DESIGN AND ANALYSIS OF FILAMENT WOUND COMPOSITE TUBES

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ABSTRACT

DESIGN AND ANALYSIS OF FILAMENT WOUND COMPOSITE TUBES

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This thesis is for the investigation of the design and analysis processes of filament wound composite tubes under combined loading. The problem is studied by using a computational tool based on the Finite Element Method (FEM). Filament wound tubes are modeled as multi layered orthotropic tubes. Several analyses are performed on layered orthotropic tubes by using FEM. Results of the FEM are examined in order to investigate characteristics of filament wound tubes under different combined loading conditions. Winding angle, level of orthotropy and various ratios of the loading conditions were the main concerns of the study. The results of the FEM analysis are discussed for each loading condition. Both pure loading and combined loading analysis results were consistent with the ones mentioned in literature, such as optimum winding angles, optimum loading ratios and optimum level of orthotropy. Modeling parameters, assumptions and source of errors are also discussed. Finally, the required data is obtained for the design of filament wound composite tubes under combined loading.

Keywords: filament wound, composites, finite element analysis, orthotropic

ÖZ

FİLAMAN SARGI TÜPLERİN TASARIM VE ANALİZİ

BALYA, Bora
Yüksek Lisans, Makina Mühendisliği Bölümü
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Bu çalışma kombine yükler altındaki filaman sargı tüplerin tasarım ve analiz çalışmasını içermektedir. Filaman sargı tüplerin çeşitli kombine yükler altındaki davranışının incelenmesi için Sonlu Elemanlar Analiz (SEM) tekniği kullanılmıştır. Filaman sargı tüpler, SEM tekniği kullanılarak tabakalı ortotrop tüpler olarak modellenmiştir. Tabakalı tüpler üzerinde değişik yüklemeler için çeşitli analizler yapılmış ve tasarım için gerekli veriler elde edilmiştir. Sarım açısı, ortotropluk seviyesi ve yükler arasındaki oran özellikle dikkate alınmıştır. Elde edilen sonuçların optimum sarım açısı, yükler arasındaki optimum oran, ortotropluk seviyesi vb. açılardan literatürde belirtilen değerlerle uyumlu olduğu görülmektedir. Ayrıca, sonlu eleman modelinin değişkenleri, hata kaynakları ve modelleme sırasında yapılan varsayımlar da tartışılmıştır. Sonuç olarak kombine yükler altındaki filaman sargı tüplerin tasarımı için gerekli olan veriler elde edilmiştir.

Anahtar Kelimeler: filaman sargı, kompozit malzemeler, sonlu eleman tekniği, ortotrop

To My Parents

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x,y,z	Rectangular coordinates
r,θ,z	Cylindrical coordinates
σ_{ij}	Stress components
τ_{ij}	Shear stress components
ε_{ij}	Strain components
γ	Shear Strain components
u,v,w	Displacement components
E_{ij}	Modulus of elesticity components
G_{ij}	Shear modulus components
ν_{ij}	Poison’s ratio components
α	Winding angle

CHAPTER 1

COMPOSITE MATERIALS AND FILAMENT WINDING

1.1 INTRODUCTION

In this chapter, a brief description of composites and filament winding process will be presented. In more details, the following section will describe components of composite materials. Commonly used resin systems and fibers will be defined in details. In the third section, metals and composite materials will be compared. The fourth section will include some basic definitions and general information about filament winding process. Finally, in the last section, a survey of up to date studies performed on filament winding will be presented.

1.2 COMPOSITE MATERIALS

Composites are the materials that are composed of at least two components and form a new material with properties different from those of the components. Most composites are composed of a bulk material and a reinforcement material, generally fibers.

The reinforcement materials usually have extremely high tensile and compressive strength. However, these theoretical values are not achieved in structural form. This is due to the surface flaws or material impurities, which results in crack formation and failure of the piece below its theoretical strength [1]. In order to overcome this problem, reinforcement is produced in fiber form, which prevents crack formation through the whole body. However, a matrix should be used to hold these fibers together, and improve material properties in the transverse direction of the fiber. The matrix also protects the fiber from damage, as well as spreading the load equally to each individual fiber.

The material properties of a composite are determined by the properties of matrix and fiber, volumetric ratio and orientation of the fibers. The volumetric ratio of fibers is mainly determined by the manufacturing method used. The higher the volumetric ratio, the closer will be the properties of composite and fiber. Orientations of the fibers are also important, since fibers have superior mechanical properties along their lengths.

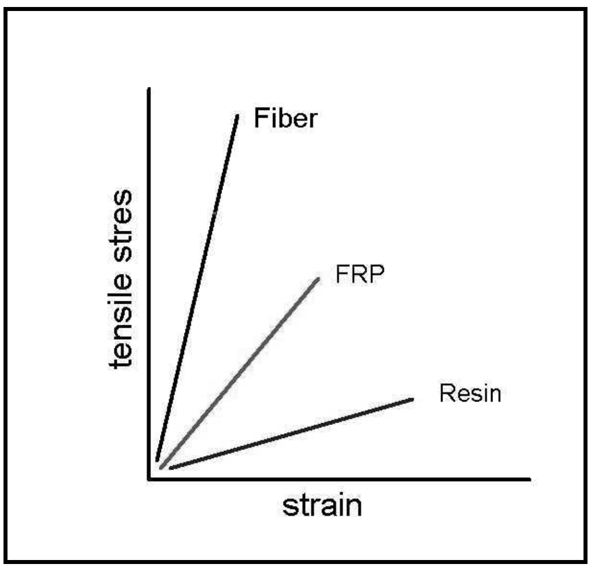

Figure 1.1 – Comparison of Fiber, FRP and Resin Mechanical Properties [2]

Composites have an increasing popularity in engineering materials, with their stiffness and strength combined with low weight and excellent corrosion resistance [1]. By studying the variable properties of composite materials, engineers use the advantage of anisotropy included within composite materials. By building a structure by properly selected resin, fiber, layer orientation and curing, optimization is successful in most cases.

1.2.1 MATRIX COMPONENTS OF COMPOSITES

Considering matrix components, modern composites can be classified in three main groups: Polymer Matrix Composites, Metal Matrix Composites and Ceramic Matrix Composites.

Polymer Matrix Composites is the most common group, which is also known as Fiber Reinforced Plastics (FRP). The components of FRP are polymer-based resins (Epoxy, Polyester, Vinyl ester, etc.) as the matrix and glass, carbon or aramid fibers as the reinforcement. Matrix components of FRP can be classified as thermoset and thermoplastic, according to the effect of heat on their properties. Thermoset resins perform a non-reversible chemical reaction. When heated above a certain temperature, which is called the glass transition temperature, its molecular structure transforms into a softer polymer structure. In this phase, mechanical properties are low and failure can occur easily. When cooled, it reverses the event and if not deformed in soft phase, gets its mechanical properties back. On the other hand, thermoplastics melt with heat, reversing the curing operation. They do not loose their properties even if melted, reshaped and cooled several times.

Although there are number of resins employed in industry, most common ones are polyester, vinyl ester and epoxy [3].

The term ‘Polyester’ is used for the unsaturated polyester, which is a thermoset resin. It has two common types: Orthophthalic Polyester and Isophthalic Polyester. Orthophthalic Polyester is used in a number of areas due to its low price, whereas Isophthalic Polyester is preferred in marine applications due to its water resistance [2].

Polyester is used with accelerators and catalyst. Accelerator makes it possible to cure at low temperatures more rapidly, whereas catalyst simply starts the reaction and is not involve in polymerization. The amount of mixed catalyst and accelerator affects the resultant material properties. Fillers, such as fire resistance fillers, color fillers, etc., can be used to improve desired properties [2].

Polyester has low adhesive properties and high shrinkage up to 8%. Heat decomposition temperature of polyester ranges from 60 to 205ºC. Elongation at break is within a range of 5 to 12% [4].

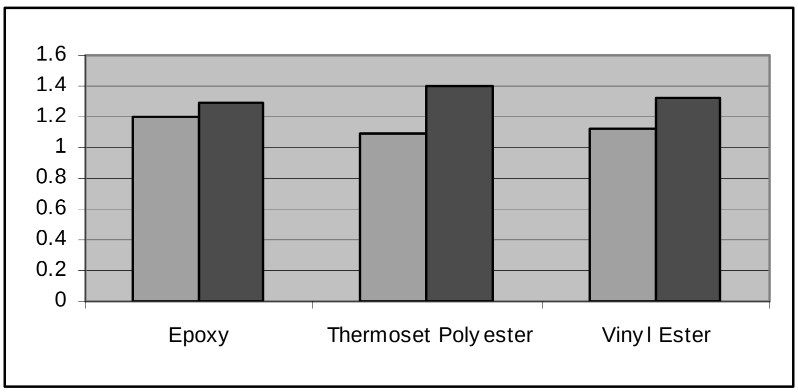

Figure 1.2 – Specific Gravity Ranges of Commonly Used Resin Systems [4]

Vinyl ester resins do not have high mechanical properties as epoxy, but are cheaper. Since vinyl ester is less prone to hydrolysis when compared with polyester, it is used as a coating material in marine industry. It has a tougher molecular structure and higher adhesive strength when compared to polyester resin. Heat decomposition temperature of vinyl ester resins range from 93 to 135ºC. Elongation at break is within a range of 3.5 to 5.5% [4].

Epoxy resins have high mechanical properties, as well as a high environmental resistance. Depending on the type of curing agent, they can be cured at any temperature. They have a high adhesive strength and they can be used as an adhesive material. Therefore, they are preferred when a honeycomb structure is used. Their shrinkage is as low as 1% and they have superior fatigue resistance [2]. A hardener, instead of a catalyst, cures epoxy resin. The amount of hardener used affects the material properties, since it can also react with cured epoxy. Epoxy resins have a coefficient of thermal expansion in a range of 50 to 80 μm/m per ºC. Their poison ratio ranges within 1 to 5% [4].

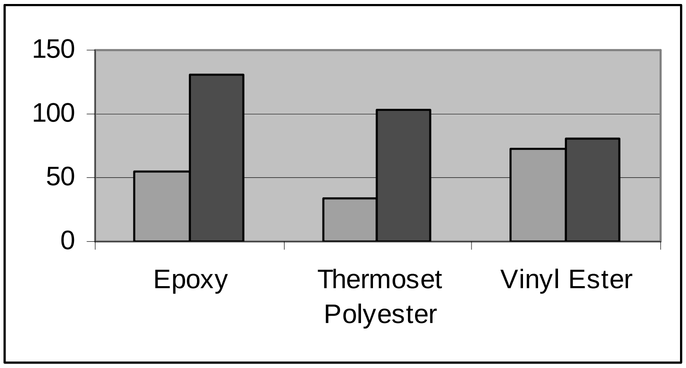

Figure 1.3 – Tensile Strength Ranges (MPa) of Commonly Used Resin Systems [4]

The amount of heat supplied and the type of hardener for epoxy; or the amount of accelerator used for polyester and vinyl ester, affects curing time of the resin. As a general rule for epoxy, higher the curing temperature, the higher will be the mechanical properties. Post curing will also improve the mechanical properties and affect the glass transition temperature of a resin system.

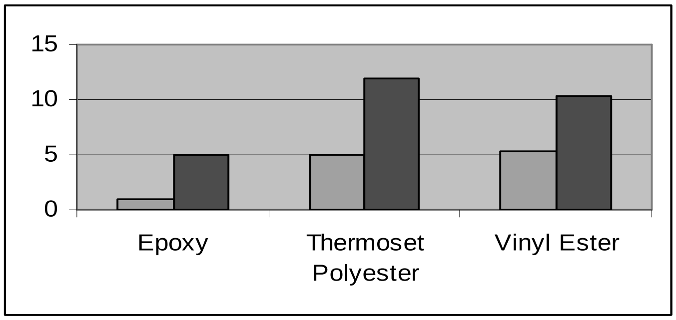

Figure 1.4 – Cure Shrinkage Ranges (%) of Commonly Used Resin Systems [4]

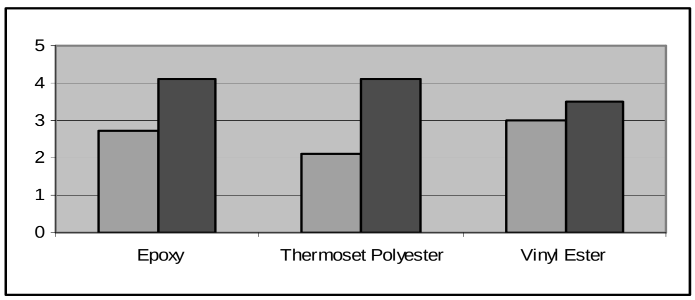

Figure 1.5 – Tensile Modulus Ranges (GPa) of Commonly Used Resin Systems [4]

A resin system should have high toughness, good adhesive and environmental resistance properties [3]. It should also have high stiffness and ultimate tensile strength similar to fiber, as well as high failure strain (Fig. 1.6). Failure strain of the matrix should be at least equal to fiber failure strain. This will prevent matrix failure before fiber fails. High failure strain is a sign of high toughness, which also indicates crack resistance behavior. In addition, adhesive properties are important that loads should be transferred to each fiber equally and neither cracking and nor debonding should be promoted. Other common resin systems used in composites are phenolics, polyimides and silicones [2].

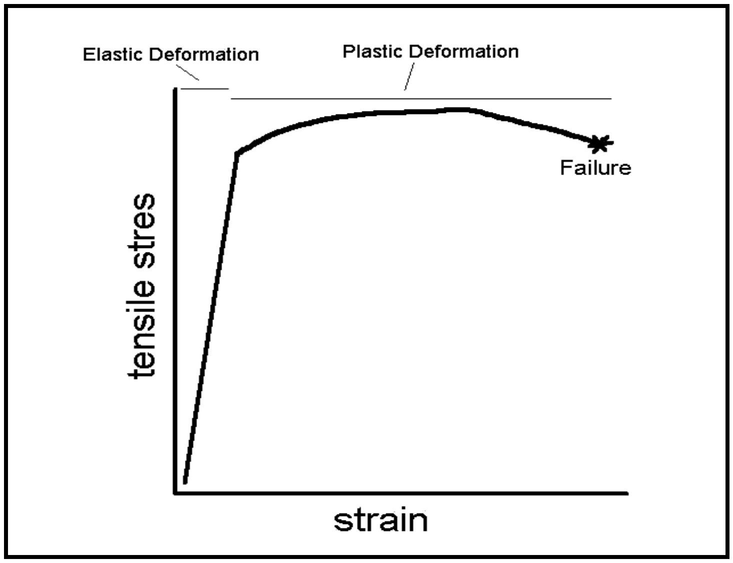

Figure 1.6 – Ideal Resin Material Properties Characteristics: high stiffness and ultimate tensile strength, high failure strain [2]

Metal Matrix Composites use metals (aluminum, titanium, alloys, magnesium alloys, nickel based super alloys, stainless steel, etc.) as the matrix and a variety of fibers (silicon carbide, etc.) as reinforcement. They are mainly used for high temperature applications [2]. Ceramic Matrix Composites, which are used in extremely high temperature and frictional environments, composed of ceramics (aluminum oxide, carbon, silicon carbide, silicon nitrate, etc.) as the matrix and short fibers as reinforcement.

1.2.2 FIBER COMPONENTS OF COMPOSITES

There are four important characteristics of a fiber, which influences the mechanical properties of the composite: mechanical properties of fiber, coating of fiber, volumetric ratio of fiber, and orientation of fiber. Mechanical properties depend on the material used to manufacture a fiber. Coating of a fiber is generally used in particular resin systems and they are announced within fiber specifications. Coating of a fiber affects the bounding force between fiber and the matrix, which has a great influence on strength. Volumetric ratio of the fiber is greatly affected by the production method used. As a rule, stiffness and strength of a composite part increases as the volumetric ratio fiber within composite increases. However, after a ratio of around 65%, generally, strength of the composite part will start to decrease. The reason for this is that, the matrix cannot hold fiber together properly [2]. The stiffness of the composite part will continue to increase even after a volumetric ratio of 65%.

There are four commonly used fibers in industry: E-Glass, S-Glass, Aramid and Carbon.

E-Glass is the cheapest type of glass fibers. Strength and stiffness of E-Glass fiber are high. However, impact resistance is not so good. Electrical resistance, fire resistance and strain at failure of E-Glass are high. It is cheaper than other fibers, which are mentioned [2].

S-Glass has higher tensile strength and stiffness than E-Glass, but it is more expensive than E-Glass. It is commonly used in aerospace and defense industries. S-Glass is also referred as R-Glass (Vetrotex-Europe) or T-Glass (Nittobo-Japan) in industry [2].

Aramid is the name used for the organic polymer, aromatic polyamide. Kevlar (Dupont), Technora (Teijin) or Twaron (Akzo Nobel) are the trademark names, which are commonly used for aramid [2]. It has high strength and low density and thus specific strength of aramid fibers is high when compared to that of other fibers. Impact resistance is also high, which gives rise to ballistic applications of aramid fibers. Chemical and abrasion resistances are good, but resistance to ultraviolet light is poor. High fire resistance, high thermal insulation, low cost and low thermal expansion are other superior properties, while low compressive strength and low flexural strength are bad properties of aramid fiber.

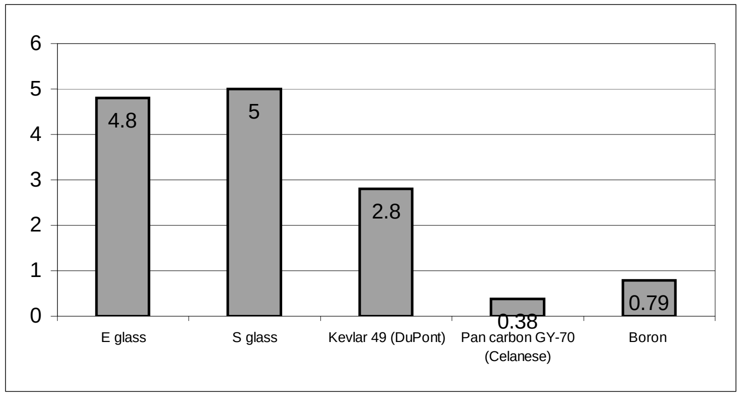

Figure 1.7 - Strain at Failure (%) of Various Fibers [4]

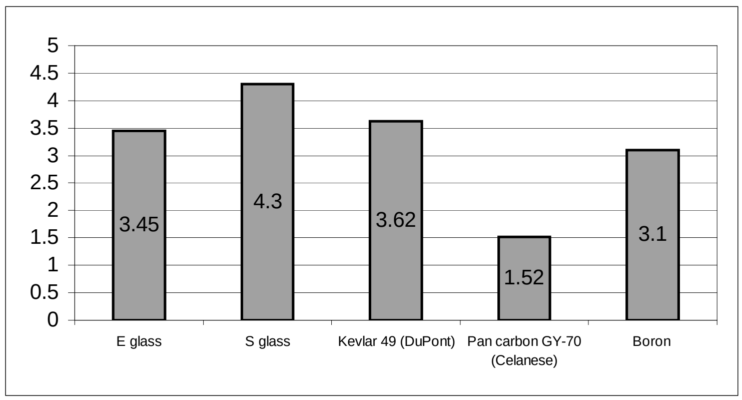

Figure 1.8 - Tensile Strength (GPa) of Various Fibers [4]

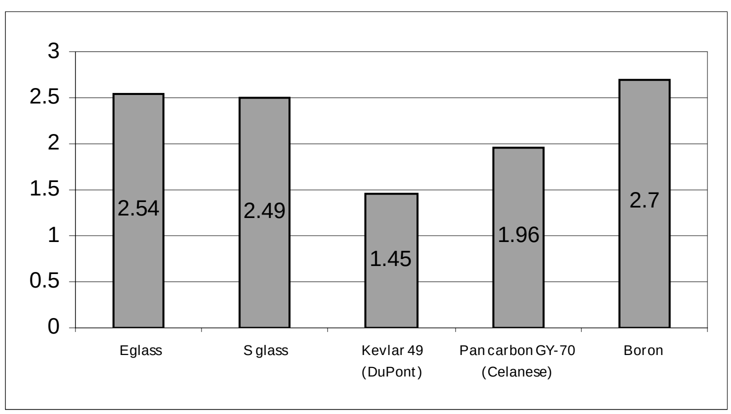

Figure 1.9 - Specific Gravity of Various Fibers [4]

The most commonly known carbon fiber material is PAN (polyacrylonitrile) [2]. A high modulus and high strength fiber can be produced from PAN. Carbon fibers can be produced in between these two extremes to form desirable properties. They have high tensile and compressive modulus, high compressive and tensile strength, high flexural strength and modulus when compared with other types of fibers. Therefore, use of carbon in a composite structure raises orthotropic behavior. Fatigue resistance of carbon fiber is also high. It has a low thermal expansion coefficient. On the other hand, fire-resistance, impact resistance, electrical insulation and thermal insulation characteristics are low. Carbon is the most expensive one of all fiber types.

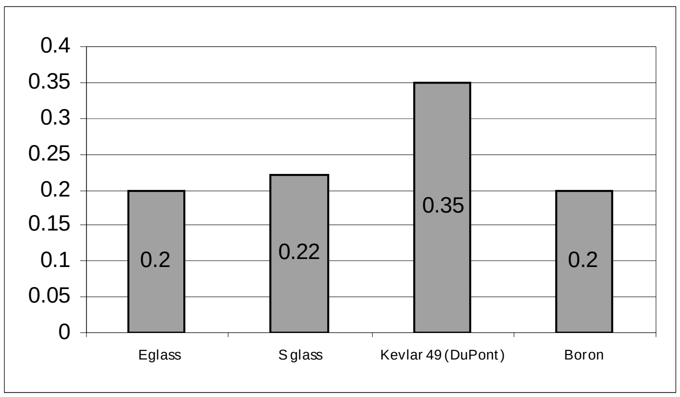

Figure 1.10 – Poison's Ratio of Various Fibers [2]

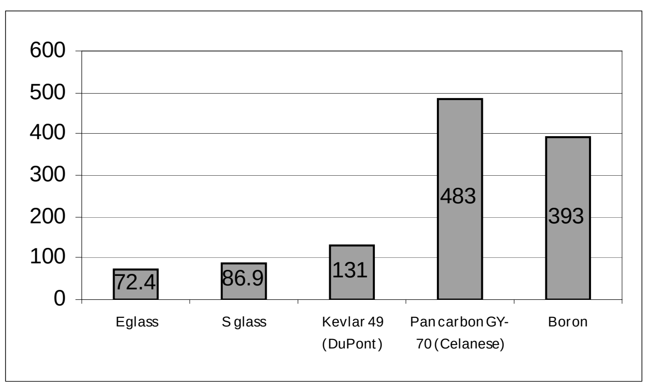

Figure 1.11 - Tensile Modulus (GPa) of Various Fibers [4]

Other types of fibers are polyester, polyethylene, quartz and boron [3]. Boron fiber is produced by coating carbon or metal fibers. Extreme cost of this fiber restricts usage of boron fiber to space applications.

1.3 COMPARISON OF COMPOSITE MATERIALS AND METALS

Regarding the design stage, composites and traditional metals are somewhat different. Designing structural components, using metals are usually straightforward. The geometry of the structural element is designated first, and then the material and production method is defined at the final stage. However, composites require the material to be designed along with the structure. Therefore, optimization of the design and iterations are usually required in the first steps of composite design. The verification of the complete design, which is done by testing, is also very important in composite structures.

Considering geometrical form, composites can give large design flexibility for the designers. Having a large number of manufacturing alternatives, almost all geometries can be produced with a low cost production and tooling. Fasteners or parts can be removed with a unique composite part production. This minimizes the cost and increases weight efficiency of designed structures.

Electrical properties also make composites functional for designers. They can also be used for conductor parts when they are produced with some filler types. Composites have lower specific gravity when compared to traditional material (Fig. 1.12).

Most of the composite materials have higher specific modulus of elasticity when compared to traditional metallic materials. This is due to low specific gravity of composite materials. A comparison of modulus of elasticity and specific modulus of elasticity of various materials can be seen in Fig. 1.13 and 1.14.

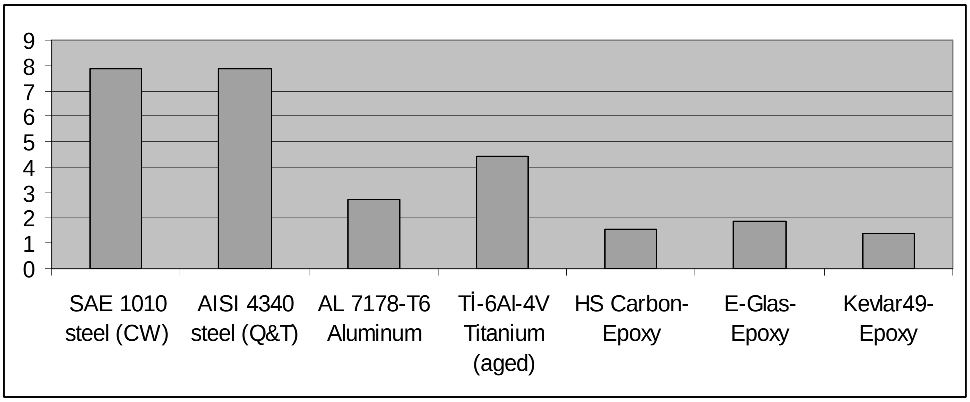

Figure 1.12 - Specific Gravity of various materials [4]

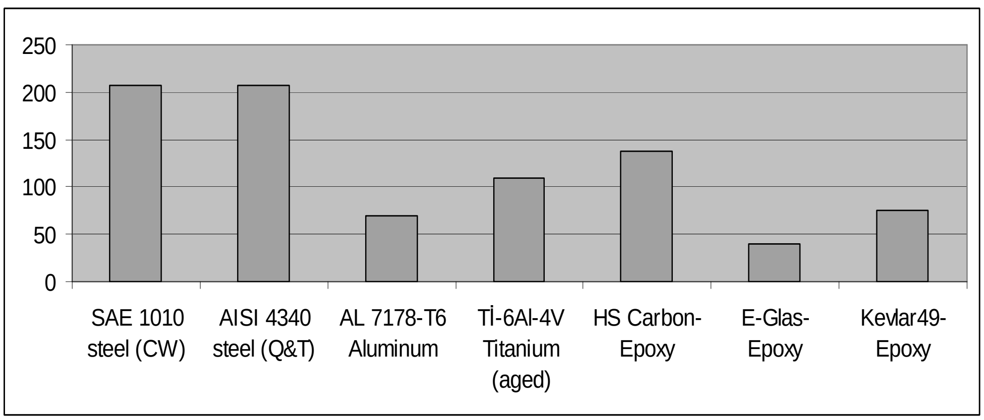

Figure 1.13 – Modulus of Elasticity of various materials (GPa) [4]

Both strength and specific tensile strength properties of composites are higher than most of the traditional metallic materials. Comparison of tensile strength and specific tensile strength of various materials can be seen in Fig. 1.15 and 1.16.

