses were beneficial to the fatigue strength, which was similar to their effects on the fatigue behavior of metals. Several mean stress models (Smith-Watson-Topper, Walker, Normalized Goodman and Soderberg models) were examined for applicability to this class of composite materials, and the Soderberg approach was shown to best represent the effect of mean stress over the covered range. The other models varied significantly in their predictability and often failed to predict the composite behavior at very high tensile mean stresses.

Elhadary [86, 87], tested of woven-roving glass fiber-reinforced polyester specimens, with two fiber orientations $[0,90^{o}]_{2s}$ and $[\pm45^{o}]_{2s}$, under combined bending and torsional moments, in-phase and out-of-phase, with different Fluctuating stresses, he was concluded that the form of Goodman's equation $\left\{\frac{\sigma_m}{S_u} + \frac{\sigma_a}{S_f} = 1\right\}$ is suitable for representing the effect of mean stress for both orientations $[0,90^{o}]_{2s}$ and $[\pm45^{o}]_{2s}$ under combined bending and torsional moments, in-phase and out-of-phase fatigue loading.

Mohamed [88] studied the fatigue tests of woven-roving glass fiber-reinforced polyester specimens, with fiber orientations $[30°,-60°]_{2s}$ $[\pm45°]_{2s}$, $[0,90°]_{2s}$ and $[-30°,60°]_{2s}$, under combined bending and torsional moments, in phase, with different negative or positive stress ratios resulted in the following conclusions:

1. The form of Goodman's equation $\left\{\frac{\sigma_m}{S_u} + \frac{\sigma_a}{S_f} = 1\right\}$ is suitable for representing the effect of mean stress for both orientations under combined bending and torsional moments with negative stress ratios.

2. The specimens with positive stress ratios have high failure rates for any life. As the stress ratio increases the rate of failure increases.

2.5.6 Effect of Environmental factors

One of the major problems in polymer/Epoxy matrix composites concerns durability under natural environmental exposure such as to moisture and temperature. These conditions are generally recognized to cause degradations in strength and mechanical properties. The durability of GFRE laminates is strongly influenced by its constituents, and notably by the matrix properties. This is because it is usually the matrix or the fiber-matrix interface that is most affected by moisture absorption and temperature changes [44].

Dalmeida et al [100] measured the water absorption behavior of fiberglass pipes and studied the effects of the absorbed water on the mechanical performance of the pipes. They found that:

1. Water absorption was independent of the specimens' direction (longitudinal or transversal to the pipes axis).
2. The tensile strength, and hence the pressure of the composite pipes was not affected by water absorption, although whitening of the pipes was observed from earlier times of immersion. From both these results, it was postulated that debonded fiber/matrix interfaces are acting mainly as interlaminar cracks, and, therefore, have less relevance in respect to the strength behavior of the pipes.
3. Water caused plasticization of the resin matrix and debonding of fiber/matrix interfaces, significantly reducing the stiffness of the pipes. This effect was the most deleterious found and can led to failure modes governed by mechanical restraints of the pipes, such as those found at joints or bended connections.

Zamri et al [101] observed the water absorption of pultruded jute/glass fiber-reinforced unsaturated polyester hybrid composites, which was subjected to various water conditions and their effects on its mechanical properties. They performed the water absorption tests by immersing composite specimens into three different water conditions, namely: distilled water, sea water, and acidic water, which were at room temperature, for a period of 3 weeks. They obtained that, for different water conditions the hybridization of natural fibers with synthetic fibers decreases the maximum moisture absorption and increases the mechanical properties of the composites.

Athijayamani et al [102] studied the effect of moisture absorption on the mechanical properties such as tensile, flexural, and impact strength of randomly oriented natural fibers/polyester hybrid composite. They concluded that:

1. When increasing the fiber content at dry condition, the tensile and the flexural strength increased. But at wet condition, the tensile and flexural strength have a high-level reduction.

2. The impact strength was reduced with the fiber content at dry and wet conditions. Exposure to moisture caused a significant drop in the mechanical properties due to the degradation of the fiber-matrix interface.