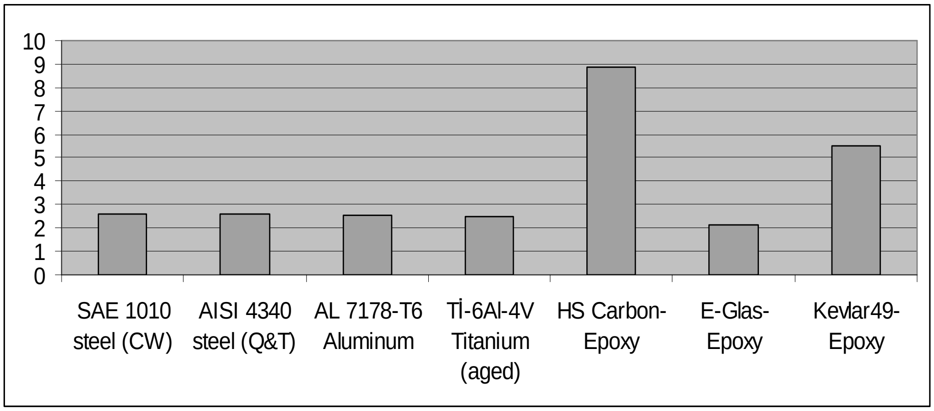

Figure 1.14 – Specific Modulus of Elasticity of various materials (10^9m) [4]

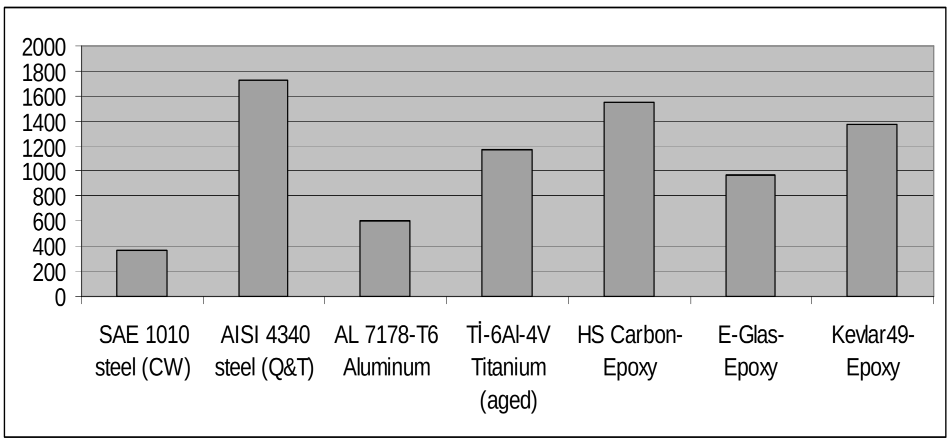

Figure 1.15 - Tensile Strength of various materials (MPa) [4]

Composites also have a higher fatigue resistance. Therefore, aerospace and automotive industry commonly employs high performance composite parts. Another important characteristic of composites is their low coefficient of thermal expansion.

Composites are also resistant to rusting or corroding. So, they are widely used in military, marine or water system applications. Acid resistance is another point, which makes composites superior to metals. There are some chemicals, which effect molecular structure of polymer based composite materials. Nevertheless, surface coating can be solution to this problem.

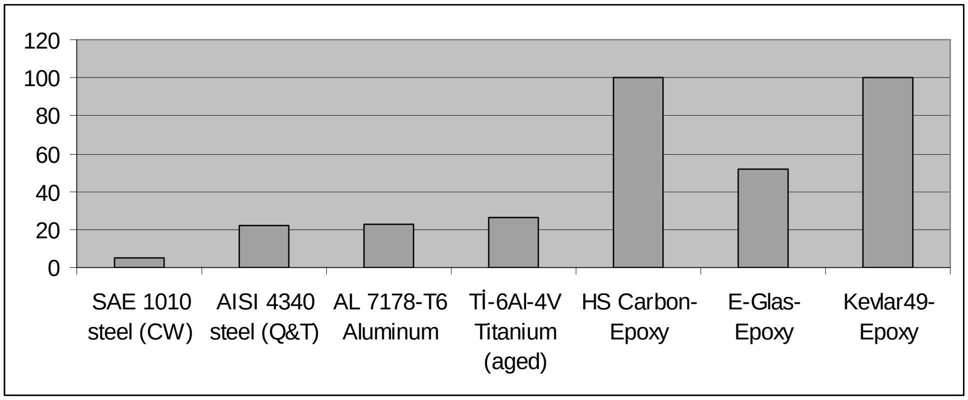

Figure 1.16 – Specific Tensile Strength of various materials (10^6m) [4]

Surface finishes of composites are also good. Although quality of a surface depends on manufacturing method, composites generally do not require a surface treatment. They can be directly painted with most of the metallic or non-metallic paints.

All above-mentioned characteristics make composite an essential source for structural engineering design. The increasing practice of composites in all brands of industries gives rise to development of new concepts in composite structures. These ascend will further increase the fraction of composite materials in engineering structures.

1.4 FILAMENT WINDING

Filament winding is a type of composite manufacturing process, where controlled amount of resin and oriented fibers are wound around a rotating mandrel and cured to produce the required composite part. It was initially used to produce pressure vessels, water and chemical tanks. The development stage of filament winding goes back to dry wire winding of rocket motor cases, which requires reinforcement. Today, the applications include aircraft fuselages, wing sections, radomes, helicopter rotor shafts, high-pressure pipelines, sports goods and structural applications of all types.

Most filament winding machines look like a lathe. The mandrel is supported horizontally between a head and tail stoke. The tail stoke is free, but head stoke is driven by required angle and speed, using a computer program. As the mandrel rotates, a carriage travels along the mandrel and delivers fiber with a given position and tension. Carriage motion is also controlled by the computer; in connection with head stoke rotation.

Winding machines are characterized by their degrees of freedom. Two of these degrees of freedoms are already defined: rotation of head stoke and horizontal movement of the carriage. Other commonly used degrees of freedoms are vertical and rotational motion of the delivery eye.

Fibers pass through a resin bath after tensioning system and gets wet before winding operation. When a pre-impregnated fiber or prepreg is used, wetting is not performed.

Tensioning system is an important part of filament winding. This importance gets critical when winding at high angles. Since tension changes the friction force between fiber and the mandrel, it should be kept at a certain value during winding operation. Fiber tension also affects the volumetric ratio of composite at a given point. Excessive resin, due to a low tension, can result in decreased mechanical properties. Therefore, tensioning systems should be capable of rewinding a certain value of fiber. This condition occurs when fiber band reverses at the end of tube, while winding at low angles.

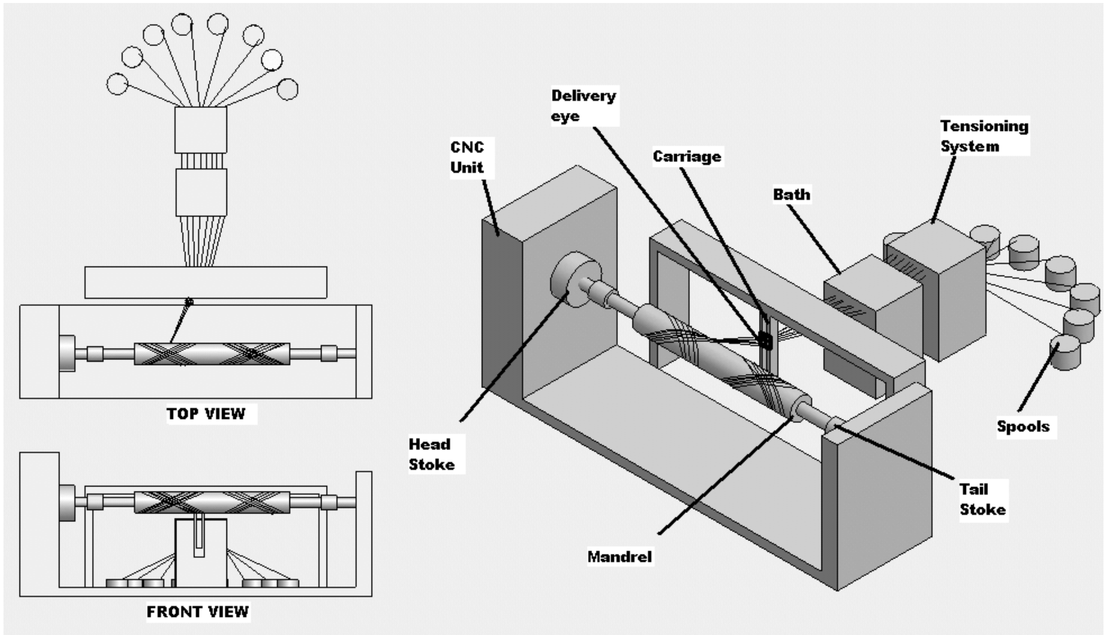

Figure 1.17 – Schematic View of a Filament Winding Machine

Wetting can be done by two commonly used bathing type; drum bath and dip bath. Drum bath provide less fiber damage than dip bath. This is especially important when using carbon fibers. On the other hand, dip bath provides a better wetting action. If fibers are not wetted in a desired way, air bubbles can be trapped between them and can cause voids in the composite part. Therefore, drum baths can be heated for a better wetting action.

Lowering resin viscosity, reducing fiber speed, increasing fiber path on the drum are other methods used for better wetting action. Dip baths are used with aramid or glass fibers. If heated resin is to be used, dip baths are preferred since drum surface cools as it leaves the resin bath. During the travel of fiber through a dip bath, non-rotating surfaces are used for guidance. Non-rotating surfaces provide good wetting, and prevents fiber built out due to broken fibers at rotating surfaces.

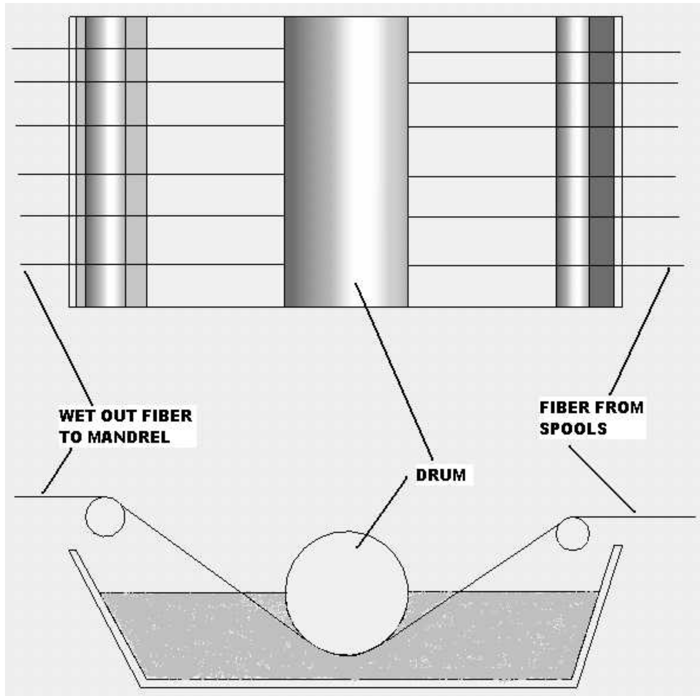

Figure 1.18 – Schematic View of a Drum Bath

Delivery eyes can be in a variety of different shapes. The shapes are defined according to the type of application and type of fiber. Like all other fiber-connecting parts, wear should be evaluated by use of hard aluminum parts and chrome coated steel parts.

Rotating mandrel can be a part of the produced composite part (such as in production of a pressure vessel with a liner) or can be removed from composite part (such as a composite tube). If it will be removed, a press should be used for removing. All mandrels, which will be removed, should have low thermal expansions in order to reduce residual stresses after curing action. Steel is generally used when producing mandrels. If a tube is used as a mandrel, tube thickness should be uniform, in order to have a symmetric composite part. In addition, surface finish is an important point, since an interface between the composite part and mandrel is generally not permitted.

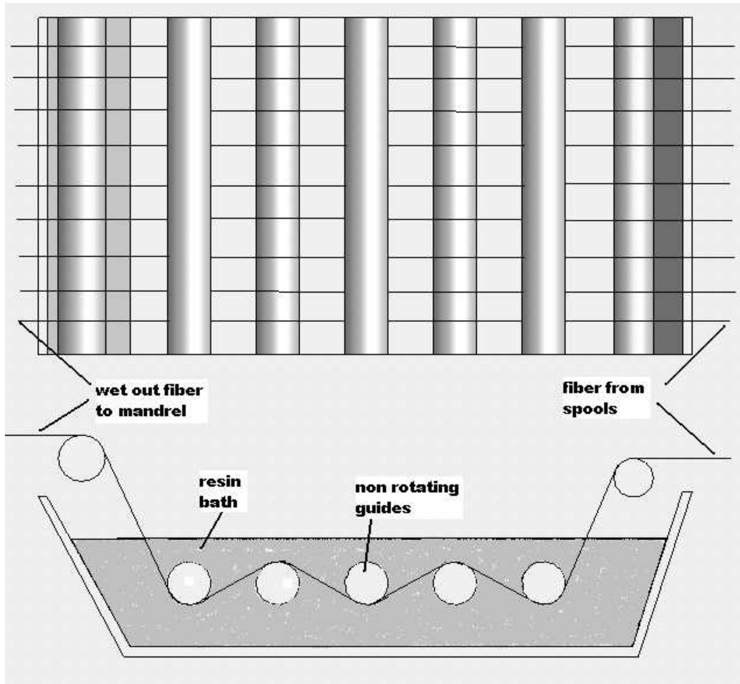

Figure 1.19 – Schematic View of a Dip Bath

If a concave part is needed on the filament wound part, a female mold can be used. In addition, excessive wet fiber can be used in order to fill concave parts. Metal parts can be mounted on mandrel in order to guide winding action.

Winding angle is the angle between fiber and the line on surface of the mandrel, which is parallel to mandrel axis. A maximum value, which is close to 90 degrees, can be approximated. Very low winding angle values need some arrangements at the ends of the mandrel, such as pins, etc.

There are many reasons to use filament winding as a composite manufacturing method. First, many part such as rocket motor cases or pressure vessels require reduced radius at the end openings. For these applications, generally a metal, plastic or rubber liner is used. Rubber liners require a dissolvable material in order to support the rubber liner.

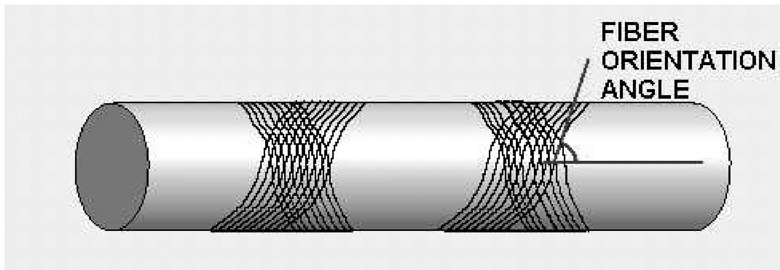

Figure 1.20 – Fiber Orientation Angle

Secondly, filament winding is an effective way to produce high strength tubes. This situation holds especially when there exists an internal pressure. In addition, it is even possible to wound endless tubes for pipelines, etc. Having no connection points, endless tubes are more economical and reliable. Winding angles can also be arranged in order to optimize the design for several usage purposes.

It is possible to use filament winding for reinforcement. Thick pressure vessels, rocket motor cases are all examples of this kind of applications. As mentioned before, filament winding can even be used to reinforce concrete columns.

When designing and producing a filament wound tube, one has to consider many possibilities and limitations. The first limitation will be the winding machine used. For complex geometries, machines that are more complex should be employed. The dimensions of the machine, the number of degrees of freedom, control unit used and the pattern generation software directly affect the limits of winding action. A three or four axis computer controlled filament winding machine will be practical for most cases. Today, use of high-tech robotic winding machines even makes it possible to wind T joints of pipes.

Second limitation will be the mandrel geometry that is used. Concave geometries are generally not permitted. Sharp edges should be avoided in order not to cut fibers. End edges should not restrict returns of winding. Pins or domes must be removable or collapsible. Surface finish of the mandrel should meet the requirements.

Difficulty of winding action is a limitation on filament winding. Fibers can be wound on the mandrel along different trajectories. Geodesic or semi-geodesic curves can be used in order to wind geometry. Similar to works done on textile industry, there are many applications on these geodesic pads and filament winding process. Deviation of fiber from these geodesic pads increases the slippage and textile point of view gets more importance. Ends of tube are the main critical point for these geodesic pads.

When the tube is subjected to a loading condition, all layers of fibers should be stressed equally. This simply implies that, for each loading condition there exists an optimum winding configuration. This makes the research and testing action necessary for filament winding applications. These are difficult design items due to the complexity of composite material behavior. Some assumptions can be done in order to simplify an analysis. If woven structure is neglected, there exist three mutually perpendicular planes in each lamina. Elastic properties are symmetric about these planes. These planes are the cross-section, the fiber plane and a plane passes through axis of the cylinder. Using this configuration, usually all design work on filament winding is performed.

1.5 ANALYSIS OF FILAMENT WOUND TUBES

Design and analysis of composites is a wide are of research, which involves huge amount of academic studies in several disciplines. These studies involve both experimental and theoretical efforts. Main areas of these efforts are determination of material properties, examination of production parameters, investigations of geometries and loading conditions. These studies can be done within both a macro scale and a micro scale.

Experimental and theoretical investigations performed on filament wound composite tubes are one of the leading parts of these studies. In most of these studies the effects of winding angle on strength of filament wound composite tubes are investigated. These investigations are based on analytical or theoretical examinations.

P. D. Soden et al [5] investigated the influence of winding angle on the strength and deformation of E-glass fiber reinforced epoxy resin (Silenka 051L, 1200 tex, Ciba-Geigy MY750/HY917/DY063) filament wound tubes subjected to uniaxial and biaxial loads through various combinations of internal pressure and axial loads. The tubes were produced with a winding angle of ±45º, ±55º and ±75º. Thicknesses ranged from 1 to 3.6 mm with an internal diameter of 100 mm. Fiber volume fractions ranged from 0.4 to 0.53. A huge set of experimental data was produced, which is very valuable for design applications. Leakage and fracture strength envelopes, as well as elastic constants were presented for different combinations of structure and geometry.

In this survey, it was found that increasing winding angle increases uniaxial tensile strength in circumferential direction and decreases tensile strength in axial direction. Axial compression strength was found to be independent of winding angle, since compression characteristics of composites are more dependent on resin properties. It was also observed that, sensitivity of tube strength to ratio of inner pressure to axial load varies with winding angle of the tube. For instance, for certain cases it was found that, decreasing the axial tension load without decreasing the inner pressure could burst the tube. In addition, stress-strain curves of ±45º and ±55º wound tubes are found to be nonlinear.

Another important result of the experiments was that for any winding angle, maximum leakage and fracture stresses are obtained at higher ratios of hoop stress to axial stress. Moreover, compression tests on tubes with different winding angles showed that shell buckling should be taken into account for thin tubes, which has a thickness of 1 mm. It is also proved that, linear elastic behavior of the tube is only valid at strain values below 0.1%. The ±75º wound tubes showed linear elastic behavior up to fracture. Other two combinations were completely nonlinear above strain levels of 0.2%. Failure strain of the tube with a winding angle of ±45º is found to be up to 25%.

P. D. Soden, R. Kitching and P. C. Tse [6] performed experiments in order to obtain experimental failure stresses for thin walled ±55º filament wound E glass (Silenka 051L, 1200 tex)-Epoxy (Ciba-Geigy MY750/HY917/DY063) tubes under axial loads. A combination of inner pressure, axial tension and compression were applied and failure envelopes were constructed. The failure modes were; spots of oil on the surface, a rapture without an initial fracture, jetting of oil and a combination of buckling and interlaminar shear. Whitening is also seen in all kind of failure modes.

An important result of these experiments was the change in type of failure mode for different values of stress ratios. For higher values of stress ratios (hoop: axial), such as ‘10:1’ and ‘18: -1’, failure was observed by delamination followed by jetting of oil. At a moderate stress level of ‘5.5:1’, former jetting of oil was followed by delamination and instantaneous bursting. With a similar stress level of 3.31, the same failure modes except that formation of delamination were observed. For negative stress ratios, which means compression is applied, failures were due to buckling and resin damage. Moreover, it was found that E-glass Epoxy tube could support larger loads for some range of stress ratios near 3.3:1. It was also observed that, maximum stress points were at different thickness levels, all along the tube. Therefore, for different loading conditions, failures occurred at different points. The mass fraction of fibers within the tubes was between 0.6 and 0.762, which must be cared when considering the results. The results had a scatter of 12% from mean values of the results.

L. Parnas, N. Katırcı [7] investigated fiber reinforced pressure vessels under various loading conditions. Using classical laminated-plate theory, for a plane strain model of a thick-walled multi layered filament wound cylindrical shell, loading conditions such as internal pressure, axial force and body force due to rotation were considered. Environmental effects were also investigated. Optimization on winding angle for different axial forces, internal pressures, hygrothermal loading, and rotational speed loading are performed. The results of the analytical procedure, which based on Lethnitskii's approach, were compared with experimental results. Thin wall and thick wall assumptions were compared. It was shown that, up to an outer to inner diameter ratio of 1.1, two assumptions gave similar result. Beyond this value, thick wall assumption is better to use. By the numerical solution performed, optimum winding angle for internal pressure is found to be ranging between 52.1º and 54.2º depending on the geometry of the tube and the type of failure criteria used for the analysis. This result was very close to netting analysis solution of 54.74º for internal pressure. It was also stated that, thick wall assumption gives higher burst pressure values than a thin wall assumption, for winding angles between 48º and 64º. In the case of a loading, due to an angular speed, optimum winding angle is found to be between 81º and 83º. This value of the angle varies with the thickness of the tube. Note that, it is usually assumed that, if ratio of radius to thickness is higher than 10, thick wall assumption is used rather than thin wall assumption.

M. Xia et al [8] investigated bending behavior of filament wound, fiber reinforced sandwich pipes. The analytical procedure developed was based on classical laminated-plate theory, for multiple layered thick pipes under bending load. The effort also included analysis of sandwich pipes under bending load. The core of the sandwich pipe was assumed isotropic, where inner and outer layers were reinforced. The solution was performed using Lethnitskii's stress function approach. Performing the calculations, the effects of winding angle, maximum-minimum stress points, deformation and different materials were investigated.

In the studies made by C. Cazeneuve, P. Joguet, J. C. Maile and C. Oytana [9] the mechanical behavior of Kevlar (49)/epoxy (M10) and carbon (T300)/epoxy (M10) filament wound tubes were predicted. Fiber volumetric ratios were 50 and 55% for carbon and Kevlar, respectively.

Usually, linear elastic laminated plate theory obtains the tube stiffness matrix by a homogenization process of each layer stiffness matrices according to thickness of the tube. It cannot predict the stress state of layer accurately (usually underestimates up to values of 10% [6]) but it predicts the layer in which damage is occurred. However, in the study performed by C. Cazeneuve et al, a nonlinear laminated plate theory was used with a gradual reduction in moduli of the tube layers. The gradual reduction in moduli is due to; force weightening caused by orientation of each layer with respected to load, woven characteristics of filament winded tube and plasticity. The affect of plasticity is easy to observe; reloading changes the moduli of the specimen. The value of reduction is strongly affected by the material properties, loading conditions and stress ratio. Three reduction constants were used in order to reduce the moduli, with different values for different portions of the stress-strain graph. Compression moduli were assumed to be equal to tension moduli.

Since Tsai Failure Criteria underestimates failure by 30 to 40%, introducing two new constants, a modified version of Tsai failure criteria was created. Both theoretical and experimental techniques were used with an agreement of less than 5%. Only carbon/epoxy tubes under torsion were failed to give good predictions. This problem was solved by further reduction in the moduli.

Delamination, which is mainly affected by through thickness elastic constants, is a major problem for thick filament wound tubes. M. F. S. Al-Khalil and P. D. Soden [10] performed an analytical procedure in order to obtain theoretical through-thickness elastic constants for filament wound tubes. The procedure is based on a linear elastic analysis, which obtains through thickness elastic constants from known unidirectional elastic constants.

Performing necessary calculations, through thickness elastic modulus is found to be slightly higher than the transverse modulus. It was also observed that, through thickness elastic modulus is not highly affected by winding angle. On the other hand, through thickness poison ratio is highly affected by winding angle. It is practiced that, if an angle-ply laminate is preferred rather than a unidirectional off-axis laminate, through thickness poison ratio gets a higher value. Through thickness, poison ratios can be negative, generally in the case of a high in plane poison ratio.