Merah et al [103] explored the combined effect of natural and accelerated weathering and seawater on tensile properties of GFRE pipe materials Saltwater filled pipes were exposed to outdoor environment for periods ranging from 6 to 12 months. From the results obtained the following conclusions:

1. Immersing of GFRE pipe specimens into seawater at 12-month outdoor weathering resulted in a reduction of average tensile strength. Because of water saturation of epoxy resin.

2. The plasticization of the GFRE composite indicated by the reduction in stiffness values with increasing exposure period was seen in minor amount.

3. Fractographic analysis showed that water uptake has resulted in weaker interfacial bonding leading to lower tensile properties.

A review by Schutte [104] covered the mechanisms that lead to the degradation of properties of the glass fibers, polymer matrix and their interface. The most significant effect of moisture absorption in polymer composites is the plasticization of the matrix. This resulted in a reduction of the glass transition temperature, hence weakening the matrix. The strength of the bonding between the fiber and the matrix has also been revealed to be degraded in the presence of moisture and higher temperature. It has been suggested that the moisture diffuses along the fibers and weakens the bonds at the fiber-matrix interface. The process is very slow and temperature dependent. Without the strong bonds in the fiber-matrix interface, the weakened matrix system then carries all the load, hence precipitating damage in forms of matrix cracks and delamination.

Lundgren and Gudmundson [105] investigated the rate of moisture absorption in cross ply GFRE laminates containing transverse matrix cracks. They discovered that the moisture absorption filled up the cracks early in the process and very little difference in moisture absorption was observed between the cracked and uncracked laminates.

Kotsikos et al [106] studied the combined effect of an aqueous environment and flexural fatigue on cross ply glass polyester laminates. They observed that the exposed samples exhibited higher crack concentrations of which the damage progressed to the delamination and debonding stages.

Komai et al [107] reported the influence of water absorption on the mechanical behavior and fatigue strength of ±45° angle ply carbon reinforced epoxy laminates. They found that water absorption caused damage to the interface bonding, resulting in decreases of tensile and fatigue strengths.

Perreux and Suri [108] discussed the effects of environmental conditions on filament wound GFRE pipes. They stated that the rate of moisture absorption for tubular-shape specimens is much lower compared to coupon specimens, which resulted in longer times being taken for impregnation. They reported that GFRE pipes can be very susceptible to damage by stress corrosion cracking due to the combined effects of applied stress and corrosive environments.

Vauthier et al [109] looked the impact of the hygrothermal aging on the fatigue behavior of glass/epoxy composites. They reported that immersion in 60°C water caused most damage and led to a drastic decrease in fatigue life.

Ellyin and Rohrbacher [110] and Ellyin [111] studied the effect of moisture and temperature on GFRE laminates subjected to monotonic load. They found that the extent of damage strongly depended on immersion temperature. They then broadened their investigation by testing under cyclic loading three types of laminates: cross ply, multiangle and angle ply. They found that fatigue resistance for immersed samples was higher than in those in a dry environment. This is likely to be due to the closure of defects such as cracks and voids from the swelling of the epoxy resin. High temperatures were also shown to have a significant detrimental effect on the behavior of laminates, yielding reductions in fatigue strength by 35%-65%.

Ellyin and Maser **[112]** studied the same effects of moisture and temperature on the mechanical properties of GFRE pipes and very similar findings were observed. The matrix system in GFRE pipe suffered plasticization and a reduction in glass transition temperature, resulting in a decline in pipe stiffness. Further observations implied that the matrix and fiber exhibited more brittle characteristics at higher temperatures.

Hale et al **[55]** investigated the failure behavior of GFRE pipes subjected to continuous exposure to hot and wet environments at various biaxial loadings. They concluded that the strength of the matrix system was considerably reduced at high temperatures, especially those approaching the resin glass-transition temperature, T_g. The degradation in strength became more critical when hoop to axial stress ratios were further away from 2:1.

Chiou and Bradley **[113]** and Hale et al **[114]** tried to simulate actual working conditions by studying the effects of sea water on GFRE pipes. They concluded that the absorption of seawater caused a significant reduction in the bursting strength of the pipe.

2.5.7 Effect of size and stress gradient

The fatigue strength of metals under conditions of bending and torsion has been observed to vary with size. It was found that this is related to the stress gradient, since no noticeable size effect is apparent under direct loading (tension or compression). It is obvious that failure is likely to occur in larger specimens than in smaller ones; i.e. those having less gradient **[65]**.

The use of a size correction factor has proved good agreement with the actual behavior of metals, being shown in many references. On the other hand, this factor is much more complicated and important for composites, because it does not depend on the size only but on the manufacturing methods also **[83]**.

A complex three-dimensional stress state usually exists near the free edge of the laminates, which can induce delamination under fatigue loading. Because of free-edge delamination it is difficult to relate laboratory fatigue test results to the behavior of structures that may or may not have free edges. Thus, size effect can be an even more important condition in the fatigue design for composites than for metals **[84]**.

2.5.8 Effect of surface finish

Because a fatigue failure generally originates at the surface, it is evident that the surface finish may be of great importance when designing components to withstand fluctuating loads. In metals, a correction factor is used to account for the difference between the surface finish of the actual component and that of the test specimen. For composites, the surface roughness is known to be small for most of the products to attain the glazed surface, but it is also necessary to improve the surface finish of the back layers to minimize this effect [83].

Subramanian et al [115] concluded that both fiber sizing and surface treatment affect the damage mechanisms and fatigue lifetimes of notched and unnotched cross-ply carbon/epoxy laminates under fully reversed cyclic loading.

Finally, the surface condition is of great importance in controlling fatigue damage initiation, growth and accumulation. For example, stiffness degradation in a laminate with machined surface is more severe than in a composite with virgin surface Wang et al [67].

2.5.9 Effect of Stress concentration

When a component is subjected to a fluctuating load, especially for high cycle fatigue, the effect of stress concentration could be quite severe for both ductile and brittle metals, resulting in a considerable reduction in the fatigue life. While in low cycle fatigue, the effect of stress concentration if often considered insignificant; and consequently at static loading [65].

In metals, stress concentration effects are attributed to the presence of stress raisers as notches, holes, sudden change in cross-section, etc. In composites, stress concentration effects appear on a larger scale. They are not only limited to holes, notches, and other well-known factors, but also appear due to the presence of extra resin content, broken fibers, imperfect bondage between fiber and resin and many other factors. Consequently, it is difficult to define a stress concentration factor that takes into account these effects in composites as it was established for metals [83].

2.6 Fatigue Failure criteria

Failure criteria for isotropic and homogenous materials like maximum stress, maximum shear and maximum distortional energy theories have been well established. Such theory

are then further extended and modified to cater for composite materials by taking into account the anisotropic nature of their strength and stiffness. This development of failure models to characterize the mechanisms that lead to failure has been the matter of rigorous study for over 30 years by research workers around the world. At present, countless theories available in the literature describe failure in various ways. This includes whether they are based on strength or fracture mechanics theories, whether they predict failure in a general sense or are specific to a particular failure mode, and whether they focus on in-plane or interlaminar failure. [49].

Table (A3.85) shows the well-known failure criteria for orthotropic materials under plane stress state [83].

In the criteria, all stress components interact and contribute simultaneously toward the failure of the composite systems. Azzi and Tsai [116] and Tsai and Wu [117] failure criteria are the two most commonly used interactive failure criteria in determining the failure of fiber reinforce polymer structures. The Tsai-Hill criterion allows for interaction between different stress components, whereas the Tsai-Wu criterion provides the capability for interaction between direct and shear stresses and accounts for differences between tensile and compressive strength [118]. These criteria assume linear elastic material properties and expect degradations in stiffness after the first ply failure. However, both criteria state only that the material will fail once the limiting stress is reached and do not explicitly identify failure modes.