D. Hull et al [11] performed tests on terephthalic polyester filament wound tubes. Tubes were tested up to failure with an applied internal pressure. Failure types were investigated according to different stress levels and different elastic properties. It was found that, with a nonlinear behavior, decoupling between resin and the fiber seems to be occurred. Closed ended tubes experienced large-scale fiber fracture, whereas unrestrained mode tubes observed failure associated with shear effects.

Olli Saarela [12] stated the fundamentals of computer programs for mechanical analysis and design of polymer matrix composites. He has observed micro mechanical and macro mechanical models, as well as analysis programs such as ABAQUS, ANSYS, NASTRAN and many special purpose programs. Fundamentals of these programs are given as well as comparison of special purpose composite analysis programs.

C. Wuthrich [13] determined the stresses on long thick-walled composite tubes under inner and outer pressure, axial forces and twisting moments. He has developed an analytical procedure, which also includes the thermal and hydrothermal effects into analysis. The results, which were presented in the report, were comparable with previous finite element results.

D. W. Jensen and T. R. Pickenheim [14] wondered if fiber undulations of filament wound tubes have an important effect on compressive behavior of composite tubes. Undulations, which are created on crossings of a filament wound tube, is modeled by specimens containing certain undulations. Failure mechanisms, compressive strength and stiffness of the test specimens are observed. Flat panel coupons, which simulate crossings, are used for the tests. Material coupling, delamination, matrix splitting and fiber fracture were observed during the tests. It is also shown that, adjacent layers have great influence on undulated laminate, both in positive and negative sense. Behaviors of the specimens were linear up to failure, which were catastrophic in most cases. It is proved that undulation points were a source of fracture initiation.

L. Dong and J. Mistry [15] performed tests on composite cylinders under combined external pressure and axial compression. The test specimens were GRP cylinders (Ciba-Geigy LY5052 epoxy and E0802 glass fiber) wound at an angle of 55°. Length to diameter ratio of tubes was 0.9 and diameter to thickness ratio was in the range of 48 to 54. Strain gages and acoustic emission is used for failure monitoring. Both, longitudinal cracks due to buckling and matrix cracks due to compression were observed.

B. Fiedler, M. Hojo and S. Ochiai [16] used Finite Element Method in order to investigate influence of thermal stresses on the transverse strength of CFRP. They have classified the failure of composites into two types. In the first type of failure, matrix fiber interface is so strong that matrix failure is the main motivation for the overall failure of the structure. In second type of failure mechanism, matrix fiber interface is weak, so that delamination is the dominating failure mechanism. Within the effort spent, the influence of thermal stresses on initial matrix failure is observed on epoxy resin and carbon fiber. Effects of volumetric ratio on level of thermal residual stresses are also investigated. This effort is important for filament winding since fiber is wound on a mandrel with a certain value of tension and curing on a mandrel creates thermal residual stresses on filament wound tubes. A commercial finite element analysis program (MARC-Mentat) is used for modeling matrix and fiber in a small scale.

Xia et al [17] developed an exact solution for stresses and deformations of filament wound tubes under internal pressure. The solution is based on three-dimensional anisotropy elasticity. They have used a procedure similar to Lekhnitskii's approach and performed several analyses on filament wound tubes with different angle orientations and internal pressure loads. Stacking sequence, wall thickness and ratio of hoop to axial stress are also considered.

Jinbo Bai et al [18] tried to relate the micro defects of filament wound tubes with failure initiation in filament wound tubes. E-glass fiber (Vetrotex, 2400 tex) and epoxy (Ciba Geigy LY 556) are used to produce the specimen tubes. After producing the tubes, they first observed the micro structural defects produced during production. These defects are grouped as fiber misalignment, fluctuation of local fiber fraction, and all kinds of porosity. Then a series of tests were performed and it is shown that micro defects initiate delamination and matrix cracks, which leads to failure of overall structure. The state of loading determines the dominated state of the failure. Pure internal pressure, pure tensile loading and combined loading were applied to the tubes. The difference of the experiment was that, tubes were cut with a diamond wheel into required lengths. In macroscopic level of the analysis, a method for predicting the macroscopic properties of the tube was presented [19]. This method was compared with finite element method, classical laminate theory and adjusted classical laminate theory results. It is found that the developed method predicts through thickness stress results in agreement with finite element results. All other stresses are found to be similar by these four methods under tensile loading, but some differences appeared under internal pressure loading.

J. M. Lifshitz and H. Dayan used classical laminate theory in order to calculate stresses and strains in non-symmetric filament wound composite tubes with thick metal liners [20]. Thick metal liners are defined as the ones, which support one third to one half of the internal pressure. Tsai-Wu failure criterion is used, where plastic yielding of the liner and transverse cracking of the composite is modeled with reduced elastic properties. Changing layer thicknesses of the composite part are considered in calculations. The numerical stress result of calculations (away from the ends) was comparable with the test results obtained on two types of tubes produced: Kevlar 49, epoxy with a liner and 300 tex Carbon-epoxy tubes with a liner.

In this study, a process, which was called as *'autofrettage'* in metal industry, or *'sizing'* in composite pressure vessel industry, is also described. In the mentioned process, after producing the metal liner composite vessel, a pressure higher than the actual operating pressure is applied to the vessel. This pressure deforms the liner plastically; where as composite layer is still in elastic range. Unloading the tube, the liner becomes in compression, where as composite layer is in tension. Later, all loading cycle for the metal liner within operating life will be in elastic range, decreasing fatigue tendency of the liner.

Symmetry of a composite tube is also investigated regarding the coupling effects. It is stated that, no coupling exists and coupling matrix is zero for a symmetrical wall lay-up. However, when the wall is nonsymmetrical, a biaxial load will result in both extension and change in curvature of the laminate (bending of laminate).

J. M. Lifshitz and H. Dayan also considered the thermal effects on liner and composite layer of the vessel: During cooling prior to curing process, thermal residual stresses expected to appear on composite material. Since metal liner shrinks more than the composite material, also a small gap was assumed to appear between composite material and the liner. When internal pressure is applied to the vessel, liner is loaded first, which is found to affect the behavior of the vessel.

L. Zhao, S. Mantell, D. Cohen and R. McPeak developed a finite element model for the filament winding process [21]. The model was developed on a commercial finite element code with three subroutines written by the authors. These subroutines were named as ‘fiber consolidation/compaction model’, ‘thermo chemical model of the resin system’ and ‘resin mixing model’. Fiber Compaction Model calculated the effect of fiber pressure on previously wound fibers. The effect assumed to be started as the winding started and ended when the resin was completely cured. Thermo chemical Model considered curing thermodynamics and viscosity of the resin. It was based on conservation of the overall energy. Lastly, Resin Mixing Model calculated the mixing of resin on old and new wound fibers. Up to curing point, mixing of the resin was considered. Then, finite element analysis results were compared with the experimental results. The results were comparable to each other for a wide range of winding conditions.

J. S. Park et al considered change of winding angle through the thickness direction [22]. They calculated the winding patterns using a semi-geodesic fiber path equation and performed finite element analyses using commercial finite element code ABAQUS. They have also prepared a subroutine called ORIENT, which considers the change of winding angle to orient solid elements of the finite element analysis. Internal pressure tests on a test bottle are performed in order to compare with FEA results. The test results and the finite element analysis results were comparable for the strains recorded in fiber direction.

J. Rousseau et al investigated the influence of winding patterns on the damage behavior of filament wound glass/epoxy pipes [23]. They considered the woven characteristics of the filament wound fiber with respect to various loading conditions. Microstructure is also monitored during the analysis of the tubes. It is found that undulations and the void created around undulations were responsible for crack initiation. For closed end – internal pressure tests, as the number of crossovers of the fiber increased, the damage growth and weeping prone to increase. In the case of off-axis loading, the effect of winding pattern was found to be negligible. In addition, it is pronounced that carbon and aramid fibers will be more affected with increased number of interweaving. For torsion of the filament wound tubes, an improvement in strength of the tube was expected.

A. Beakou and A. Mohamed studied the influence of variables on optimum winding angle of filament wound tubes [24]. These variables were listed as elastic constants of fiber and resin, loads, strength parameters, etc. They applied classical laminate theory and Tsai-Wu failure criterion calculations on axially loaded pressure pipes and pressure vessels. A reliability analysis (using commercial software, RYFES) is performed for optimization of the process. It is found that; optimum winding angle is highly affected by transverse strength and modulus of elasticity values.

A new method to design composite pressure vessels with high stiffness is developed by A. A. Krikanov [25]. He has performed strain gage tests on pressure vessels and by a graphical method. He has concluded some results on different type of restrictions. He found out that, if axial strain of the vessel is restricted, ±1 degree outer hoop layer should be placed inside of the helical layers. However, when hoop strain is restricted, he advised to change fiber of the hoop layer in order to get a better result.

Indentation of filament wound tubes was investigated by S. Li et al [26]. Theoretical analysis of the GRP tubes was performed as well as tests on these tubes. Balanced angle ply laminate tubes, which are placed between a flat surface and 50 mm indenter, were used in these experiments. The dimensions of the tubes were 100 mm diameter and 500 mm long. 1 mm thick, ±55 and ±75 degrees wound tubes were failed by shell buckling, where 2 mm thick, ±55 degrees wound tubes were failed by delamination. Theoretical results were comparable with experiment results.

A monolithic and a laminated model were compared in theoretical analysis. It was found that; monolithic model was stiffer than the laminated model. This condition is interconnected with monolithic model, since twisting is not considered in monolithic model. Both experimental and theoretical results are compared with finite element analysis performed on commercial FEA software, ABAQUS.

J. Scholliers and H. V. Brussel developed a computer integrated filament winding system which is composed of CAD, FEA, robotic winding and robotic ultrasonic C-scanning [27]. Computer Aided Design part includes geometrical design, fiber pad calculations and defining winding parameters. Since other computer programs could not achieve to export the geometry in the desired manner, a computer program (CAWAR) was developed for this purpose. FEA software program NASTRAN was used in order to perform FE analyses. Then, a two axis-winding machine and a robotic winding cell were used to produce required parts. An ultrasonic C-scan pulse-echo method with water jet transmission was used for quality control operation. Two T-piece (one dry and one wet piece) were produced successfully using this system by using a wax mandrel. The mandrel is mounted on a CNC machine, and winding is performed by PUMA-762 robotic arm.

Hydrothermal effects during the manufacture of the filament wound Kevlar 49–Epoxy (DER 330, Tonox 60:40, RD-2, and an amine cured system) tubes were explored by A. M. Marom et al [28]. The volumetric ratio of the tubes was 70%. They produced and tested many tubes, which were wound at different temperatures (20-35°) and different relative humidity ratios (40 - 90%). Winding operations are done in a closed room (without windows and covered by PVC / glass wool). The tubes were cut by a laser-cutting device; in order to perform shear and NOL ring burst tests.

It is observed that, increasing temperature and decreasing relative humidity improved burst value of the vessels. Increasing the temperature from 20 to 35°, increased burst pressure by 10%. On the other hand, decreasing humidity from 95 to 40% increased burst pressure by 13 to 19%. Two extreme conditions (%90 RH, 20° and %40 RH, 35°) had a difference up to 30% in burst pressure.

The transverse shear strength of the Kevlar / Epoxy tubes was known to be very sensitive to relative humidity environments. However, relative humidity and temperature changes *'during production'* had no significant effect on shear strength of the tubes.

Resin viscosity, which is the third factor that affects the water absorption of liquid resin, was not considered. It is mentioned that, boiling in water for 72 hours can do aging of the Kevlar/epoxy tubes. In addition, it is noted that NOL ring test is found to be more convenient than split disc tests for pressure vessels.

The effect of uniform temperature change on thermo-elastic stresses in a filament wound elliptic tube was formulated by G. A. Kardomateas [29]. Using a formulation for curvilinear anisotropy derived by the author in a previous study, displacement equations were derived for elliptical body and numerical results were presented for stress resultants on elliptical wound tube. For numerical calculations, a uniform temperature change of 100°C was used.

K. L. Alderson et al [30] investigated the failure mechanisms during the transverse loading of filament wound pipes. Both static and low velocity impact conditions are considered. Strain gages and video camera is used for inspection of signs of failure. It was found that, first failure mechanism was matrix yielding, and second failure mechanism was delamination through the body. Matrix yielding was found to be independent from tube diameter and boundary conditions. However, delamination period of failure was highly effected by tube diameter and boundary conditions.

The tests were performed on ±55 degrees wound E-glass / Epoxy (Epikote 828) tubes, with a volumetric ratio of 68%. Two different pipe diameters were used, both with 15 layers.

D. Cohen et al [31] studied effect of fiber volume fraction on graphite/epoxy filament wound pressure vessel strength by using a statistical method. They investigated the variables, which effect pressure vessel quality. These variables include winding tension, winding speed, orientation of laminates, difference between winding tension of layers and relation of these variables. All test data for variables of manufacturing is presented. Volume fraction and failure strain relationship is also investigated. It is found that, failure strain of fibers is a better variable to characterize volumetric ratio of fibers. A computer program was developed in order to calculate volumetric ratio of fibers in a filament wound composite tube. It is found that, if a layer is wound with a low speed, volumetric ratio of fibers at previous layers decrease due to the bleeding resin from inner layers. This creates resin rich volumes in the filament wound tube.

Tae-Kyung Hwang et al [32] surveyed influence of size effect on fiber strength of composite pressure vessels. They used both experimental techniques and analytical methods. The analytical method was based on Weibull weakest link model. The model assumes that a structure is consist of a number of individual elements arranged in series and the entire component fails when one of these elements fails. The model was also compared with sequential multi-step failure model. Sequential multi-step failure model distributes the remaining load after a failure and assumes that final failure occurs when all elements have failed. Experimental tests were performed on fiber strand specimens, unidirectional laminate specimens and filament wound pressure vessels. Volumetric size effect on fiber strength was found to be increased with increasing stressed volume.

P. Mertiny et al [33] investigated effect of filament winding tension on physical and mechanical properties of reinforced plastics. Fiber volume fraction and effective wall thickness was considered during determination of mechanical properties. It is found that, under fiber dominated loading conditions, higher winding tension increased performance of the structure. On the other hand, under matrix dominated loading conditions, reduced fiber tension was observed to increase performance of filament wound structure. It is also found that, winding tension highly affects volume fraction of fiber within structure. Lastly, stresses and strains during normal operating conditions were found depended on winding tension.

S. Aleçakır [34] surveyed structural design and experimental analysis of filament wound composite tube under combined loading. Analytical derivations of governing differential equations of Lekhnitskii Stress Function Approach were performed for axi-symmetric loading and for pure bending. A numerical method, which uses stresses and displacements found by analytical procedure, was introduced to analyze of multi-layered orthotropic tubes. In addition, an experimental study was carried out for investigating the bending behavior of filament wound tubes. The comparison of test results and numerical method is performed.

C. Kaynak et al [35] studied uniaxial fatigue behavior of filament-wound glass-fiber/epoxy tubes. They observed both macroscopic and microscopic failure mechanisms. Tests were performed on ±55° E-glass (Vetrotex 600 Tex) epoxy (Ciba Geigy LY556/ HY917/ DY070) filament wound tubes, for a range of loading frequencies. S-N curves were prepared for cycles between 10^2 and 10^6. No fatigue limit was observed within applied load range. For all frequencies of loading, increasing load decreased life of the specimen. Moreover, increasing loading frequency increased life of the specimen, since the time under-load was decreased for the specimen.

CHAPTER 2

ANALYSIS OF LAYERED ORTHOTROPIC TUBES BY FEA

2.1 ANSYS AS A FINITE ELEMENT ANALYSIS TOOL

Finite Element Algorithms has become a very powerful tool in order to analyze and solve a wide range of engineering problems. Well developed, user friendly, well supported, flexible and multi-field computer codes become a commercial field of engineering tools. One of the challenging and most popular commercial all-purpose program used in Finite Element Modeling is the commercial FEA software “ANSYS”.

ANSYS/Multiphysics product can perform implicit analysis in a wide range of disciplines: structural, thermal, electrostatic, magneto static, acoustic and CFD analyses. Structural analyses include static, dynamic and time transient problems as well as vibration and topological optimization [36].

Multi-field solver permits to perform multi disciplinary applications. Multiply disciplines are coupled in two different ways; by solving the problem in one discipline, obtaining the DOF’s and transferring the loads and the BC’s to the other discipline, or by directly solving all DOF’s by matrix computations. The first option generally includes thermal, structural, CFD and electrostatic-magnetic applications, where as the second option generally includes piezoelectric, electromagnetic and electrostatic applications [36].

2.2 COMPOSITE MODELING WITH ANSYS

Modeling composites within any FEA software has three important stages different than modeling any isotropic material: choosing proper element type, defining the layers of the element and defining the failure criteria for the material.

ANSYS has more than 40 different material models, such as linear elastic models, nonlinear elastic models, nonlinear inelastic models, foam models, pressure dependent plasticity models or equation of state models, etc. Within these models, composite materials can be modeled using layered elements with orthotropic or anisotropic material properties.

In order to model layered composite materials, ANSYS serves a number of layered element types [36]:

- SHELL 99- Linear Layered Structural Shell Element,
- SHELL 91 - Nonlinear Layered Structural Shell Element,
- SHELL 181 - Finite Strain Shell,
- SOLID 46- 3-D Layered Structural Solid Element,
- SOLID 191- Layered Structural Solid Element,

In addition, SOLID 95, SHELL 63 and SOLID 65 elements can also be used for composite modeling with some key options; basically for single layers or for approximate calculations. The type of element to be used in the model depends on the specific application, and the results that are needed at the end of the analysis. As a rule in finite element analysis technique: if one dimension of the model is 10 or more times greater than the other two, shell elements should be preferred instead of solid elements. If two dimension of the model is 10 or more times greater than the other one, beam elements should be preferred [36].

Shell elements can be imagined as collapsed solid elements, which have negligible through thickness stress values. Since some edges are absent in shell elements, generally more degrees of freedom (rotational degrees of freedom) are defined for nodes of a shell element.

For our specific application, solid elements should not be used due to geometrical considerations. SHELL 91 is not preferred either, since it is used with nonlinear applications such as large strain, sandwich construction or plasticity. SHELL 181 is not preferred since highly nonlinear behavior exists.

Layered configuration can be modeled by specifying the layer properties; such as material properties, orientation angle, layer thickness and number of integration points per layer. For SOLID 46 and SHELL 99 element types of ANSYS, constitutive matrices can be defined with an 'infinite number of layers' opportunity. Within layered configuration, SHELL 63, SHELL 91, SHELL 181 and SHELL 63 elements of ANSYS permit sandwich construction using one layer and real constants. It is possible to model ply drop-off, by using SHELL 181, SHELL 91 and SHELL 99 elements, by the method of node offsetting.

ANSYS permits to use three different failure criterions for composites: Maximum Strain Failure Criterion, Maximum Stress Failure Criterion and Tsai-Wu Failure Criterion. Within these models, failure strains, failure stresses and coupling coefficients in all directions of orthotropy or anisotropy can be modeled as a temperature dependent parameter.

ANSYS Parametric Design Language can be used in analyzing a composite structure. See 'Section 2.3' for details on APDL.

For an application, it should be decided whether which element type or material model to use. Then the layered configuration should be defined. Layer orientation and orthotropic properties should be checked. Before running the analysis, failure criteria should be chosen.

2.3 'SHELL 99 ELEMENT'

Shell 99 is an eight node Linear Layered Structural Shell Element, which can be used to model composite structures up to 250 layers. Beyond this value, using a user-input constitutive matrix, more than 250 layers can be modeled [36]. It does not support some nonlinear properties that SHELL 91 supports, but it has smaller computational time [36].

Shell 99 has eight nodes: four corner nodes and four midside nodes. Each node has six degrees of freedom: translations in three directions and rotation about three axes. An average or each corner thickness can be defined explicitly, which gives a bilinearly varying thickness over the area of the layer, with the thickness input at the corner node locations. [36] Interlaminar shear stresses can be calculated. Elastic properties, layer orientation and density are the user-defined material properties. Stress stiffening and large deflections are supported. Element properties can be seen in Fig. 2.1.

As seen in Fig. 2.1, element coordinate system is right handed. Positive x-axis of the element coordinate system is defined by the direction from 'node I' to 'node J' of the each element. The first layer is defined as the bottom layer, on negative z direction. Angle of fiber orientation is defined as the angle from x-axis to a direction, rotated toward y-axis of element coordinate system [36].

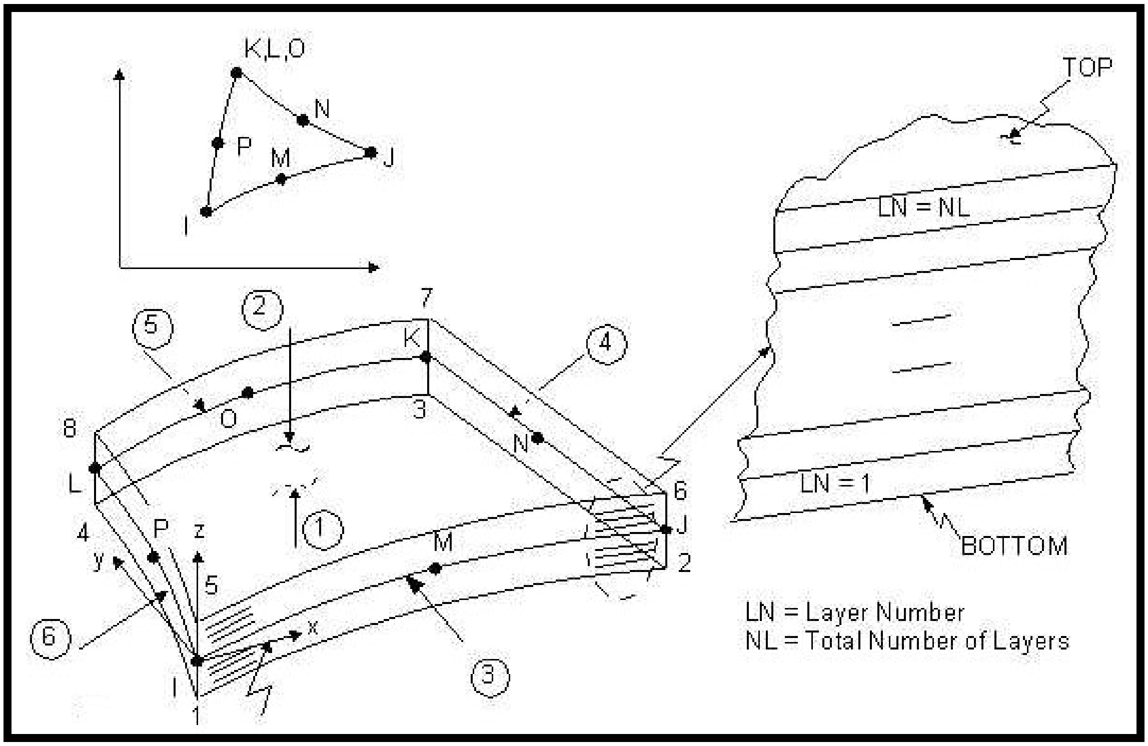

Figure 2.1 – Shell 99 Linear Layered Structural Shell Element [36]

It should be noted that, tube radius should be modeled according to the average of inner and outer radius of the tube, where the shell elements has nodes, by default, at the mid of their thickness. All shell elements are defined according to this mid surface assumption, except that SHELL 91 and SHELL 99 elements use a key option (11) in order to define tube surfaces [36].

Numbers of integration points define the accuracy of the model. For very thin layers, one integration point can be appropriate. For an element consists of multiple layers, more integration points should be used. The default value of integration points for Shell 99 elements is three points [36].

2.4 ANSYS PARAMETRIC DESIGN LANGUAGE

ANSYS Parametric Design Language (APDL) is a script language that can be used for developing macro files, which are capable of self-executing an analysis. They can contain if-then-else branching, do-loops, subroutines, and matrix operations, repeating, reading and storing data. Macro files can be used to automate common operations such as building geometry or analyzing it. More than one macro files can be called within an analysis. APDL can perform repeating analyses, with changing variables. APDL is such open ended that; it can even be used to optimize a structure using only one or more well-written macro file. APDL permits some operations, which cannot be performed by graphical user interface of ANSYS, such as fatigue analyses [36].

APDL is an important tool for composite analyses, since it can repeat any analysis within a very short time. This tool can be used for analyzing composites, such as determining maximum value of Tsai-Wu failure index for a complicated composite part. APDL is mainly important in optimization of a composite structure; such as layer orientations of a filament wound tube under specified loading conditions.

Two APDL script is given in ‘Appendix A.1’ and ‘Appendix A.2’. They are capable of analyzing internal pressure loading of layered orthotropic tubes and combined loading of layered orthotropic tubes, respectively. The user is allowed to give input data of dimensions of tube, number of layers and their orientation, elastic properties, strength properties, mesh intensity and boundary conditions and loading. Post-processing of the analysis is not performed within these macro files. Looping for optimization is not performed.

2.5 REMARKS ON APDL MODELING AND ANALYSIS OF LAYERED ORTHOTROPIC TUBES

During analysis of layered orthotropic tubes and at the stage of post processing of an analysis, following remarks should be kept in mind [36]:

- Memory management is very important when working with restricted hardware resources. The total memory in any analysis is defined as total workspace. Total workspace is divided into two parts as database memory and scratch space. All geometrical information (nodes, areas, meshing etc.) and results (all inputs and outputs) are allocated in database memory. Scratch space is used for temporary files such as: matrix calculations, boolean operations, internal calculations, etc. If allocated memory for database memory is not enough, a page file will be created. This will slow down the calculations. However, if allocated memory for scratch space is not enough, system enlarges the scratch space, so the total workspace. Therefore, in order to have a better performance, it is better to use more scratch space in preprocessing and solution steps and it is better to use more database memory in post-processing. ‘PGG solver’ options, although not recommended for shell elements, can also be considered when performance increase is needed. It will be efficient to use 1 GByte of workspace, per million DOF’s and 10 GByte disk space per million DOF’s.

- If it is needed to keep all the output files for every run, giving different names to each run will be a solution.

- In structural linear analyses, it is better to use quadratic or hexagonal elements instead of triangular elements.

- It is advised that, the thickness of a shell element is less than twice the radius of curvature, and bigger than one-fifth of the radius of curvature. This will guarantee having reliable results.

- During post processing of any value, if there appears to be more than two grids on any element, revising the solution with a higher mesh density is necessary. If a better meshing is required, the whole geometry should be meshed in one step. It is recommended to perform all boolean operations before meshing a solid or shell.

- It is better to prefer pressure loads on nodal loads.

- If there exists high deformation with respect to the geometrical values of the tube, it is better to change analysis option from default value of "Small Displacement - Static" to "Large Displacement - Static"

- 'Error Estimate – Stress Deviation' plot can be used in order to observe accuracy of the results.

- During post processing stage, it is better to observe stresses at the elements. Contrarily, it is better to observe strains at the nodes.

- It is a known fact that, 'FEA of a body is used to be stiffer than the real world'.

- It is better to always keep in mind that, the yield point and the proportional limit are assumed same in ANSYS FEA package program.

- In order to create a macro and run it in ANSYS software, it is easy to study and write the code with the required technique in an available common text editor such as WordPad or Notepad. Then, one can open MS-DOS prompt and use ‘EDIT’ command to open a new ASCII type text editor or to directly open the text file. Pasting the code into this editor and saving it into the working directory with a name and a ‘mac’ extension, will be sufficient to create macro file. In GUI window, checking whether the current directory is okay and typing the name of the macro in command line will start execution of the macro. It is a good idea to use Nedit, Vim, Ultra Edit or Text Pad text editors, which supports syntax highlighting, to write complicated macros. Syntax highlighting will ease readability and the effort performed for coding.

- Nineteen scalar parameters (arg1 to arg19) are permitted to be input for a macro file. These values are input while calling a macro. Parameter names are not permitted to be longer than eight characters.

- It is recommended to start a macro name with the string ‘x_’, so that it does not collide with ANSYS commands. The name of the macro cannot exceed 32 characters, cannot begin with a number and cannot contain spaces.

- All local variables are deleted at the end of macro execution.

- A macro is not able to call another macro.

- It is not recommended to write a macrocode, which uses numbers for identifying shell, volume, line or an area. The numbers of the objects can be changed with slight geometrical changes. It can even be affected by the operating system used. Rather, using location, material or real constants are recommended.

- Although UIDL programming is not officially released, it can be used to define user-defined menus and dialog boxes.

- It is possible to use '/COM' or '*MSG' command in order to inform users. Also using '!' in order to cancel a line or to place commends within a macro file is possible. Command '$' can be used in order to put more than one command on a line. Using '/NOPR' or '/GOPR' commands to hide or resume text output is possible.

- For an orthotropic material, there exist nine independent elastic constants. In ANSYS APDL, use 'MP' command in order to input elastic moduli, poison ratio and shear moduli in three directions.

- Since composites are prone to coupling effects, it is not recommended to use model symmetry, even if there is symmetry on the loads and the geometry.

- Interlaminar shear stresses at the free edges are needed to be cared. Along these free edges, it is recommended to have element sizes equal to total laminate thickness in order to get accurate results.

- Considering the interlaminar shear stresses, it is good to keep in mind that: Interlaminar shear stresses of a shell element are computed for the center of the element.

- Element coordinate system is used to define the orthotropy orientation, forces, stresses, strains etc. within each element. Using 'ESYS' command or key options of the element is needed, in order to define a new cylindrical system, which will be used for a layered tube.

- Results of a solution are by default stored in Global Cartesian System. These data is also listed, processed and displayed in Global Cartesian System. Using 'RSYS' command in order to transfer results into other coordinate systems is needed, such as the cylindrical system used to define the orthotropic tube.

- It is not recommended to use Hill Yield Criterion for failure analysis of composites since tension and compression strength of the material is assumed same in this criterion. It is better to use this model in creep and rate-dependent plasticity problems.

- Tsai-Wu Failure Criterion is the most commonly used failure model for composite materials. Both Tsai-Wu Failure Index and Tsai-Wu Failure Ratio can be obtained from an analysis. Contrasting the definition of Tsai [3], ANSYS can result a negative Tsai-Wu Strength Index for compression. Therefore, negative values should be considered accordingly. Failure models will not determine post-failure behavior of the material. However, they can give a sight to use in design of composite materials.

2.6 ANSYS APDL MODELING OF HOMOGENEOUS LAYERED ORTHOTROPIC TUBES UNDER COMBINED LOADING

Within the scope of the thesis, two APDL script is written in order to analyze filament wound composite tubes, under combined loading and internal pressure loading, respectively.

In the FEA model of the filament wound tubes, the tubes are assumed to be made of orthotropic adjacent layers. Therefore, crossing of fibers and changes in the fiber orientation are neglected. All layers are assumed equal in thickness and the thicknesses of the layers are calculated by dividing the thickness of the tube by the number of layers.

In ‘Internal Pressure Loading Analysis’, the tube is fixed from a node at one end and internal pressure is applied to inner surface of the tube (Fig. 2.2). There are no other constraint or loading in this analysis.

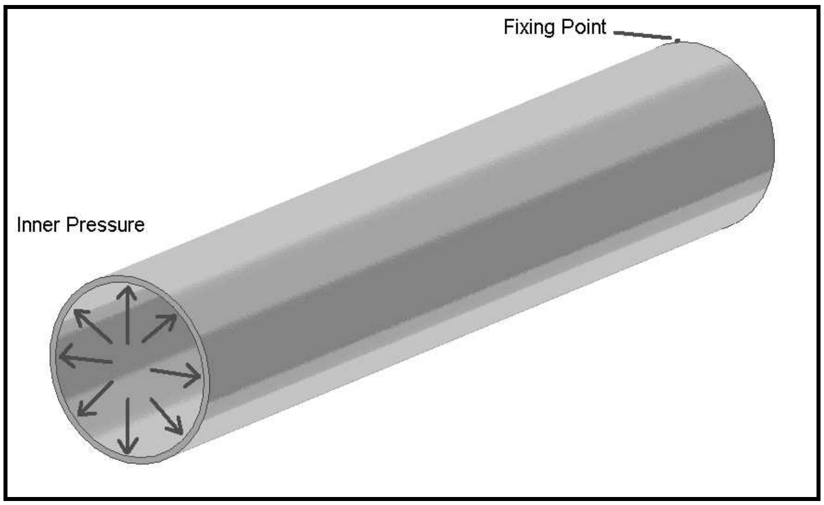

Figure 2.2 – Loading and Constraints of Internal Pressure Loading

In ‘Combined Loading Analysis’, the tube is fixed from one end, by applying ‘all DOF constraint’ on end lines of the tube surface. Then, an axial load, a transverse load and a torque are applied to the other end, namely on nodes within the fixing length. This fixing length is specified during entering user-defined inputs (Fig. 2.3). Tube dimensions can be found in Table 2.1.

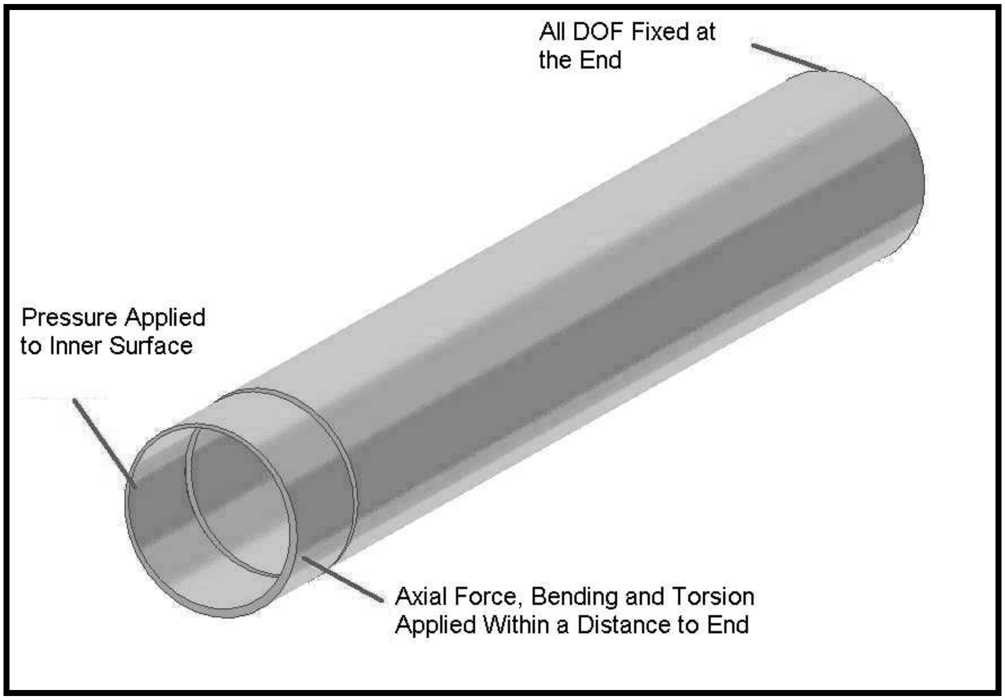

Figure 2.3 – Loading and Constraints of Combined Loading

TABLE 2.1 – Dimensions of the tube

Length of the tube (mm)	400
Fixing length (mm)	20
Average radius (mm)	60.565
Tube thickness (mm)	1.13

Input parameters of the APDL analyses, which are entered by using GUI (Fig. 2.4), are as follows:

- Geometry of the Tube (diameter, length and thickness)
- Number of Layers
- Angle Orientations for each Layer

- Fixing length, where end loads will be applied (for combined loading model)
- 9 Elastic Constants
- 9 Strain Strength Constants
- 9 Stress Strength Constants
- 3 Coupling Coefficients
- Loading (Inner and outer pressure, Transverse Load, Axial Load and Torque)

Analyses are done with the following order of operations:

1. Geometrical Properties are entered
2. Elastic Constants are entered
3. Strength Constants are entered
4. Loading Conditions are entered
5. Layer Orientation and mesh density are entered
6. Analysis is defined as a structural analysis
7. Element type is specified
8. Layer orientation and thickness are specified
9. Geometry is constructed with specified properties
10. Fixing areas are specified
11. Meshing is constructed
12. Boundary conditions are applied
13. Solution is done
14. Post processing is done

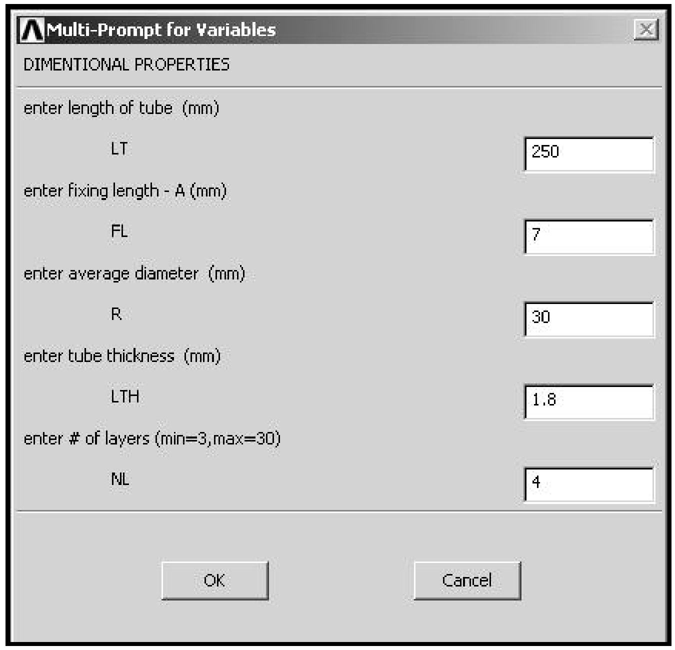

Figure 2.4 – Sample Dialog Box, which is used by user in order to input variables of an analysis

Having the solution, in the post-processing step, results of the analysis are considered for middle sector of the tube, where fewer gradients are occurred. Results from 'fixed end of the tube' and the part, where loading applied are ignored, except in bending analysis. All layers of the tube are investigated in results, in order to determine the critical layer and obtain a maximum Tsai-Wu Failure Index, stress value, etc. Therefore, commonly few numbers of layers are used in analyses. Listing of desired results is performed instead of plotting them, in order to see scattering values on nodes or elements. Then a meaningful value is selected, which can represent middle sector of the tube. These values are collected in an ‘Excel File’ in order to process later on for consideration of effects of different variables in terms of different positions.

In Chapter 4, some more details of the analysis and the results and discussion of the analyses can be found.

CHAPTER 3

DISCUSSION AND COMPARISON OF FEA RESULTS

3.1 INTRODUCTION

In this chapter, finite element analysis results of layered orthotropic tubes under various loading conditions will be presented. The chapter starts with a section that details sources of various errors in analyses. Then, the verification study of the finite element model is described. The proceeding sections also include analyses results on layered orthotropic tubes. The results are discussed in detail, in order to comprehend the exact behavior of layered orthotropic tubes under various loading conditions.

3.2 SOURCES OF ERRORS

Finite element results naturally involve some deviations from exact solutions due to characteristics of composites. As mentioned in Section 1.5, unlike metals, composites involve a number of uncertainties, resulting in deviations from expected results to increase.

For instance, in previous FEA studies, layer thicknesses of composite tubes are generally assumed to be constant. However, filament wound tubes are observed to have some variations in layer thicknesses. First, due to compression of upper layers on lower ones, the inner layer of the tube tends to be thinner compared to outer layers. Secondly, if the fiber tension of a filament-winding machine is not adjusted appropriately for each layer, winding angle affects transverse fiber tension, which leads to thicker layers as winding angle decreases. Even if an adjustment for the fiber tension is applied, it should be kept in mind that the fixed value of fiber tension cannot be accurately estimated.

The path of the fiber depends on the characteristics of the surface, on which the fiber is wound. However, during the winding operation, the geometry of the wound structure, as well as the surface characteristics, keep on changing from one winding to another. This leads to a variation in winding angle through the thickness direction, as well as the longitudinal direction. Especially, around the dome or end sections, the composite layer becomes thinner when compared with other parts of the tube. This is due to the slippage of the fibers [28].

The winding process itself also introduces some error to the analysis. It is assumed that the filament wound tube is composed of adjacent orthotropic layers, although the wound fibers construct a woven three-dimensional structure. Number of overlapping increases as winding angle decreases, which generates stress concentration points due to irregularities within layers.

The major source of errors in composite modeling, however, arises from uncertainties in elastic constants. They cannot be predicted or taken from literature directly. The production process, type of the material or the design process itself affects the material properties. The properties of materials in the market change gradually. Moreover, research done on material properties of the composite materials is very limited.

Another source of error is from testing of composite material which is not an easy process when compared with metals. For example, some three-dimensional elastic constants are approximated in majority of the academic studies. Some analytical approximations are used in order to make predictions on the values of these constants.

‘Size Effect’ is a good example, which introduces a certain amount of error in an analysis. Sizing states that the number of possible defect initiating points increase as the size of the structure increase. Therefore, while designing large structures, a factor of safety should be considered accordingly. There are many similar situations, which are difficult to consider due to the behavior of the composites. For instance, if a liner is used, cooling after curing will produce a gap between the liner and the composite layer.

As a result, the following FEA results should be considered accordingly. However, these results are beneficial when deciding on parameters for the design of composite filament wound tubes or for preliminary design purposes.

3.3 MODEL VERIFICATION AND ANALYSIS PARAMETERS

There are two points, which need to be verified before performing a finite element analysis: ‘process’ and ‘inputs of the process’. The process is the APDL code, the FEA model and FEA Code. Inputs of the process are however elastic constants and strength constants, which are used as input data. After completely clarifying these two points, further analyses can be performed successfully.

Verification of both is done, by performing analyses similar to the experiments performed in literature [37]. FEA results are very close to test results, although there is some scattering involved in experimental results. It is important to note that, the composite structure in FEA are observed to be slightly stiffer than the ones in experiments.

The elastic constants for various composite materials can be taken from [3], [7], [8], [10], [19], [20], [26], and [37]-[40]. Elastic constants used in this study can be seen in Tables 3.2 through 3.7. Carbon/Epoxy (C/Ep) and E-Glass/Epoxy (Eg/Ep) are preferred in the analyses, due to more reliable data present for these items and their dissimilar degree of orthotropy. Aramid/Epoxy (A/Ep) is rarely used in order to investigate the effect of level of orthotropy.

TABLE 3.1–Comparison of Results Obtained by Experiments [37] and FEA

TEST TYPE	MATERIAL	EXPERIMENT [37]	FEA
Internal Pressure of 126Kg/cm2	C/Ep	Axial Strain=2.290x10E-3 Hoop Strain=7.665x10E-3	Axial Strain= 2.023x10E-3 Hoop Strain=6.251x10E-3
Tension Test	C/Ep	Axial Strain=6.630x10E-3 Hoop Stress=376.21 MPa	Axial Strain=5.11x10E-3 Hoop Stress=398 MPa

TABLE 3.2 – C/Ep Elastic Constants [37], [10]

E_{xx} (MPa)	127700	ν_{xy}	0.33	G_{xy} (MPa)	6900
E_{yy} (MPa)	7400	ν_{yz}	0.188	G_{yz} (MPa)	4300
E_{zz} (MPa)	7400	ν_{xz}	0.188	G_{xz} (MPa)	4300

TABLE 3.3 – C/Ep Strength Constants [10], [20]

S_t -x (MPa)	1717	S_c -x (MPa)	-1200	S -xy (MPa)	33
S_t -y (MPa)	30	S_c -y (MPa)	-216	S -yz (MPa)	33
S_t -z (MPa)	30	S_c -z (MPa)	-216	S -xz (MPa)	33

TABLE 3.4 – Eg/Ep Elastic Constants [37], [26]

E_{xx} (MPa)	45600	ν_{xy}	0.27	G_{xy} (MPa)	8500
E_{yy} (MPa)	16200	ν_{yz}	0.27	G_{yz} (MPa)	5500
E_{zz} (MPa)	16200	ν_{xz}	0.27	G_{xz} (MPa)	5500

TABLE 3.5 – Eg/Ep Strength Constants [37], [26]

S_t -x (MPa)	1243		S_c -x (MPa)	-525		S -xy (MPa)	73
S_t -y (MPa)	40		S_c -y (MPa)	-145		S -yz (MPa)	73
S_t -z (MPa)	40		S_c -z (MPa)	-145		S -xz (MPa)	73

TABLE 3.6 – Aramid/Epoxy (A/Ep) Elastic Constants [37], [10]

E_{xx} (MPa)	83000		ν_{xy}	0.41		G_{xy} (MPa)	2100
E_{yy} (MPa)	7000		ν_{yz}	0.4		G_{yz} (MPa)	1860
E_{zz} (MPa)	7000		ν_{xz}	0.4		G_{xz} (MPa)	1860

TABLE 3.7 – A/Ep Strength Constants [10], [3]

S_t -x (MPa)	1377		S_c -x (MPa)	-235		S -xy (MPa)	27
S_t -y (MPa)	18		S_c -y (MPa)	-53		S -yz (MPa)	34
S_t -z (MPa)	18		S_c -z (MPa)	-53		S -xz (MPa)	34

Several test runs are conducted in order to determine acceptable model parameters before performing analyses. For instance, before deciding on mesh density of the model, any analysis result can be obtained for increasing number of elements. Fig. 3.1 shows an example for determining the optimum mesh density of an analysis. The graph shows that, as the number of elements increases, the measured value (percentage scatter of ε_{rr}) becomes more stable. For this specific example, practically 6000 elements are shown to be sufficient to get acceptable results. After several analyses, 7500 elements are decided to be sufficient.

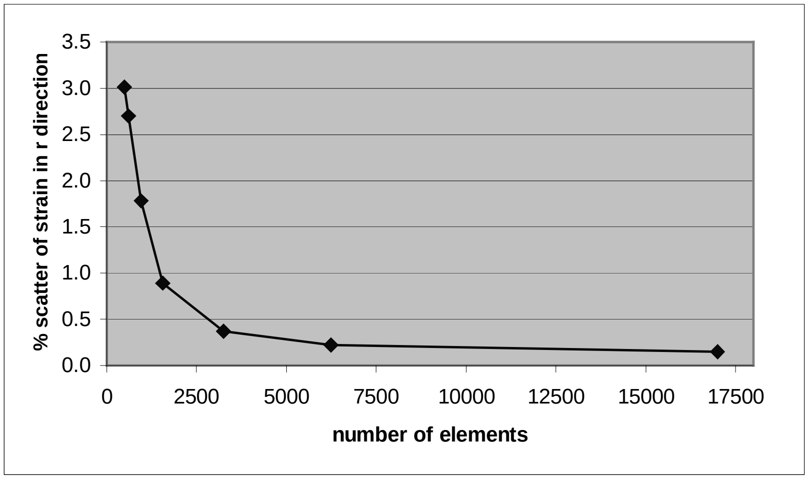

Figure 3.1 – Percentage scatter of ε_{rr} vs. Number of Elements for Pure Internal Pressure Loading of an Eg/Ep Tube

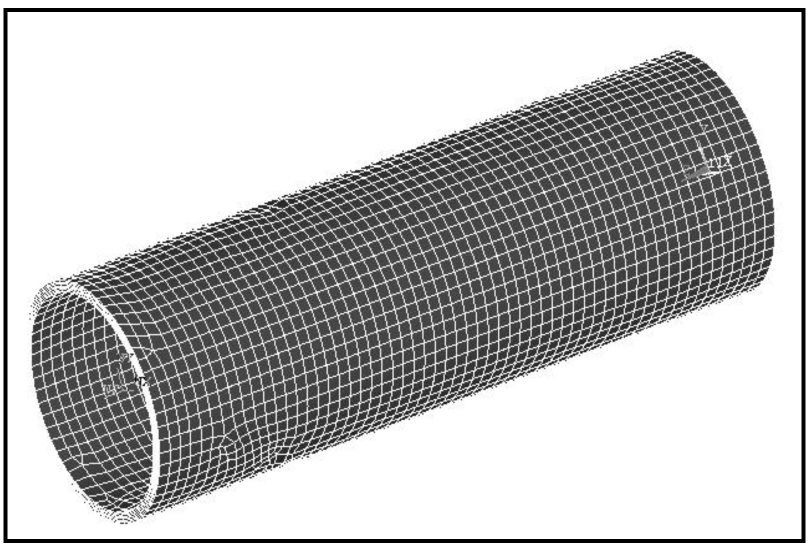

Figure 3.2 –Mesh Density (7500 elements)

Another parameter to be determined is the number of integration points for a shell element. As mentioned before, a higher number of layers require a higher number of integration points. In order to examine this effect, a number of analyses are performed as shown in Fig. 3.3. By default, the written APDL codes had three integration points per shell element. As shown in Fig. 3.3, failure indices for an axially loaded C/Ep tube with constant thickness remain constant up to a certain number of layers. Beyond this value, the number of integration points is not sufficient for the number of layers modeled. Some error occurs and the failure index starts to increase. Similar results can be obtained for stress or strain values, which are obtained from the same analysis (Fig. 3.4).

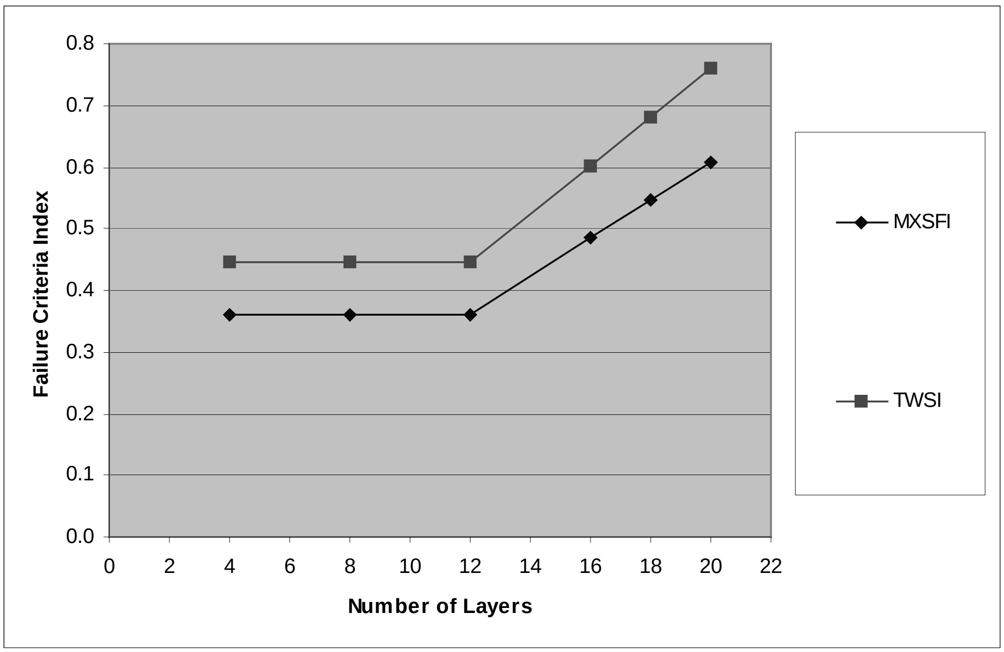

Figure 3.3 – Variation of Failure Indices by Number of Layers, for an axially loaded C/Ep tube with constant thickness

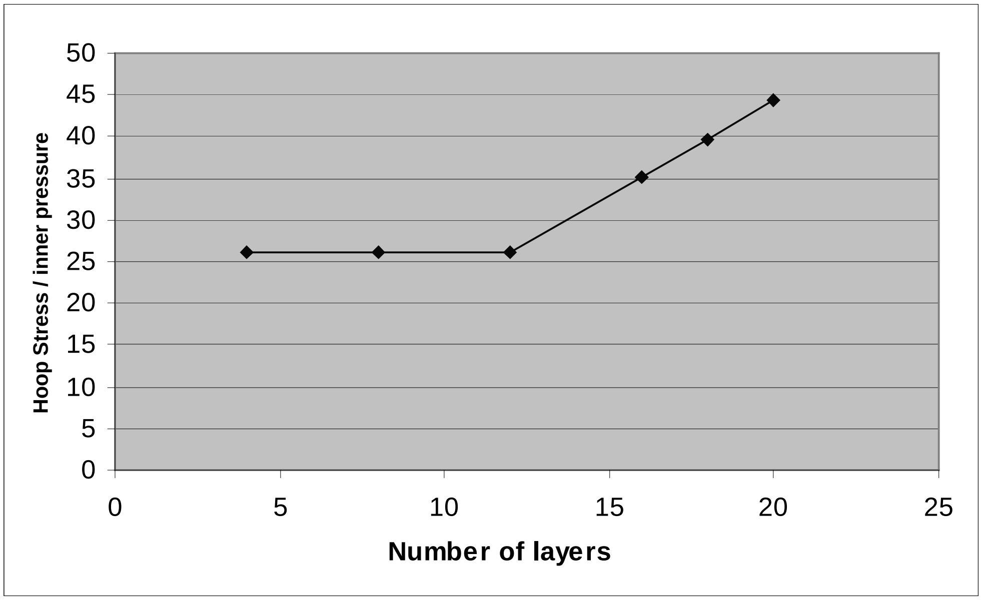

Figure 3.4 – Variation of Hoop Stress/Inner Pressure by Number of Layers, for an axially loaded C/Ep tube with constant thickness

3.4 PURE INTERNAL PRESSURE LOADING

Four types of analysis are performed in order to investigate the behavior of layered orthotropic tubes under pure internal pressure. No end constraints or loads are applied to the tubes. Only one node at one end of the tube is fixed in all degrees of freedom in order to prevent instability in finite element analysis. Solutions are recorded for the middle sector of the tube, since ends experience high gradients in desired parameters (See Fig. 3.5). Dimensions of the tube used in the study are given in Table 2.1.