Tsai Hill's criterion [116] is based on the Von Mises distortional energy criterion. It was later modified by Hill to cover anisotropic materials before been applied to composite materials by Tsai. For orthotropic materials similar to GFRE pipes.

Another widely used interactive criterion was first proposed by Tsai-Wu [117]. The criterion describes the combined stress failure surface in a quadratic polynomial relation represented in chapter (3). The Tsai-Wu criterion can be applied to a laminate and used to find the first ply failure. This can be further extended to be related to a progressive damage model to produce a final failure envelope and predicts the stress-strain response of composite laminates. This criterion is widely used in laminate analysis as it is easy to exercise and can be simplified into a single-valued function which enables an extension to cater for cases of three-dimensional failure [119].

Both the Tsai-Hill and Tsai-Wu failure criteria have been applied extensively in many composite applications. For example, Puck and Schneider [120] modified the Tsai-Hill criterion to construct a micro mechanical failure theory to predict failure strength based on stresses of the fiber, the matrix system and the fiber-matrix interface.

Sim and Brogdon [121] formulated probably the first explicit extension of the Tsai Hill static failure criterion to describe the fatigue behavior of composites under various loading modes. This was achieved by replacing the static strength parameters with fitting fatigue functions that depend on the ratio of the alternating stress to the mean stress as well as the number of load cycles. They found that, the normalized strain energy changes defined separately for normal and shear stresses enable one to determine the master S–N relationship for the off-axis fatigue behavior of composite.

Philippidis and Vassilopoulos [122] further extended the Tsai-Wu criterion to cover cyclic loading to predict the fatigue strength of multidirectional laminates, which was tested under multiaxial loading conditions. They established and validated a new criterion, in fact, FTPF (Failure Tensor Polynomial in Fatigue). They found that, the agreement between experimental values and theoretical predictions is good. And they showed that, the FTPF criterion seems to predict all data under consideration at least with the same accuracy as the Tsai-Wu criterion.

Hashin [123], on the other hand, modified the Tsai-Wu criterion to establish three dimensional theories for unidirectional fiber composites. He then collaborated with Rotem [124] to develop the Hashin-Rotem failure criterion, which was one of the earliest to concentrate on two separate failure criteria: one for fibers and the other for resin. This criterion also enjoys wide popularity among researchers. However, it appears to be suitable only for defining the onset of damage and is more sound in the cases of unidirectional and angle ply laminates than for general composite structures.

2.7 The Smith-Watson-Topper (SWT) parameter

The Smith–Watson–Topper (SWT) parameter, when proved to be valid, it allowed a great reduction in the number of tests required to estimate the effect of mean stress on the fatigue life of metals and some composites. Plotting it, instead of the maximum or the amplitude stress component, against the number of cycles to failure tends to plot a single curve regardless of the value of the mean stress.

In several past decades, research studies accounting for the mean stress effect on fatigue life were based on the conventional S-N approaches, one of this approaches is the Smith-Watson-Topper (SWT). A better fit to the experimental data can be obtained by using SWT parameter ($\sqrt{\sigma_{max}\,\sigma_a}$) proposed by Smith [125].

Conle and Ingall [126] tried to validate the same parameter for composite materials to account for the effect of mean stress in axially loaded cases. They used un-notched, axially loaded GFRP flat specimens, with $V_f = 60$ %, and fiber orientation of [±45°] at room temperature. They found that:

1. The SWT parameter will not work directly for composites as for metals, because of the multiplicity of failure modes. For axially loaded specimens we must use the form ($\sqrt{\sigma_{max}\,\sigma_a}$) for tensile failure, while use the form ($-\sqrt{|\sigma_{min}|\sigma_a}$) for compressive failure.

2. Other types of fatigue loading must require further experimental investigations. In other words, the SWT parameter may and may not work in other cases.