In the first analysis, a C/Ep tube is subjected to pure internal pressure of 7 MPa and the analysis is repeated for varying degrees of winding angles. TWSI and MXSFI results are collected, which can be seen in Fig. 3.6. As expected, failure indices decreased with increasing winding angle. It can be concluded that, for the optimum design of high internal pressure applications, the winding angle should be close to 90°.

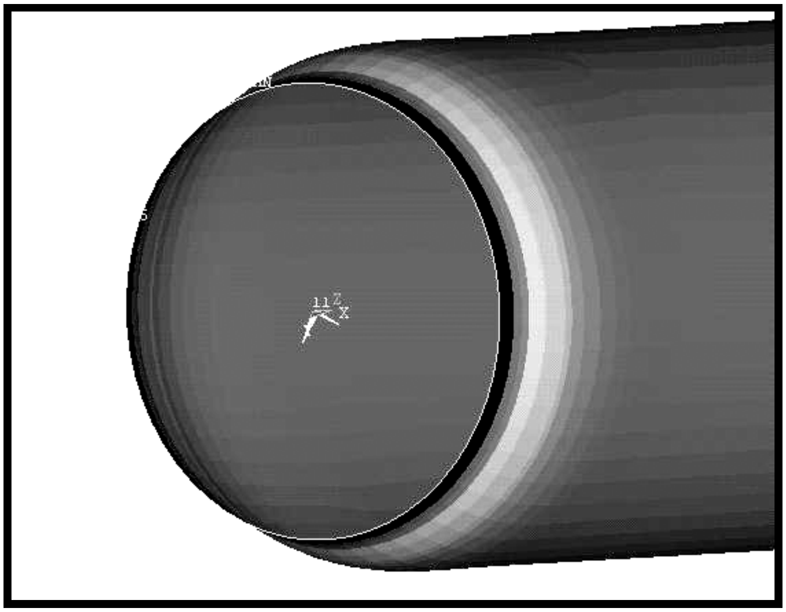

Figure 3.5 – TWSI Gradients at the ends of the tube

In the second analysis, 6-layer, ±60° wound, C/Ep tube is subjected to pure internal pressure. Failure indices and stresses are obtained for each layer. Then, in order to investigate the effect of winding angle on stresses and failure indices in each layer, the same analysis is performed for ±75° wound, 6-layer, C/Ep tube. Finally, in order to investigate the effect of level of orthotropy, the same procedure is performed for 6-layer, ±60°, Eg/Ep tube. Results of these three analyses can be seen in Fig. 3.6 to 3.13.

Examination of analysis results for pure internal pressure loading, can lead to the following conclusions:

- Increase in the winding angle has a decreasing effect on both Tsai-Wu Failure Index (TWSI) and Maximum Stress Failure Index (MXSFI) (Fig. 3.6).

- Effect of level of orthotropy is not simply related to failure indices (Fig. 3.7). Winding angle and level of orthotropy should be considered simultaneously in order to investigate the effect of orthotropy on failure indices. In the following sections, this investigation will be conducted.

- Radial stress in the inner layer is close to inner pressure for pure internal pressure loading. Similarly, if there exists no outer pressure, radial stress at the outer layer is close to zero. The radial stress distribution along thickness is almost linear. The effect of winding angle and level of orthotropy is practically negligible (Fig. 3.8).

- Hoop stress in the inner layer has a maximum value, whereas it has a minimum value in the outer layer (Fig. 3.9). Considering other components of stress tensor, we can state that hoop stress in the inner layer of the tube highly responsible for a possible failure. It can also be predicted that, decreasing winding angle increases hoop stress difference between inner and outer layers of the tube, which promotes failure. This fact is consistent with the data depicted in Fig. 3.6.

- Axial stress is found to be tensile in the inner layer and compressive in the outer layer of the tube (Fig. 3.10). The distribution of axial stress is linear between inner and outer layers of the tube. In the fourth layer, it gets a value of zero.

- $\sigma_{r\theta}$ is almost constant through the thickness, as expected (Fig. 3.11).

- $\sigma_{\theta z}$ change sign across layer interfaces as expected (Fig. 3.12). Increasing winding angle decreases magnitude of this stress component, since the difference between fiber directions of adjacent layers decreases. If this reason is true, ± 45º winding should have the highest difference, whereas under ±45º decreasing winding angle should decrease $\sigma_{\theta z}$. A separate analysis is done for a ±30º wound, 6-layer, C/Ep tube in order to check this conclusion and results show that it holds true.

- The above statement also depicts that; decreasing angle between fibers and decreasing level of orthotropy has the same physical meaning when considering $\sigma_{\theta z}$, σ_{rz}, $\sigma_{r\theta}$, σ_{zz} and $\sigma_{\theta\theta}$.

- σ_{rz} is found to be decreasing by increasing winding angle (Fig. 3.13). Decreasing level of orthotropy also decreased σ_{rz}.

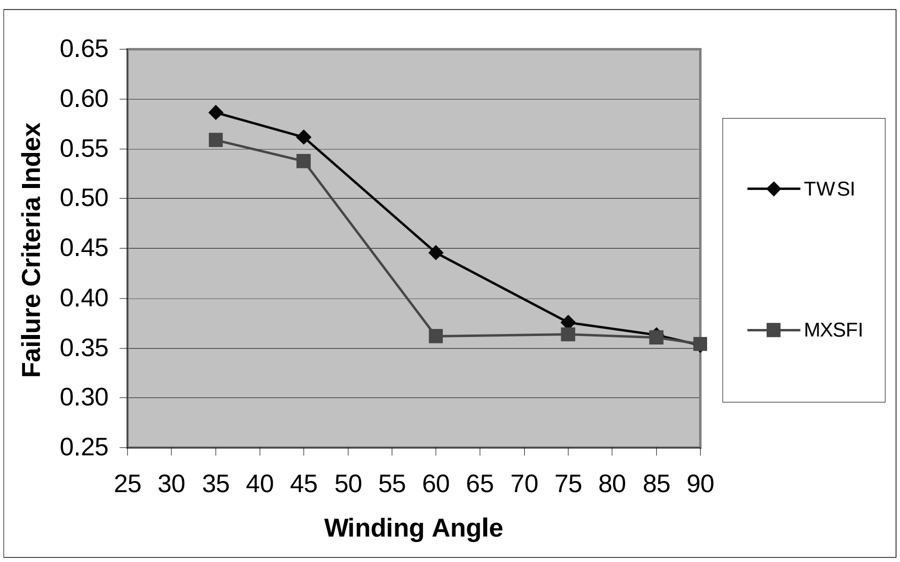

Figure 3.6 – Variation of failure indices by winding angle for a C/Ep tube, which is loaded by pure internal pressure

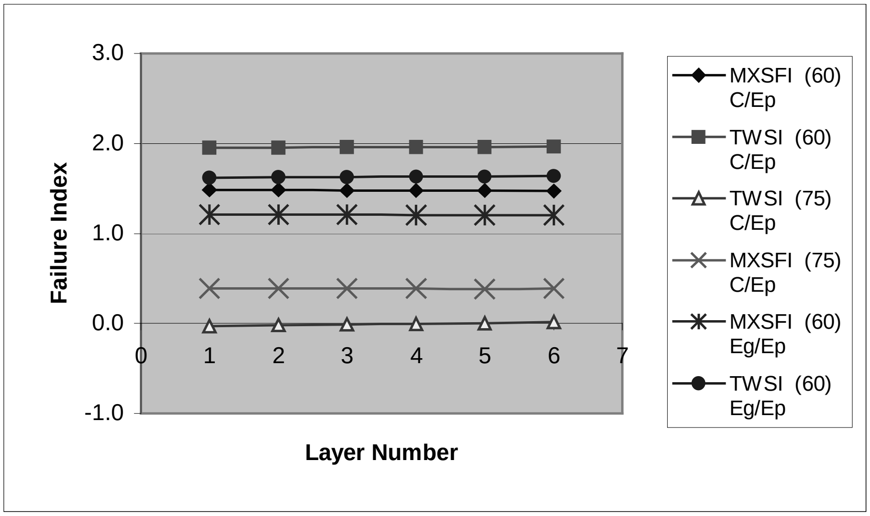

Figure 3.7 – Variation of failure indices by layers for different tubes, which are loaded by pure internal pressure

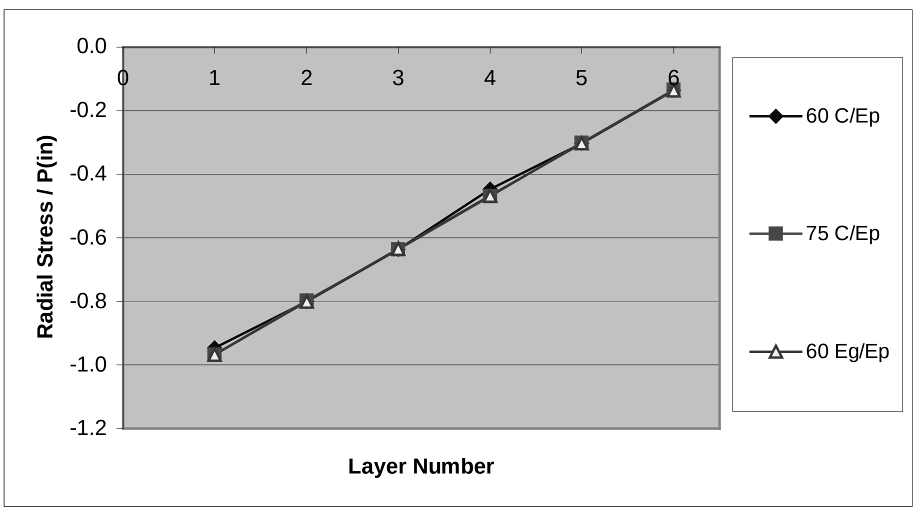

Figure 3.8 – Variation of ‘radial stress / P_{in}’ by layers for different tubes, which are loaded by pure internal pressure

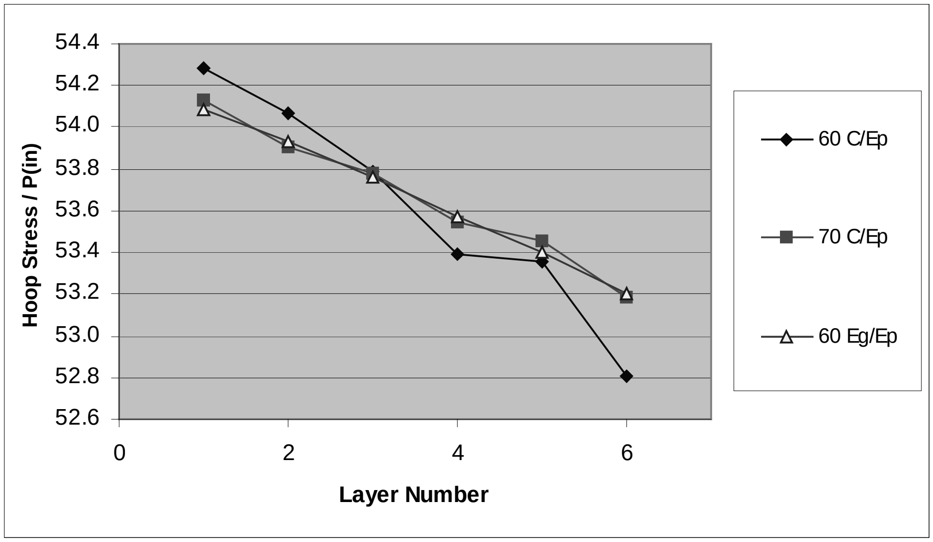

Figure 3.9 – Variation of 'hoop stress/ P_{in}' by layers for different tubes, which are loaded by pure internal pressure

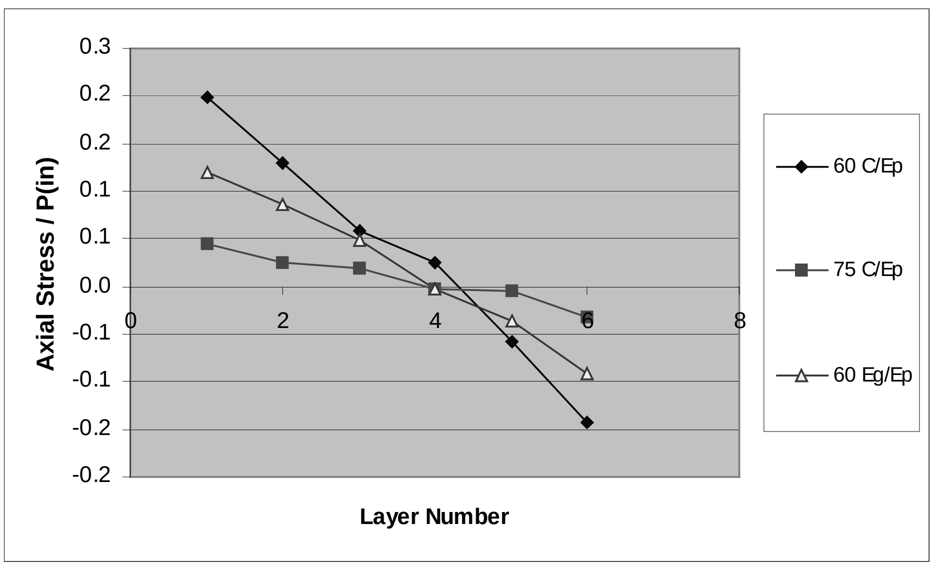

Figure 3.10 – Variation of 'axial stress/ P_{in}' by layers for different tubes, which are loaded by pure internal pressure

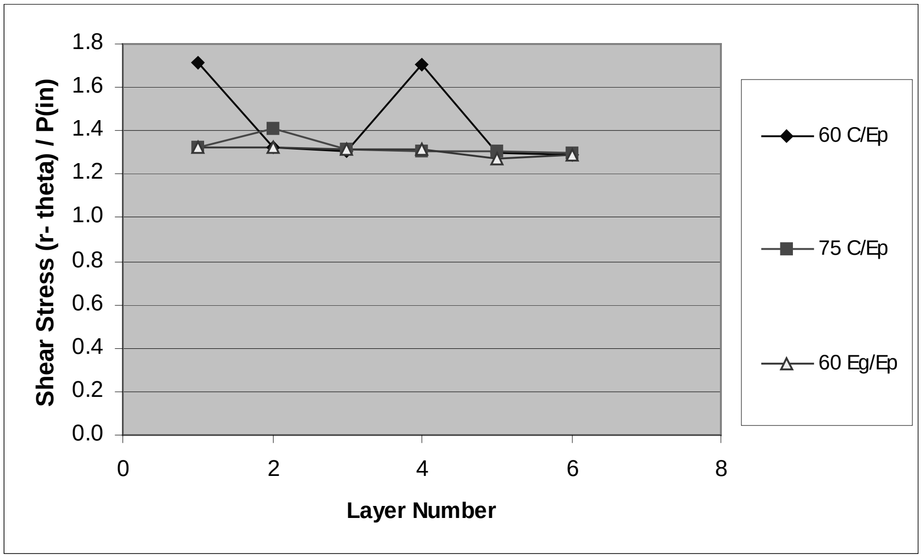

Figure 3.11 – Variation of '$\sigma_{\theta r}$ / P_{in}' by layers for different tubes, which are loaded by pure internal pressure

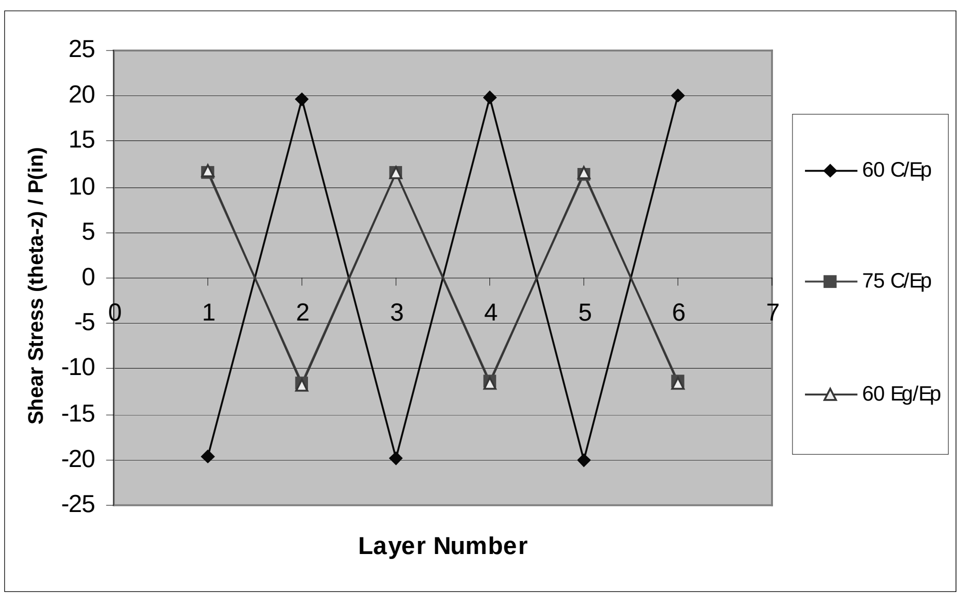

Figure 3.12 – Variation of '$\sigma_{\theta z}$ / P_{in}' by layers for different tubes, which are loaded by pure internal pressure

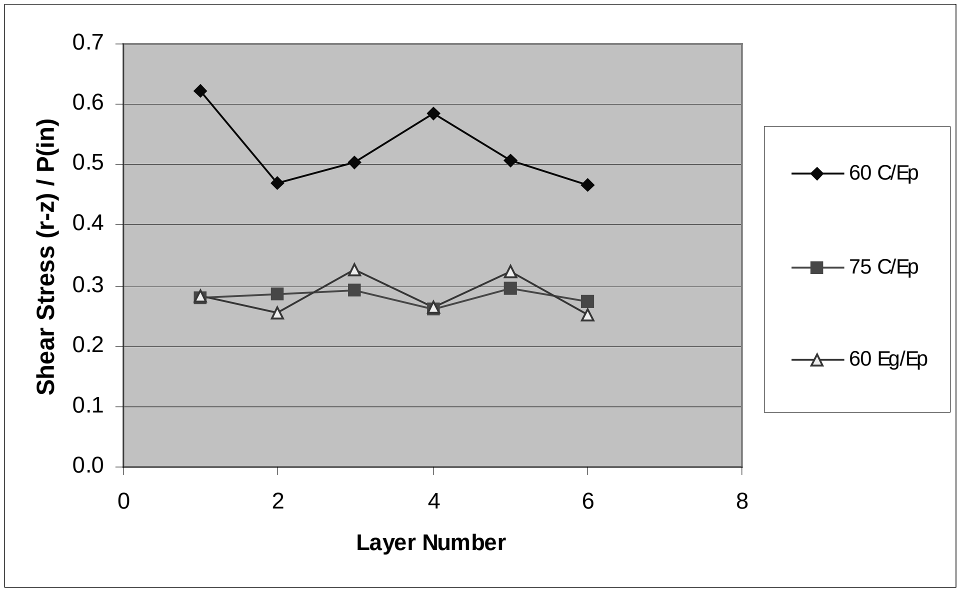

Figure 3.13 – Variation of 'σ_{rz}/P_{in}' by layers for different tubes, which are loaded by pure internal pressure

3.5 PURE TORSION

Four types of analysis are performed in order to investigate behavior of layered orthotropic tubes under pure torsion. Tubes are fixed from one end, using an all DOF's constraint on end lines of the tube surface. Then, on the other end, within a user-defined length (see Fig. 2.3), a torque of 800 Nm is applied. Dimensions of the tube are given in Table 2.1. Solutions are recorded for the middle sector of the tube, since ends experience high stress gradients.

In the first analysis, a 6-layer, C/Ep tube is subjected to pure torsion and analysis is repeated for varying degrees of winding angles. TWSI results obtained can be seen in Fig. 3.14. As expected, failure indices have a minimum value around ±45°

winding angle. An optimum angle, which is between 30 to 60^{o} seems to be acceptable for torsion considerations. In the second analysis, a 6-layer, ±60^{o} wound, C/Ep tube is subjected to torsion. Failure indices and stresses are obtained for varying layer numbers. Then, in order to investigate the effect of winding angle on stresses in each layer and failure indices, the same analysis is performed for a ±75^{o} wound, 6-layer, C/Ep tube. Finally, in order to investigate the effect of level of orthotropy, the same procedure is performed for 6-layer, ±60^{o} wound, Eg/Ep tube. Results of these three analyses can be seen in Fig. 3.15 - 3.22.

Examining the pure torsion analysis results, following conclusions can be drawn:

- Optimum winding angle for torsion is ±45^{o}. This seems to be due to the high value of shear stress within the body. However, considering Fig. 3.14, an angle between 30 to 60^{o} can be acceptable as optimum.

- One of the innermost two layers is the critical layer for pure torsion, depending on the sign of torque applied (Fig. 3.15).

- For angles around ±45^{o}, MXSFI seems to be more conservative than TWSI. For angles, which are far from ±45^{o}, TWSI, however, seems to be more conservative (Fig. 3.15).

- It can be confirmed that, a lower degree of orthotropy increases the difference in failure indices for adjacent layers (Fig. 3.15).

- Axial, hoop and radial stresses vary in sign for adjacent layers. Radial and hoop stresses increase in magnitude with the degree of variation from ±45^{o}. On the other hand, axial stress decreases in magnitude with the degree of variation from ±45^{o}. Moreover, a lower level of orthotropy causes the magnitude of axial, radial and hoop stresses to be decreased (Fig. 3.16 - 3.18).

- The values of $\sigma_{r\theta}$ and σ_{rz} are negligible when compared with magnitude $\sigma_{\theta z}$ (Fig. 3.19 - 3.21).

- The magnitude of $\sigma_{r\theta}$ increases with the degree of variation from ±45^{o} and decreases with a lower level of orthotropy (Fig. 3.19).

- $\sigma_{\theta z}$ is not significantly affected by winding angle and level of orthotropy (Fig. 3.20).

- σ_{rz} has a negligible value and variation through thickness (Fig. 3.21).

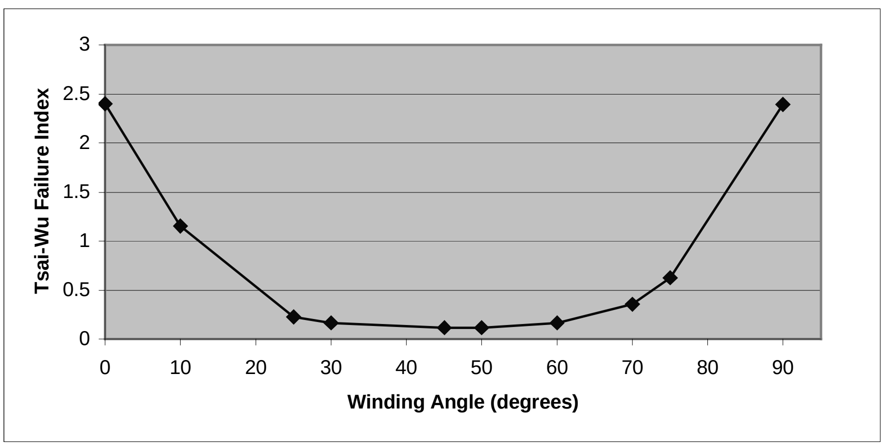

Figure 3.14 – Variation of TWSI by increasing winding angle, for a 6-layer, C/Ep tube under pure torsion

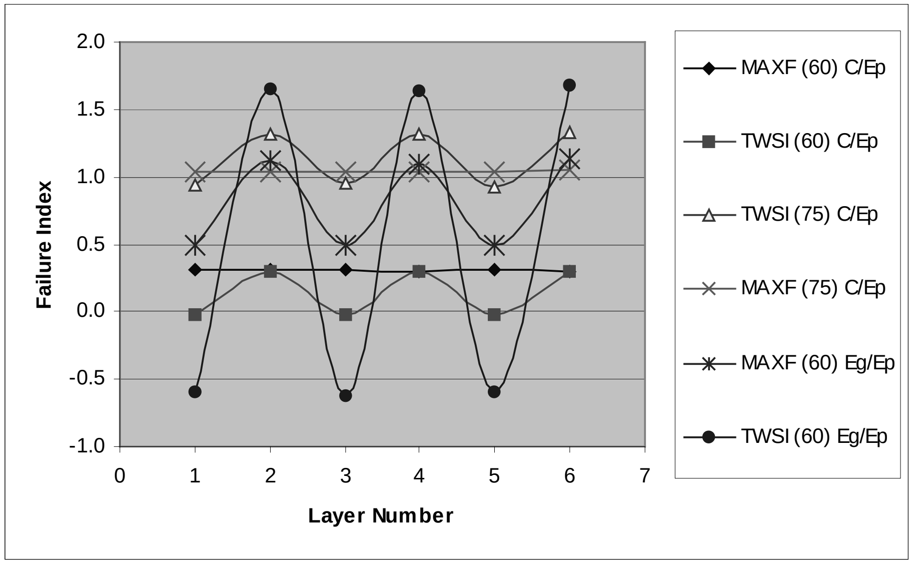

Figure 3.15 – Variation of failure indices by layers, for different tubes under pure torsion

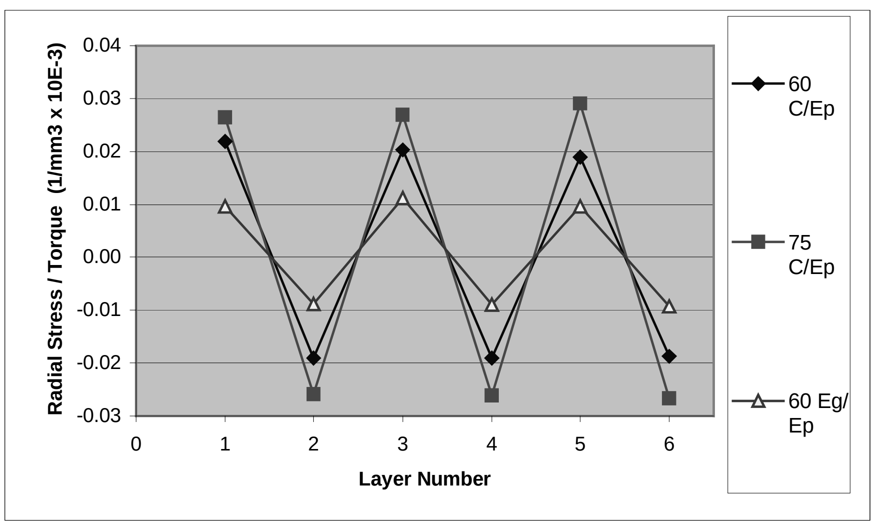

Figure 3.16 – Variation of 'σ_{rr}/torque' by layers, for different tubes under pure torsion

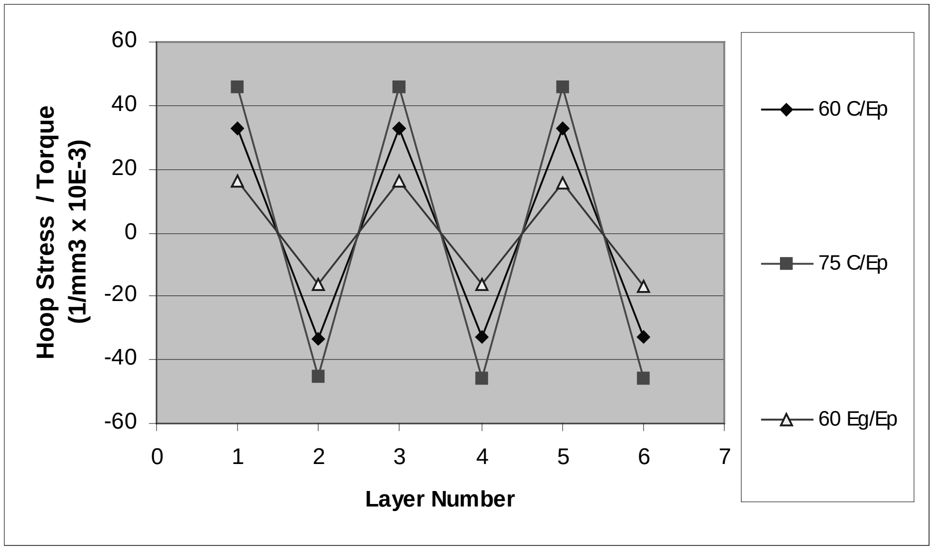

Figure 3.17 – Variation of '$\sigma_{\theta\theta}$/torque' by layers, for different tubes under pure torsion

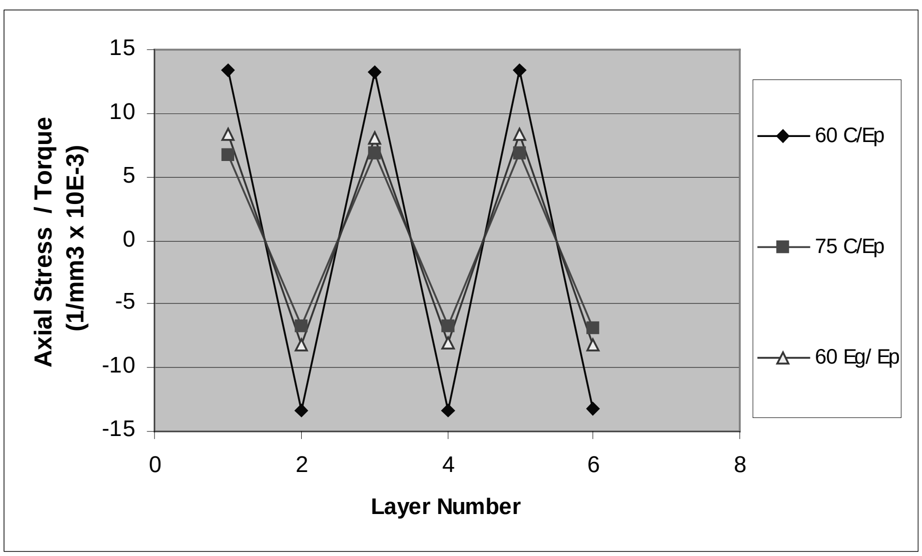

Figure 3.18 – Variation of 'σ_{zz}/torque' by layers, for different tubes under pure torsion

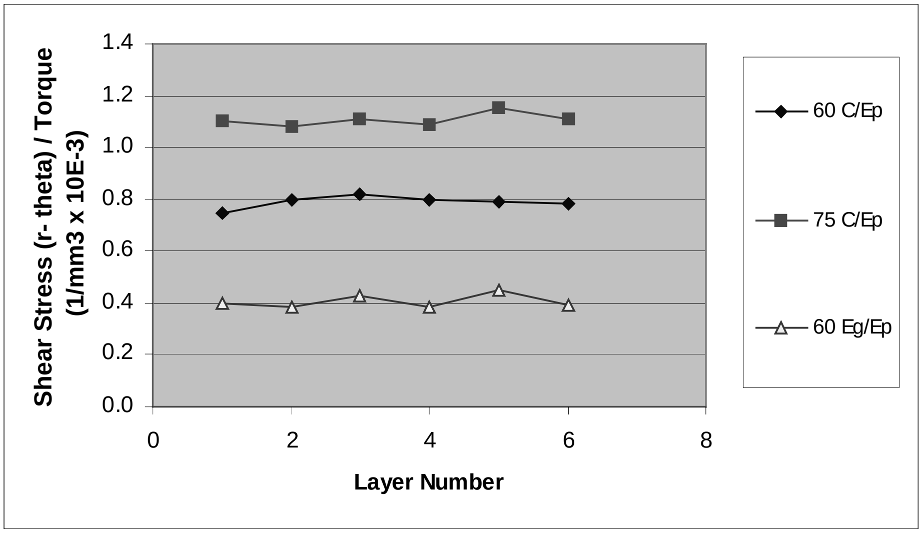

Figure 3.19 – Variation of '$\sigma_{r\theta}$/torque' by layers, for different tubes under pure torsion

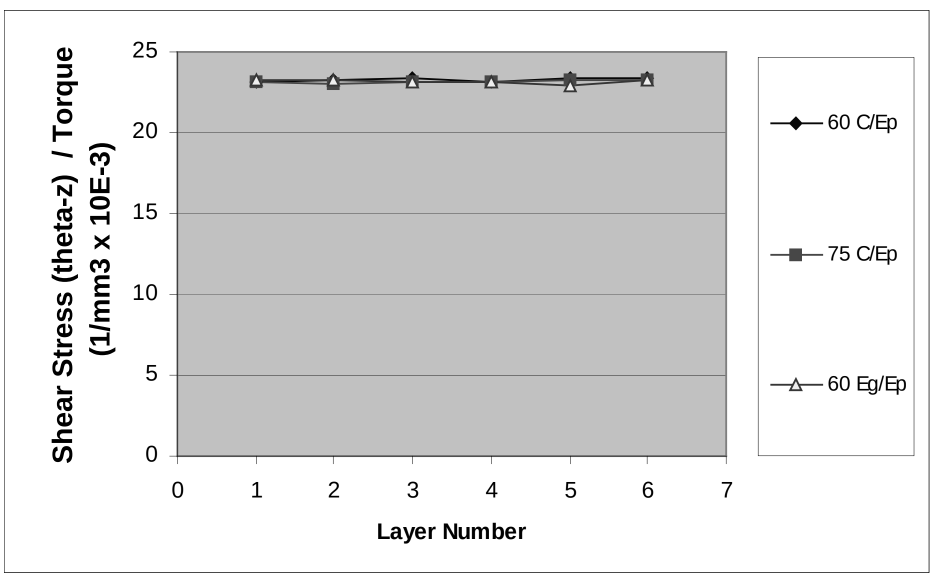

Figure 3.20 – Variation of '$\sigma_{\theta z}$/torque' by layers, for different tubes under pure torsion

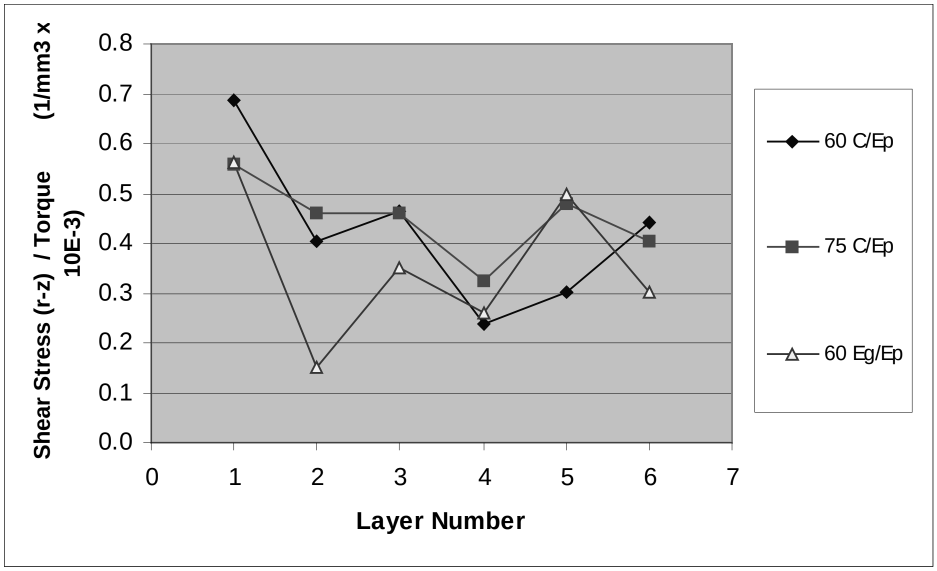

Figure 3.21 – Variation of 'σ_{rz}/torque' by layers, for different tubes under pure torsion

3.6 PURE AXIAL LOADING

It can easily be calculated that, the optimum angle orientation for an axially loaded orthotropic tube is close to zero degree. As the angle of winding increases, failure indices for the tube increase. A series of analyses are performed in order to investigate this behavior for different materials.

In FEA model, the tube is fixed from one end, as done in pure torsion. On the other end of the tube, a constant axial tension load is applied. Dimensions of the tube are given in Table 2.1. Solutions are recorded for middle sector of the tube.

In the first analysis, a 6-layer, C/Ep tube is subjected to axial loading only and the analyses are repeated for the same boundary conditions, but for varying winding angles. TWSI results are obtained for each winding angle. Then the same procedure is performed for Eg/Ep and A/Ep tubes as well.

For a further investigation on the effect of level of orthotropy, one more tube, which has a slightly higher level of orthotropic properties than C/Ep, is analyzed. In order to increase level of orthotropy, elastic and strength constants of C/Ep in fiber direction are increased by 10%.

As seen in Fig. 3.22, although there exists a general trend of increase in TWSI with increasing winding angle, there are local differences for different materials. Investigating the figure, a trend related with the level of orthotropy seems to be difficult to obtain. The reasons for these variations are thought to be due to strength constants of materials and definition of Tsai-Wu Failure Criterion.

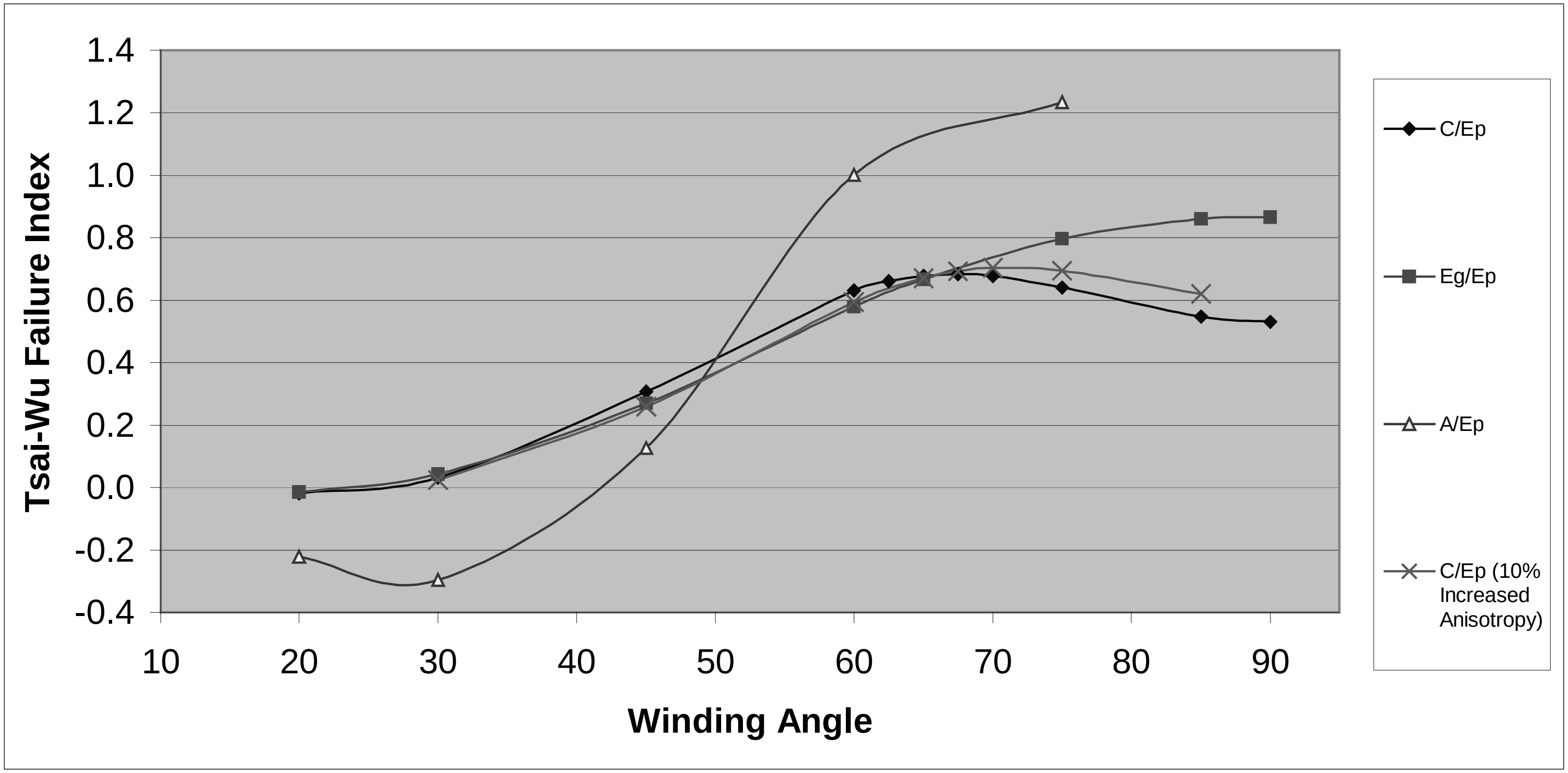

Figure 3.22 –Winding Angle vs. Tsai Wu Failure Index, for a variety of composite materials

3.7 COMBINED INTERNAL PRESSURE AND AXIAL LOADING

Three types of analysis are performed in order to investigate the behavior of layered orthotropic tubes under combined internal pressure and axial loading. In FEA model, the tube is fixed from one end, using an all DOF's constraint on end lines of the tube surface. Within a user-defined length (see Fig. 2.3) on the other end of the tube, a varying axial load is applied. An internal pressure of 25 MPa is applied to the inner surface of the tube. Dimensions of the tube are given in Table 2.1. As in previous analysis, solutions are recorded for the middle part of the tube.

In the first analysis, an Eg/Ep tube is subjected to internal pressure loading and the analysis is repeated for varying winding angle and varying axial load. TWSI results obtained can be seen in Fig. 3.23. In the second analysis, a C/Ep tube is subjected to the same conditions, in order to investigate influence of level of orthotropy (Fig. 3.24). Comparison of C/Ep and Eg/Ep tubes for varying winding angles can be seen in Fig. 3.25–3.30. Note that, the term 'Axial Force Ratio (AFR)' is the ratio of axial force to axial force generated by internal pressure. Finally, in the third analysis, the effect of tube thickness on TWSI, for different winding angles is investigated. Results can be seen in Fig. 3.34 and 3.35.

Examining the combined internal pressure and axial loading analysis results, following conclusions can be drawn:

- The optimum-winding angle of a tube, which is loaded by combined internal pressure and the axial load, depends on the magnitude of pressure and axial load. When axial load gets dominant, the optimum winding angle decreases as in the case of a pure axial loading. Similarly, as the internal pressure gets dominant, the optimum winding angle increases as in the case of pure internal pressure loading (Fig. 3.23).

- When the axial force ratio is equal to one, as in the case of a pressure vessel, the optimum winding angle has an optimum value, which is about 60^{o} (Fig. 3.23).

- If there is no axial force, the optimum winding angle is equal to 90^{o} as mentioned in Section 3.4 (Fig. 3.23).

- For negative axial force ratios, a winding angle of 60^{o} becomes the optimum value for a wide range (Fig. 3.23).

- A tube has an optimum axial force ratio. It can be concluded that, when TWSI is equal to one, even decreasing the axial load can cause the failure of a tube. When a different material is used for the same winding angle, the optimum axial force ratio can change (Fig. 3.23).

- For a specific ratio of axial force and internal pressure, two winding angles can give the same TWSI. Both winding angles can be an optimum for that axial force ratio (Fig. 3.23).

- For winding angles between 75 to 90^{o} the tube has a very similar behavior under combined internal pressure and axial loading conditions (Fig. 3.23).

- For a winding angle, two different ‘axial force / internal pressure’ ratios can have the same TWSI (Fig. 3.23).

- As the level of orthotropy increases, TWSI changes more dramatically. Therefore, when using highly orthotropic materials, more attention should be given to the material orientation (see Fig. 3.33).

- Tubes with high winding angles are not easily affected by the thickness of the tube, when compared with the tubes with low winding angles (see Fig. 3.34).

- The tubes, which are made of highly orthotropic materials, are more affected by the thickness of the tube (see Fig. 3.35).

- Above an axial force ratio of -4.5, a winding angle of 90^{o} becomes an optimum value for C/Ep tubes. Similar results can be obtained by further increasing number of data points for Eg/Ep tubes.

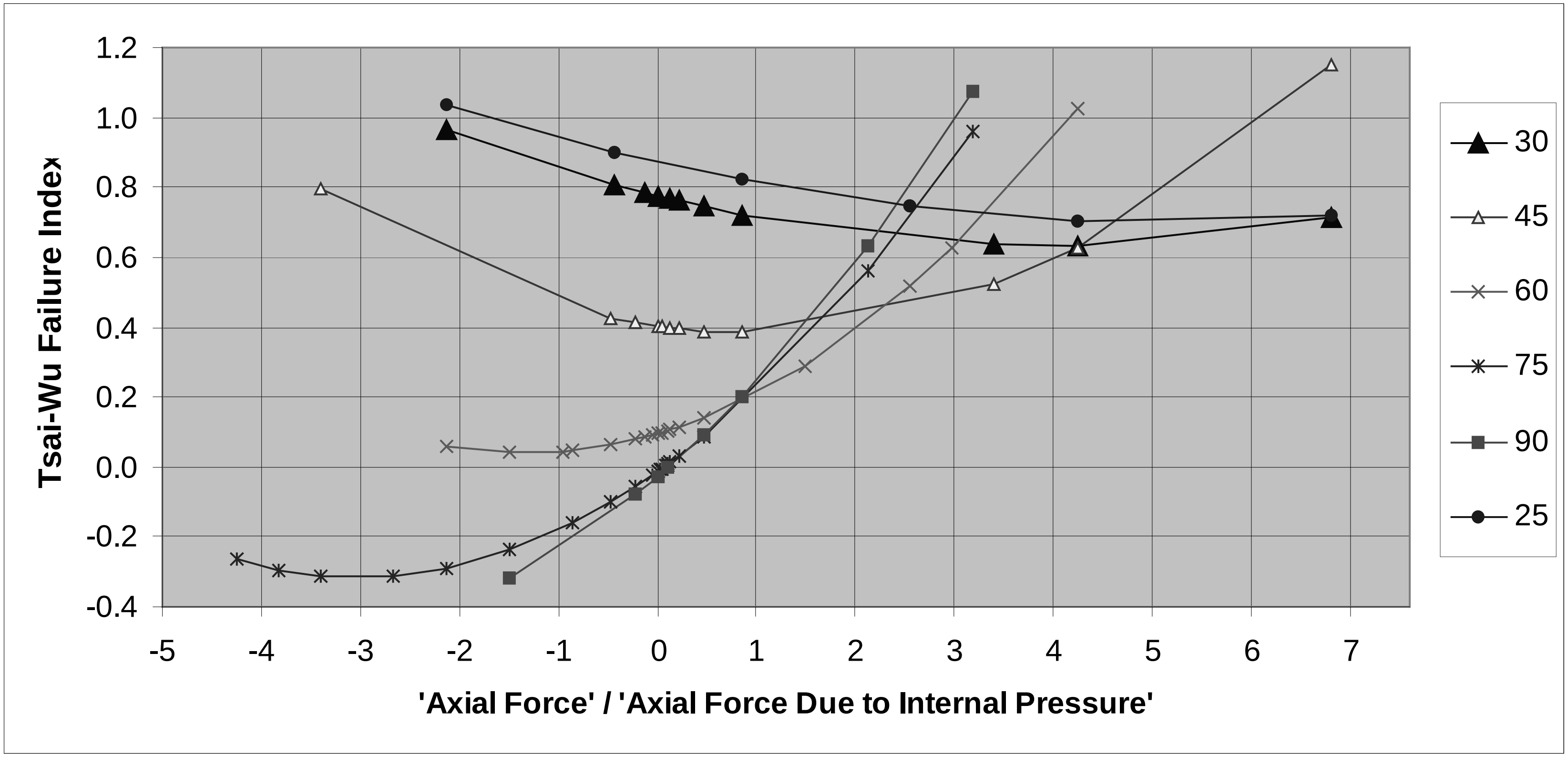

Figure 3.23 – Variation of TWSI with ‘Axial Force / Axial Force, which is generated by Internal Pressure’, for different winding angles of an Eg/Ep tube