Sauer et al [127] examined un-reinforced axially loaded polystyrene samples, at several tensile mean stress values. They made two groups of tests; the first one was with constant amplitude stress and different mean stresses resulting in varying maximum stresses, and the second group was with constant maximum stress with different combinations of mean and amplitude stresses. When plotting the test results, they used three forms of S-N curves; they used (σ_{max}), (σ_a) or ($\sqrt{\sigma_{max}\,\sigma_a}$) as the ordinate versus the number of cycles to failure as abscissa. The plots indicated that, using the ($\sqrt{\sigma_{max}\,\sigma_a}$), which is the SWT parameter, is slightly better than using (σ_{max}) and both are better than (σ_a). This was because ($\sqrt{\sigma_{max}\,\sigma_a}$) succeeded in showing the effect of mean stress in both types of tests.

Ryder and Walker [128] performed axially loaded fatigue tests with various tensile mean stresses on un-notched quasi – isotropic T300/934 graphite - epoxy specimens. Using the same procedure as Sauer et al. [127], they found that, in this case, both of (σ_a) and ($\sqrt{\sigma_{max}\,\sigma_a}$) represent the data equally well and better than (σ_{max}).

Both of Sauer et al. [127] and Ryder and Walker [128] have found that the SWT parameter can be used exactly in the same manner as it is applied in metals, when expecting a tensile failure mode.

Smith and Owen [129] studied the axial fatigue behavior of low and high reactivity polyester, chopped strand mat specimens. They found that the SWT parameter is a suitable method in depicting the fatigue life of both types of materials under tensile and zero mean stresses. When using compressive mean stresses, they found that this parameter did not work in the same manner, and it failed in representing the test data. They attributed this difference to various microscopic effects that arise in the case of compression, such as fiber or specimen buckling.

Schuetz and Gerharz [130] studied the possibility of differences between tensile and compressive failure mechanisms in axially loaded carbon fiber reinforced plastic. Their tests covered the range of stress ratios from 0.1 to –5, and indicated that the compressive mean stress results are not well represented by the ($\sqrt{\sigma_{max}\,\sigma_a}$) parameter. When they used ($-\sqrt{|\sigma_{min}|\sigma_a}$) instead, the results were better represented, but the lack of further information regarding the failure modes made it impractical to ensure the use of this new form.

Other investigations were done successfully on using the form ($\sqrt{\sigma_{max}\,\sigma_a}$) in tension and ($-\sqrt{|\sigma_{min}|\sigma_a}$) in compression. Ramani and Williams [131] checked their applicability on [0,30°] graphite / epoxy specimens and Sturgeon and Rhodes [132] on [±45°] carbon / epoxy specimens. They both found that using ($\sqrt{\sigma_{max}\,\sigma_a}$) for tensile and zero mean stresses and ($-\sqrt{|\sigma_{min}|\sigma_a}$) for compressive mean stresses work very well for the studied cases.

Nassr [84] checked the validity of the SWT parameter in the form $SWT = \sqrt{\tau_{max}\,\tau_a}$ for woven-roving Glass Fiber-Reinforced Polyester (GFRP) with ([±45°]$_{2s}$ and [0,90°]$_{2s}$) fiber orientations under torsional loading with different negative stress ratios and he found that the SWT parameter was valid. He also tried to check validity of the SWT parameter to other loading conditions, used data obtained from the work of Sharara [85] since the specimens had nearly the same specification as those of his work, and tested under uniaxial bending stress with the same stress ratios. He found the SWT parameter ($\sqrt{\sigma_{max}\,\sigma_a}$) was also valid in this case of loadings.

Elhadary [86, 87] examined the validity of the SWT parameter in the normal stresses form $SWT = \sqrt{\sigma_{max}\,\sigma_a}$ for woven-roving Glass Fiber-Reinforced Polyester (GFRP) with ([±45°]$_{2s}$ and [0,90°]$_{2s}$) fiber orientations under combined bending and torsional moment,

out-of-phase, with different fluctuating stresses, and with different negative stress ratios and he found that the SWT parameter was valid. He also used the power formula $SWT = a_1 N^{b_1}$ and he had resulted in having a nearly constant ratio between (a_1) and the corresponding static strength for both fiber orientations.

Mohamed [88] verified the validity of the SWT parameter in the normal stresses form $SWT = \sqrt{\sigma_{max}\sigma_a}$ for woven-roving Glass Fiber-Reinforced Polyester (GFRP) with ([30°,-60°]$_{2s}$ [±45°]$_{2s}$, [0,90°]$_{2s}$ and [-30°,60°]$_{2s}$) fiber orientations under combined bending and torsional moment, with different negative stress ratios, he found that the SWT parameter was performing only the completely reversed (R=-1) fatigue test and using modified SWT parameter will be sufficient to find out the strength of the material. He also modified the SWT parameter to form $SWT = K_{Wafa}\sqrt{\sigma_{max}\sigma_a}$, and he was plotted the modified SWT parameter against the number of cycles to failure (N) for all fiber orientations and he found that:

1) The new form of SWT parameter was valid for all fiber orientations and also simple to use with comparison to the original form.

2) The modified SWT parameter can be drawn in the same diagram for all fiber orientations instead of the original form that its plot the relation between the SWT parameter against the number of cycles to failure (N) for each of fiber orientations.

3) The modified SWT parameter values can be considered to be constant of 0.5471 with applicable value of slandered deviation of 0.05337 for all fiber orientations.

The SWT parameter has been also applied by Gravett [133] for predicting the fatigue life of Sc S-6 / Ti-15-3 composite under isothermal fatigue. The life prediction was found to be valid for any load – temperature cycle as well as for different fiber volume fractions. But, he drew the attention to a great important point; which is the approach of using the SWT parameter is valid for conditions of matrix-dominated failure mode, as usually the matrix being ductile.

2.8 Fatigue Strength Ratio

One of the important targets of the fatigue work is to find an effective measure for fatigue data analysis to establishing the master S-N relationship that is independent of both stress ratio and fiber orientation in order to predict the fatigue at any arbitrary stress ratio or fiber orientation. The simplest non-dimensional scalar measure for fatigue strength can

be defined as: $\psi = \frac{\sigma_{max}}{\sigma_b}$ which is usually called the fatigue strength ratio, where σ_{max} is the maximum fatigue strength, which is a function of number of cycles to failure, and σ_b is the static strength.

The fatigue strength ratio ψ becomes an effective measure for fatigue data analysis, which was confirmed by Basquin [134] for the fatigue behavior of metals and by Awerbuch and Hahn [135] for the off-axis fatigue behavior of unidirectional graphite/epoxy composites at room temperature.

Since the fatigue strength ratio ψ is defined using only the maximum fatigue stress, it is insensitive to any difference in the waveform of fatigue loading. In order to incorporate the sensitivity to different modes of loading, the stress ratio R, defined as: $R = \frac{\sigma_{min}}{\sigma_{max}}$ was used by Kawai [136], He decomposed σ_{max} into two parts $\sigma_{max} = \sigma_a + \sigma_m$. Where σ_a and σ_m represent the alternating stress and mean stress, respectively, and are expressed as: $\sigma_a = \frac{1}{2}(1 - R)\sigma_{max}$ and $\sigma_m = \frac{1}{2}(1 + R)\sigma_{max}$. Using σ_a and σ_m, he confirmed that the static failure condition $\sigma_{max} = \sigma_b$ is expressed as: $\frac{\sigma_a}{(\sigma_b+\sigma_m)} = 1$. And by analogy to ψ, therefore he defined a non-dimensional scalar quantity Ψ as: $\Psi = \frac{\sigma_a}{(\sigma_b+\sigma_m)}$, or with the help of R, Ψ can be expressed as: $\Psi = \frac{\frac{1}{2}(1-R)\psi}{1-\frac{1}{2}(1+R)\psi}$.

This means in the case of completely reversed tension-compression fatigue loading (R=-1), $\Psi_{(R=-1)} = \psi$. This explains that the non-dimensional scalar measure Ψ is generalization of the fatigue strength ratio ψ.