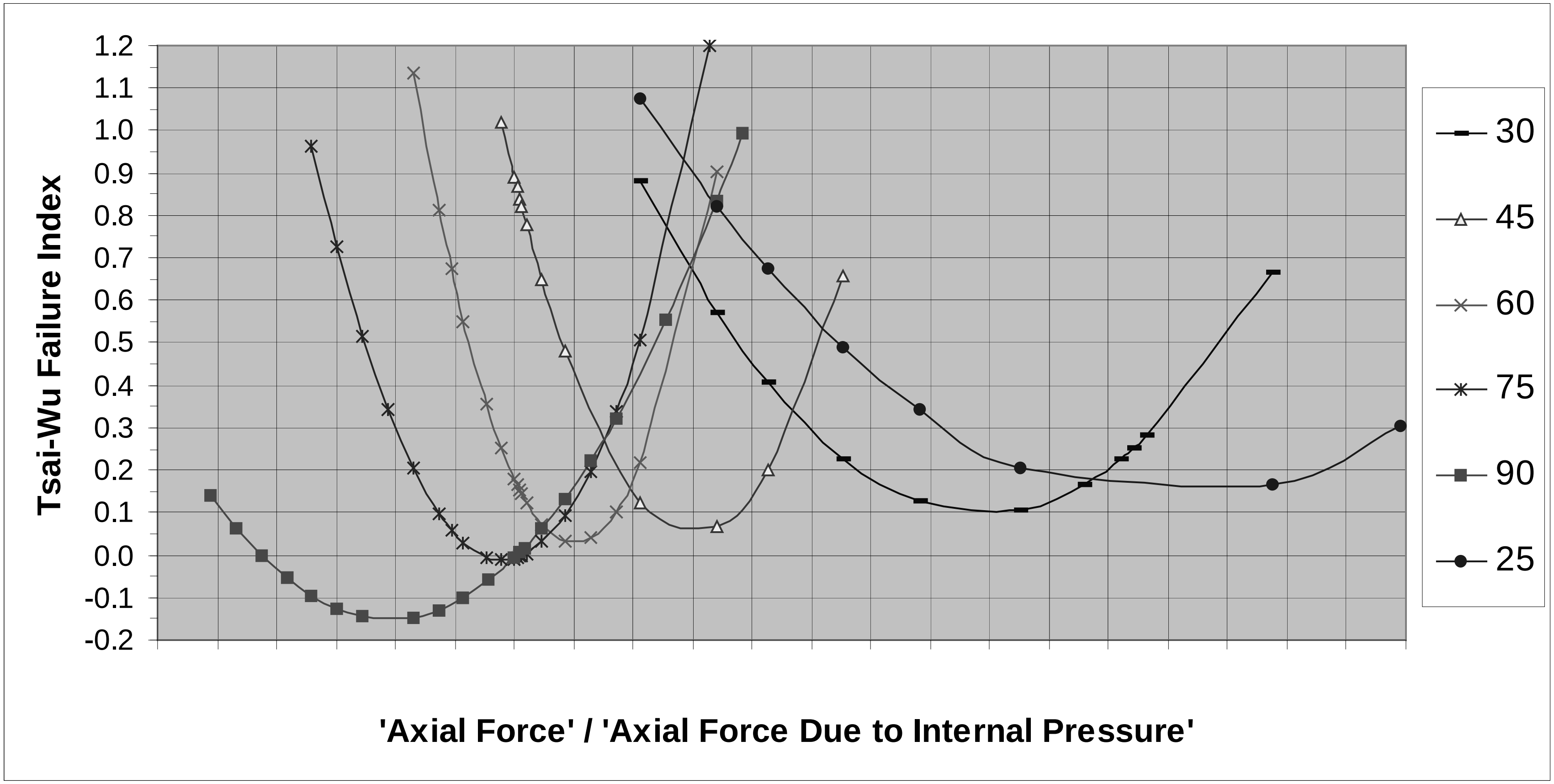

Figure 3.24 – Variation of TWSI with ‘Axial Force / Axial Force generated by Internal Pressure’ for different winding angles of a C/Ep tube

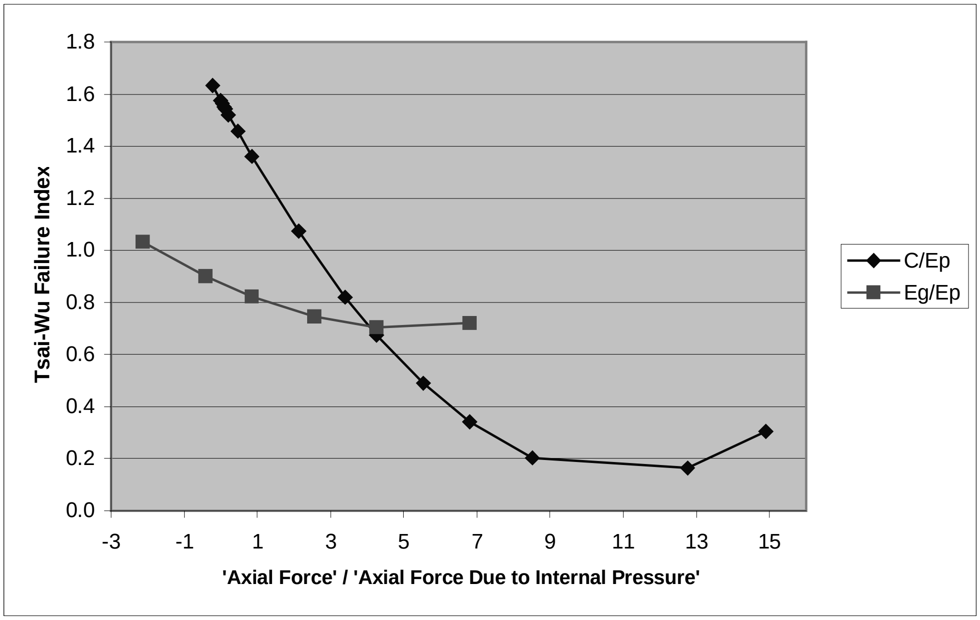

Figure 3.25 – Comparison of C/Ep and Eg/Ep Tubes under combined internal pressure and axial load, with a winding angle of ±25

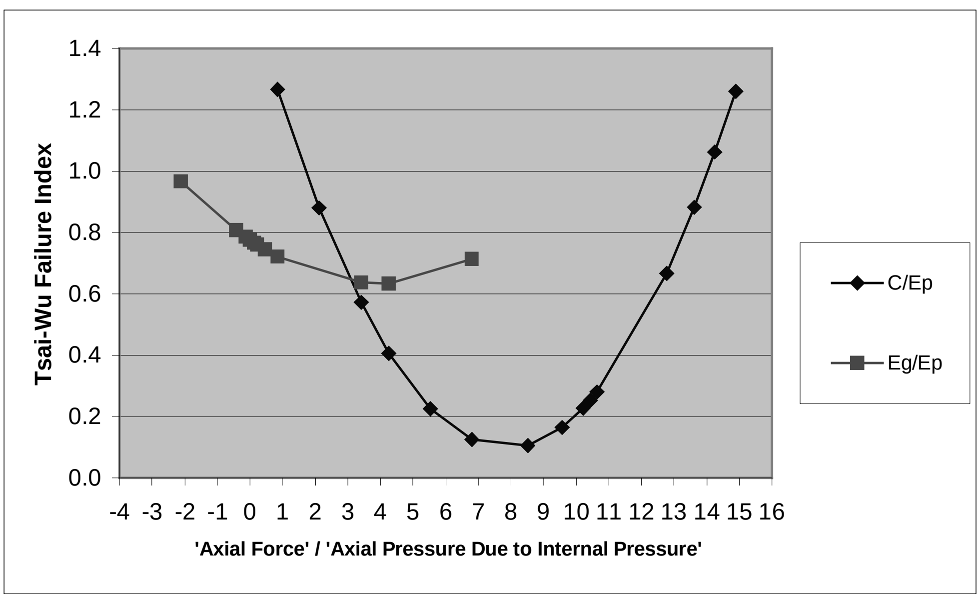

Figure 3.26 – Comparison of C/Ep and Eg/Ep Tubes, under combined internal pressure and axial load, with a winding angle of ±30.

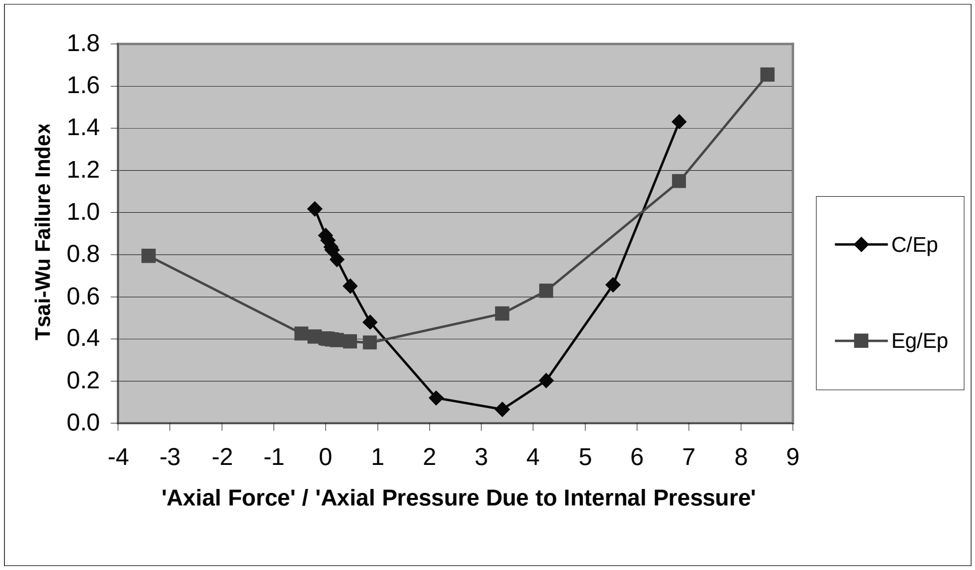

Figure 3.27 – Comparison of C/Ep and Eg/Ep Tubes, under combined internal pressure and axial load, with a winding angle of ±45.

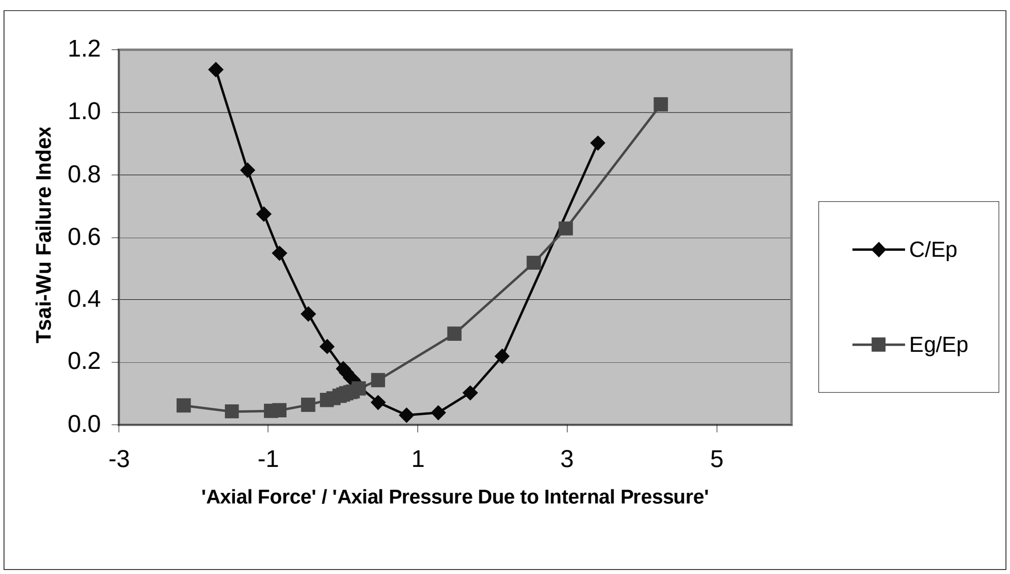

Figure 3.28 – Comparison of C/Ep and Eg/Ep Tubes, under combined internal pressure and axial load, with a winding angle of ±60

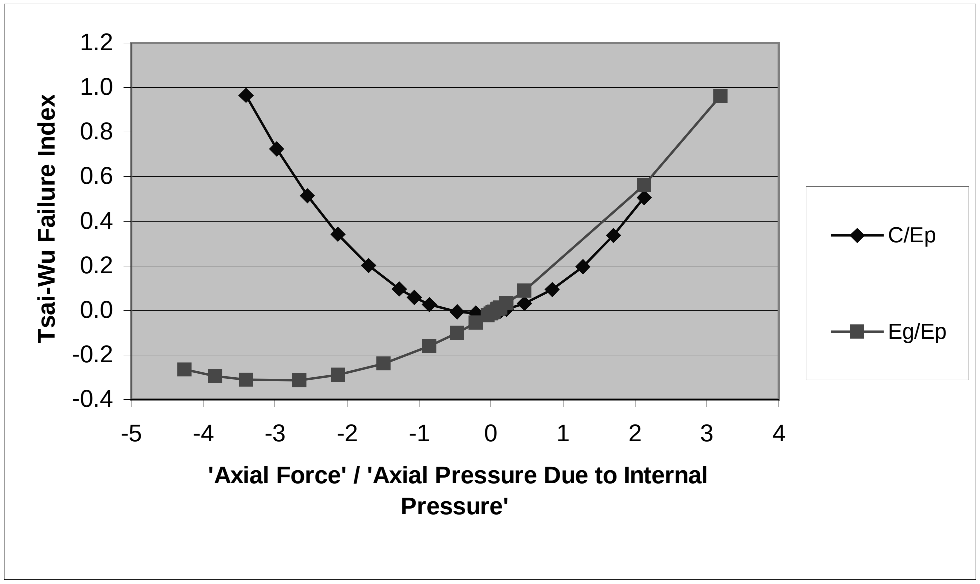

Figure 3.29 – Comparison of C/Ep and Eg/Ep Tubes under combined internal pressure and axial load, with a winding angle of ±75º

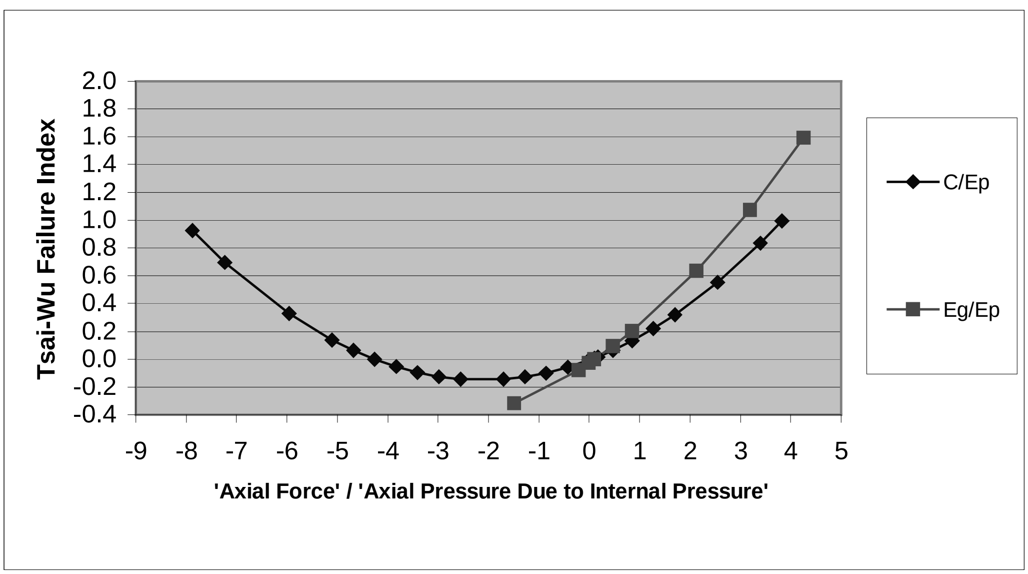

Figure 3.30 – Comparison of C/Ep and Eg/Ep Tubes, under combined internal pressure and axial load, with a winding angle of 90º

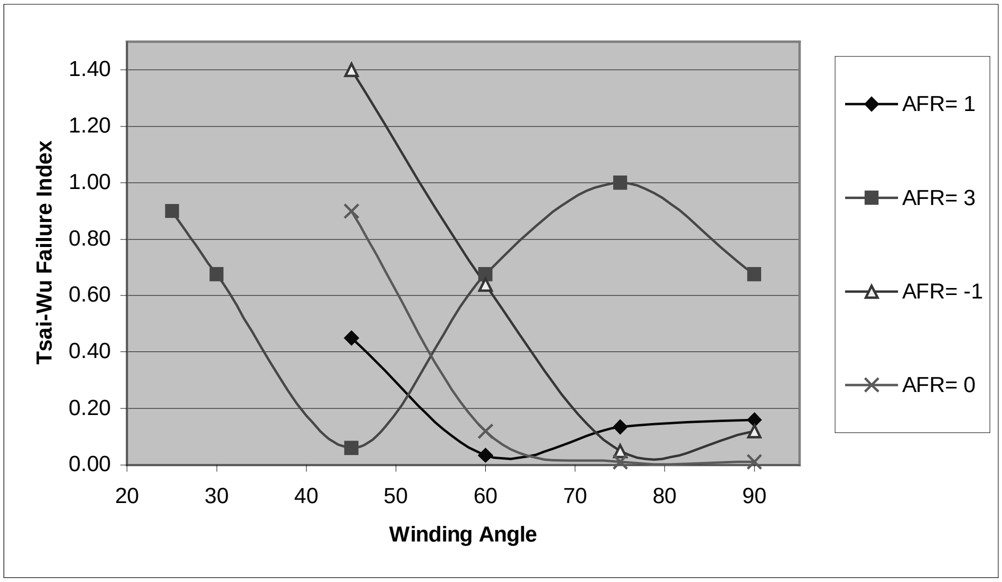

Figure 3.31 – Effect of winding angle on TWSI, for different axial force ratios (C/Ep tube)

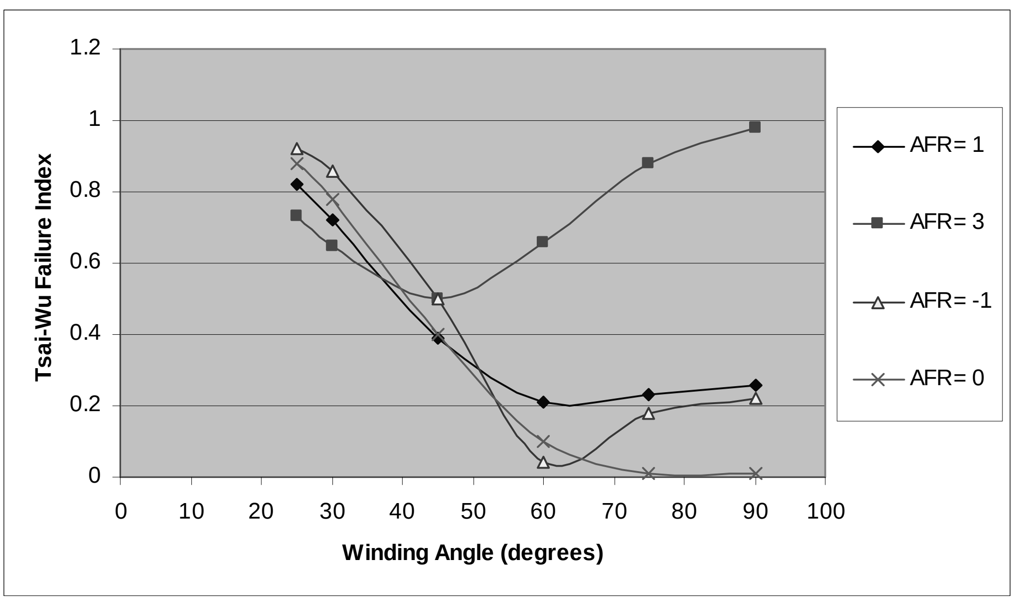

Figure 3.32 – Effect of winding angle on TWSI for different axial force ratios (Eg/Ep tube)

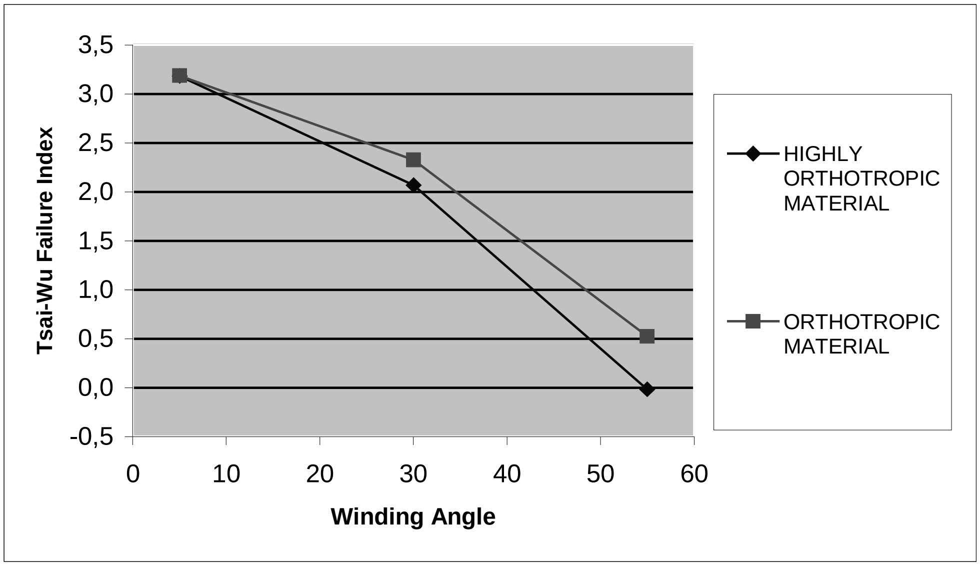

Figure 3.33 – Effect of winding angle on TWSI for different level of orthotropy

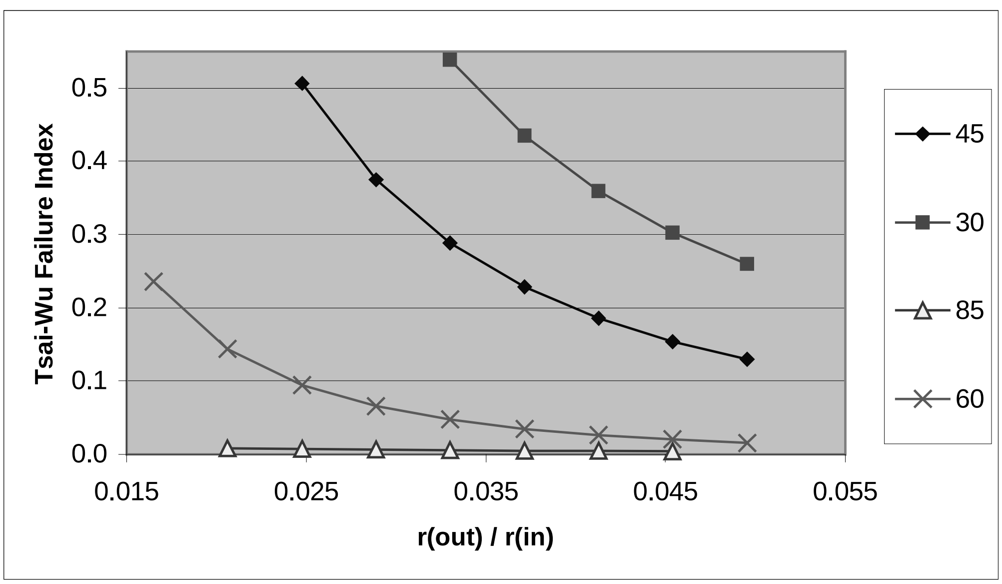

Figure 3.34 – Effect of tube thickness on TWSI for different winding angles

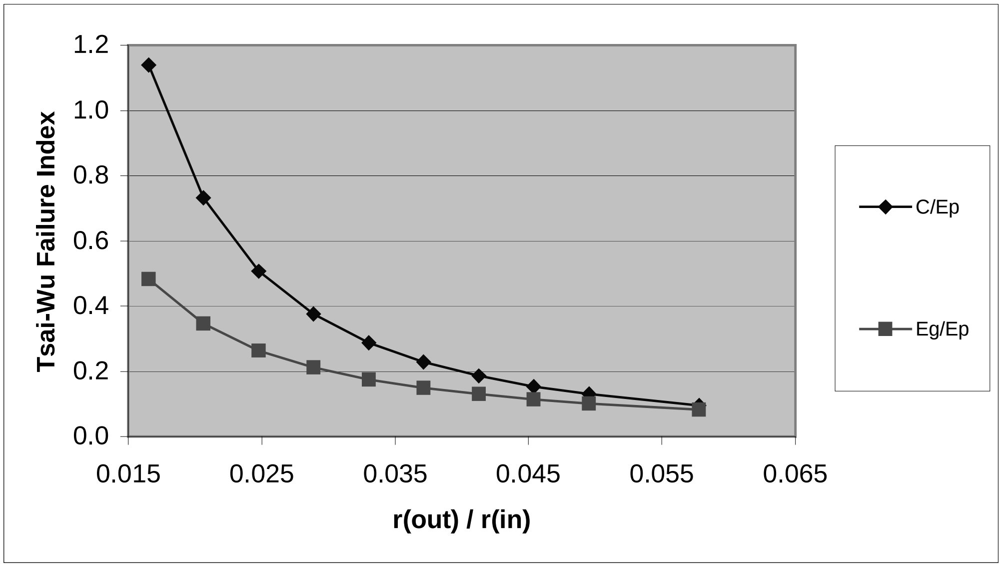

Figure 3.35 – Effect of tube thickness on TWSI, for C/Ep and Eg/Ep tubes

3.8 COMBINED TORSION AND INTERNAL PRESSURE LOADING

An analysis is performed in order to investigate the behavior of layered orthotropic tubes under combined torsion and internal pressure loading. In FEA model, the tube is fixed from one end as done in previous studies. An internal pressure, which has a constant value of 2.5 MPa, is applied to the inner surface of the tube. Within a user-defined length, a varying torsion is applied (Fig. 2.3). The same tube dimensions are used, which are given in Table 2.1.

Results are recorded for the middle of the tube. In addition, inner two layers of the tube are considered for the presentation of results, since they are more critical in combined torsion and internal pressure loading. The tube is modeled as a 6-layer, C/Ep tube. The analysis is repeated for varying degrees of winding angles and different torque values.

Examining the combined torsion and internal pressure loading of a C/Ep tube, following conclusions can be drawn:

- When there is no torque applied, as discussed in Section 3.4, higher winding angles are better for internal pressure loading (Fig. 3.36).

- Winding angles, higher than ±45º, has an increasing failure index with increasing torque value (Fig. 3.36).

- Winding angles lower then ±45º, has an optimum ‘torque / internal pressure’ ratio. This positive optimum ‘torque / internal pressure’ ratio increases with a decrease in winding angle (Fig. 3.36).

- When the torque value gets dominant compared with internal pressure loading, a winding angle of ±45º becomes an optimum value (Fig. 3.36).