The non-dimensional scalar measure Ψ was called the modified fatigue strength ratio. As for fatigue behavior of metals, it is demonstrated by Landgraf [137] that the mean stress effect can be accounted for using the modified fatigue strength ratio Ψ in the fatigue data analysis.

Kawai [136] studied the validity of Ψ for the off-axis fatigue behavior of unidirectional composites, using the experimental results of El Kadi and Ellyin [97] conducted on a unidirectional glass/epoxy composites with 0°, 19°, 45°, 71°, 90° fiber orientations at variety of stress ratios, R = -1.0, 0, 0.5 as plots of the maximum fatigue stress σ_{max} and modified fatigue strength ratio Ψ against the number of reversals to failure on logarithmic scales, he observed that:

1. The off-axis S-N relationship plotted using the maximum fatigue stress σ_{max} depends on both fiber orientations and stress ratios.

2. The modified fatigue strength ratio Ψ eliminated the fiber orientation dependence as well as the mean stress dependence.

3. Finally he confirmed that the modified fatigue strength ratio Ψ becomes a unified strength measure to cope with the mean stress effect as well as the fiber orientation effect on the off-axis fatigue behavior of unidirectional composites undergoing constant amplitude stress cycling over a range of stress ratios.

Elhadary [86, 87] examined the validity of the modified fatigue ratio Ψ for woven-roving Glass Fiber-Reinforced Polyester (GFRP) with ([±45°]$_{2s}$ and [0,90°]$_{2s}$) fiber orientations under combined bending and torsional moment, out-of-phase, with different fluctuating stresses, and with different negative stress ratios and he found that the modified fatigue ratio Ψ was valid for establishing the master S-N relationship.

Mohamed [88] verified the validity of the modified fatigue ratio Ψ for woven-roving Glass Fiber-Reinforced Polyester (GFRP) with ([30°,-60°]$_{2s}$ [±45°]$_{2s}$, [0,90°]$_{2s}$ and [-30°,60°]$_{2s}$) fiber orientations under combined bending and torsional moment, with different negative stress ratios, he found that the modified fatigue ratio Ψ has become useful measure for establishing the master S-N relationship.

2.9 Aim of The Present Work

The wide literature indicates that, all researches conducted on composite materials subjected to pure static or dynamic pressure, pure bending, pure torsion or combined bending and torsional moments. The combined bending moments and pressure with different working pressure was not studied for composite materials. In the present work, there are many targets:

1. The main target is to study the fatigue behavior of Woven-roving Glass Fiber Reinforced Epoxy (GFRE) subjected to combined completely reversed bending moments and internal hydrostatic pressure. One working pressure dose not enough to get clear information about the investigation for the effect of internal pressure load on fatigue behavior. This is to be performed by testing the specimens under different ratios between the applied pressure and burst pressure equal to (0, 0.25, 0.5 and 0.75).

2. The second target is to improve the mechanical and fatigue behavior of multilayer composite tubes of Woven Roving Glass Fiber Reinforced Epoxy (GFRE). This is to be

established using a new methodology for specimen manufacturing (M_2). Then the test results from this method are to be compared with the other test results obtained from the old method of specimen manufacturing (M_1). Two fiber orientations, $[0^o,90^o]_{3s}$ and $[\pm45^o]_{3s}$ are to be considered for each specimen manufacture method to study the effect of fiber orientations on the fatigue behavior of Woven-roving Glass Fiber Reinforced Epoxy (GFRE) pipe subjected to completely reversed pure bending or torsional moments, and combined completely reversed bending moments and internal hydrostatic pressure, and then the test results will be used to plot the corresponding stress-strain and S-N curves.

3. Checking the validity of the Smith-Watson-Topper (SWT) parameter.

4. Checking the validity of the modified fatigue strength ratio (Ψ).

5. Find out a suitable failure criteria, for the case under study.

6. Design an artificial neural network (ANN) for case study to predict the fatigue life of composite materials.