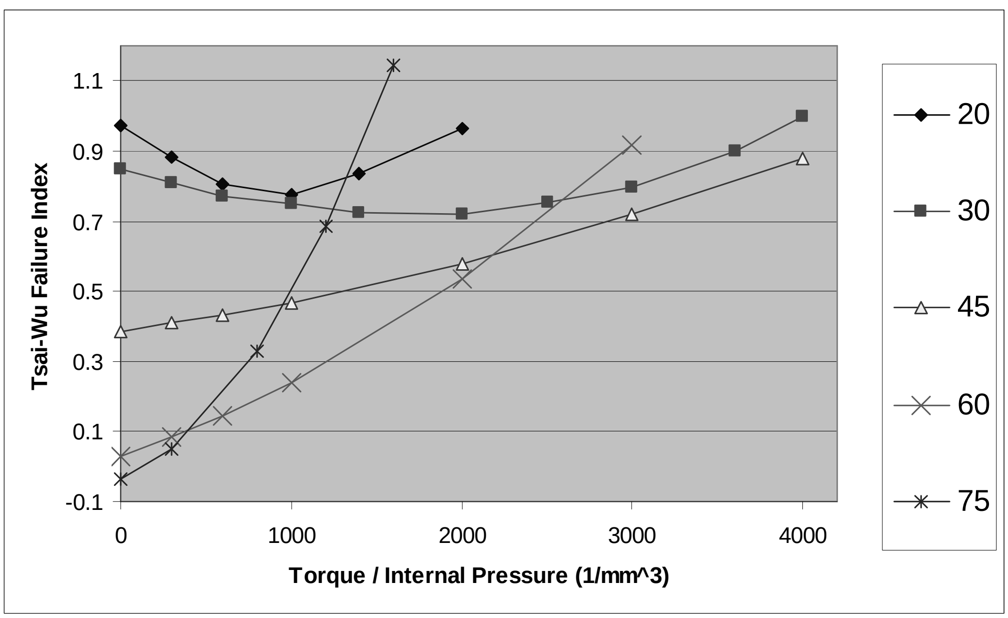

Figure 3.36 – ‘Torque / Internal Pressure’ vs. TWSI for a 6-layer, C/Ep tube, under combined torsion and internal pressure loading

3.9 COMBINED BENDING AND AXIAL LOADING

An analysis is performed in order to investigate the behavior of layered orthotropic tubes under combined bending and axial loading. In FEA model, the tube is fixed from one end. Then, on the other end of the tube, within a user-defined length (see Fig. 2.3), a transverse load, which has a constant value of 4000 N, and a varying axial load are applied. The tube dimensions are given in Table 2.1.

Solutions are recorded for the most critical part of the tube, which depends on specific loading condition. It can be noted that, the critical point is always on the outer layer. For both axial tension and axial compression cases, the point is assumed 10 mm away from the fixed end of the tube, in order to get rid of high stress gradients. For axial compression loading condition, direction of transverse load generally indicates the side of the tube, where critical point exists. On the other hand, for axial tension loading condition, direction of transverse load generally indicates opposite side of the tube, where critical point exists.

The tube is modeled as a 6-layer, C/Ep tube. The analysis is repeated for varying winding angle and varying axial load. TWSI results can be seen in Fig. 3.40.

Bending of layered tubes creates a non-symmetric stress distribution. Moreover, gradients are affected by the winding angle. Fig. 3.37 - 3.39 show Tsai-Wu Stress Failure Index on a ±60º tube under bending. Note that, left and right views are different from each other. In addition, gradients that follow material direction can be observed on top view.

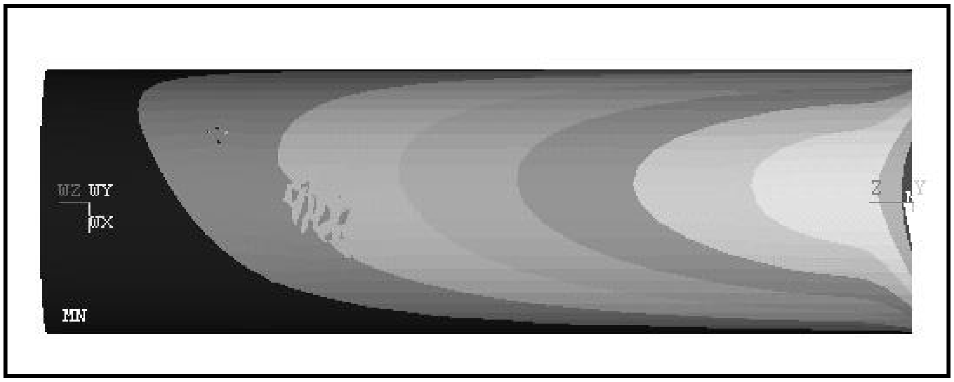

Figure 3.37 – Top view (outer layer plot) of a 6-layer, ±60º, C/Ep tube under pure bending

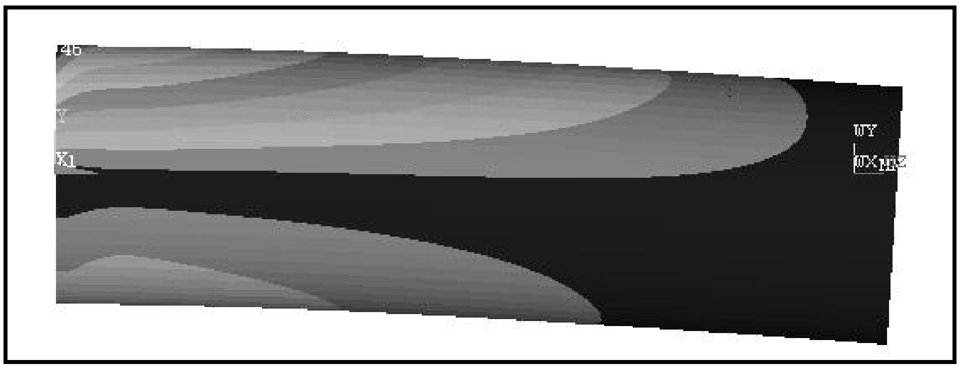

Figure 3.38 – Right View (outer layer plot) of a 6-layer, ±60º, C/Ep tube under pure bending

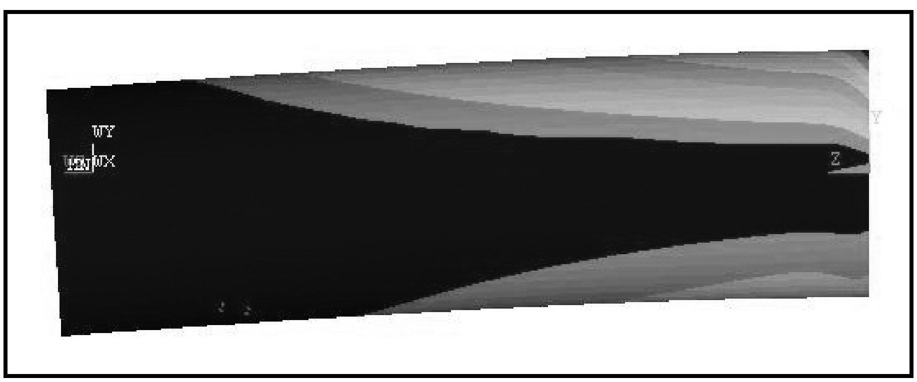

Figure 3.39 – Left View (outer layer plot) of a 6-layer, ±60º, C/Ep tube under pure bending

Examining the combined bending and axial loading analysis results, following conclusions can be drawn:

- If ‘Axial Force / Transverse Force’ ratio value is close to zero, TWSI is almost same for different winding angles. This fact indicates that, the pure bending of layered orthotropic tubes is not significantly affected by winding angle configuration (Fig. 3.40).

- For higher values of ‘Axial Force / Transverse Force’, the effect of winding angle on TWSI increases (Fig. 3.40). However, winding angles between 30 to 60^o, cause a lower variation in failure index when compared with the range of 60 to 90^o (Fig. 3.40).

- All winding angles have an optimum value of ‘Axial Force / Transverse Force’ in the negative axis (Fig. 3.40). It indicates that, when TWSI is equal to zero for a tube under bending and axial compression load, decreasing axial compression can cause failure of the tube.

- Two different values of ‘Axial Load / Transverse Load’ ratio can have the same value of failure index, even if they have different signs (Fig. 3.40).

- All tubes, which are wound with different winding angles, have one optimum ‘Axial Load / Transverse Load’ ratio in the neighborhood of ‘- 10’. The second optimum point depends on the winding angle and has a negative value of ‘Axial Load / Transverse Load’ ratio, which increases in magnitude with increasing winding angle (Fig. 3.40).

- ±45^o tubes have a lower failure index for positive values of ‘Axial Load / Transverse Load’ ratio.

- Above a value of -100 for ratio of ‘Axial Load / Transverse Load’ ratio, a winding angle of 90^o becomes an optimum value.

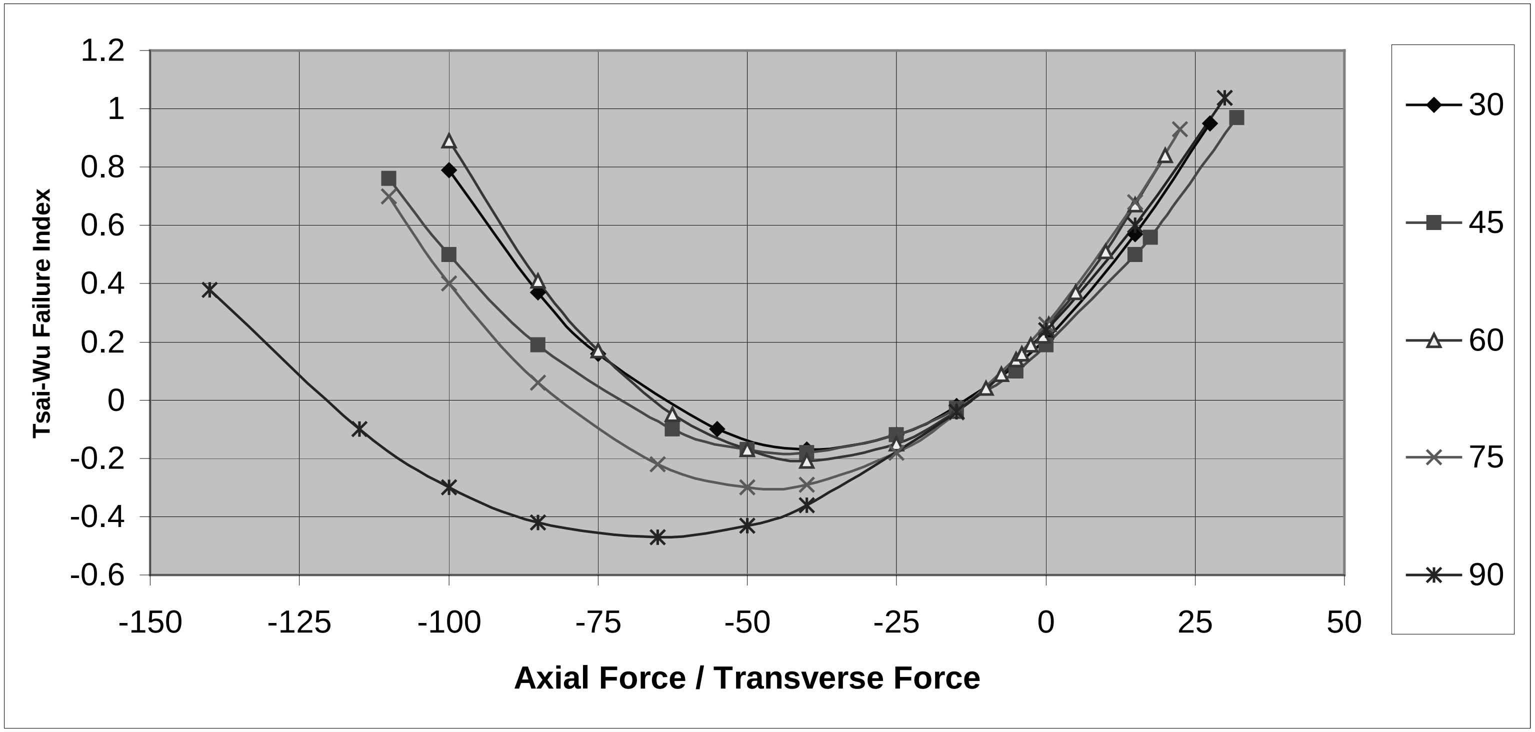

Figure 3.40 – Effect of ‘Axial Force/Transverse Force’ on TWSI, for different winding angles of a C/Ep tube

3.10 VARIATION IN WINDING ANGLE

Consider a pressure vessel (PV), under internal pressure loading, which comprises a multitude of layers wound at different angles, rather than repeating a single wind angle through thickness. Patterns, which include three winding angles, are commonly used in industry for production of pressure vessels. These angles vary with each specific application and dimensions of the tube.

For our analyses, three different winding patterns for three different tubes are chosen as tabulated in Table 3.8. An internal pressure and an axial force are applied to the tubes. Axial force assumed to be created by only internal pressure. Dimensions of the tube are given in Table 3.9.

TABLE 3.8 – Different Winding Patterns for Tube 1, 2 and 3

Layer Number	T -1	T -2	T -3
1	25	25	90
2	-25	-25	90
3	45	55	-45
4	-45	-55	45
5	90	90	-25
6	90	90	25

TABLE 3.9 – Dimensions of the Tube

Length of the tube (mm)	400
Fixing length (mm)	20
Average radius (mm)	60
Tube thickness (mm)	6

Analyses are performed on these tubes, in order to investigate effect of different winding patterns. Dimensions of the tube are given in Table 2.1. FEA model is similar to ones, described in section 3.7. Comparison of T-1 and T-2 can be seen in Fig. 3.41- 3.46.

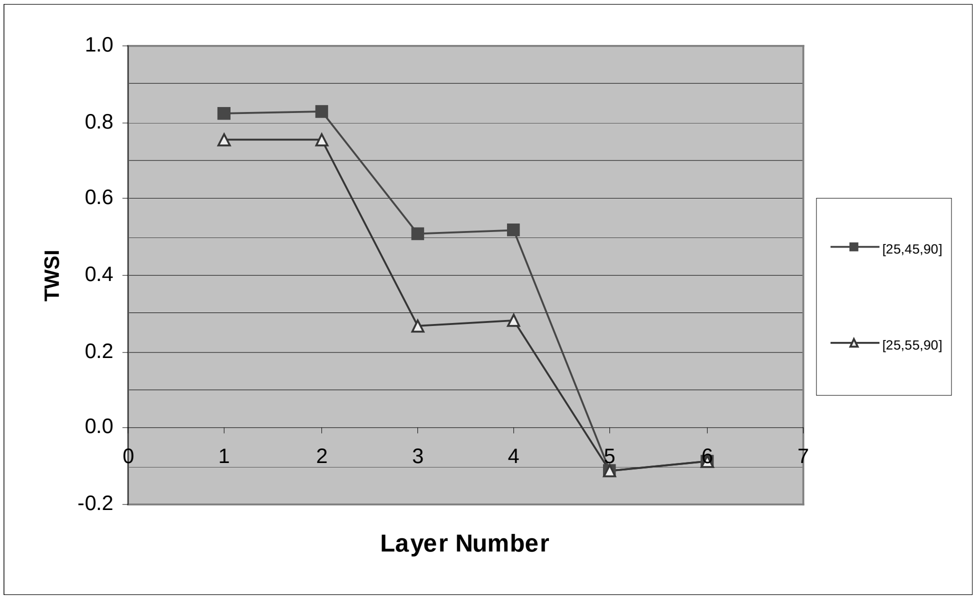

Figure 3.41 – Layer Number vs. TWSI, for T-1 and T-2

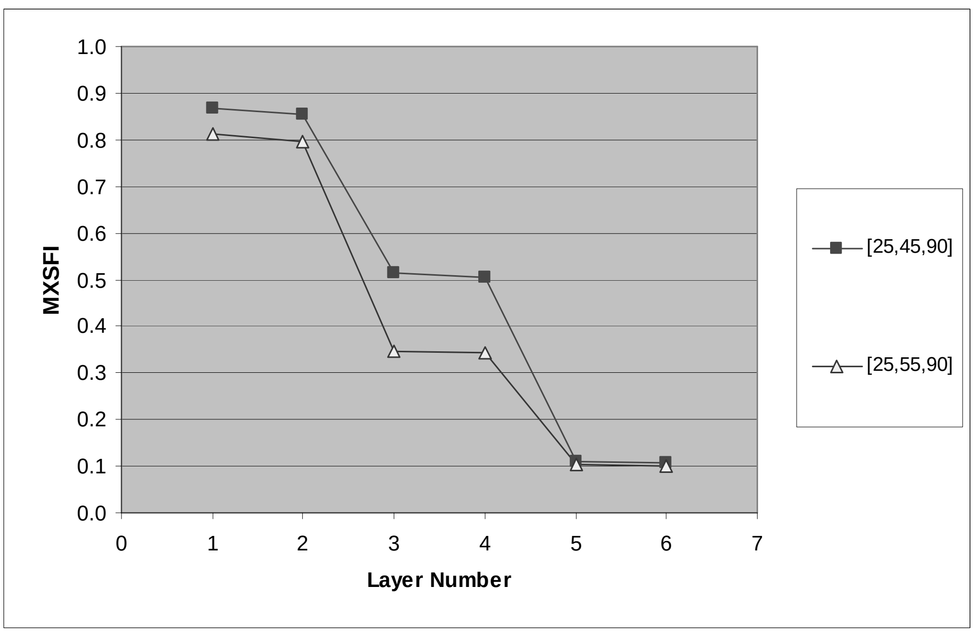

Figure 3.42 – Layer Number vs. MXSFI, for T-1 and T-2

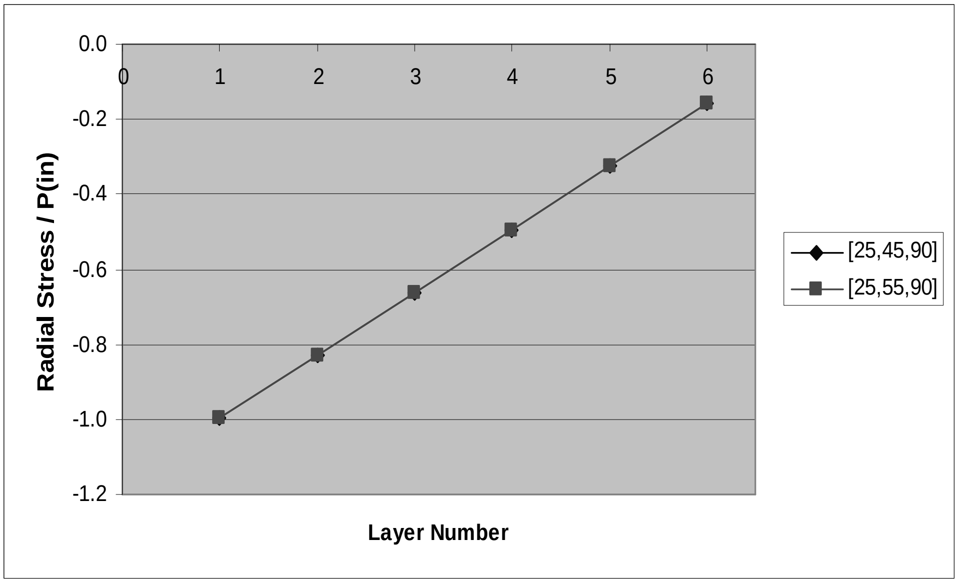

Figure 3.43 – Layer Number vs. σ_{rr}/P_{in}, for T-1 and T-2

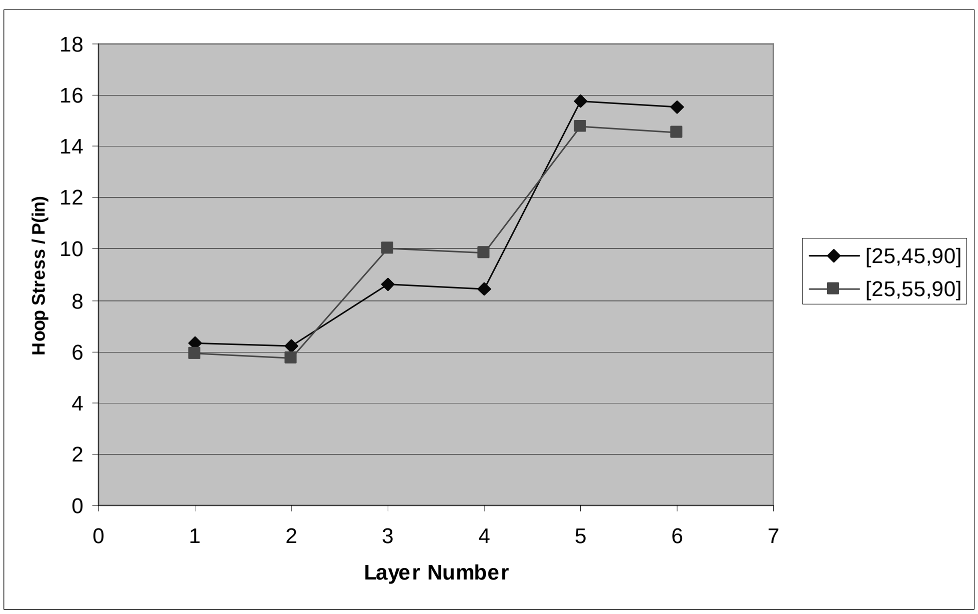

Figure 3.44 – Layer Number vs. $\sigma_{\theta\theta}/P_{in}$, for T-1 and T-2

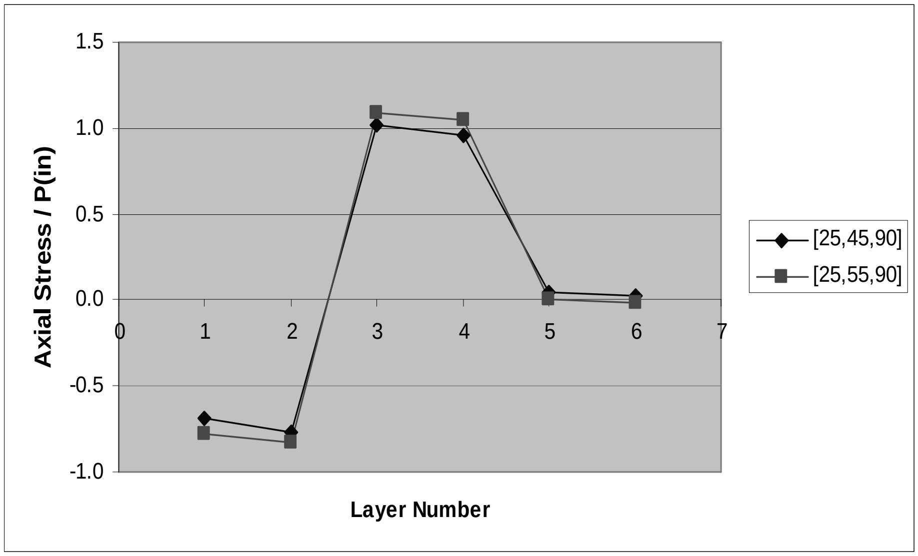

Figure 3.45 – Layer Number vs. σ_{zz}/P_{in}, for T-1 and T-2

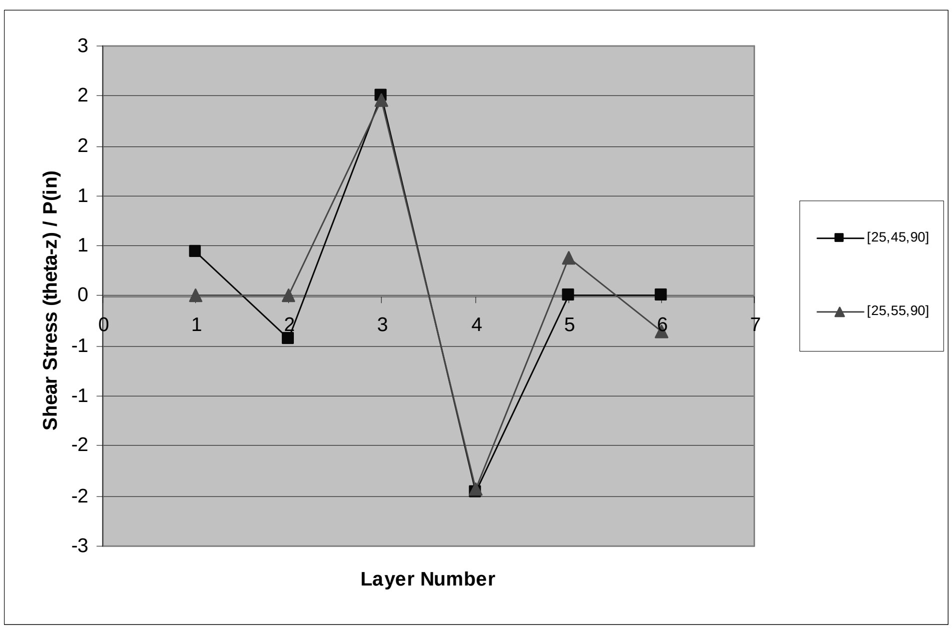

Figure 3.46 – Layer Number vs. $\sigma_{\theta z}/P_{in}$, for T-1 and T-2

Considering the two analyses performed on T-1 and T-2, following conclusions can be drawn:

- T-2 has a better winding pattern; since TWSI and MXSFI of T-2 is lower (Fig. 3.41- 3.42).

- σ_{rr} is not affected by winding pattern (Fig. 3.43). On the inner surface, σ_{rr} is equal to P_{in}. On the outer surface, σ_{rr} has a value, which is close to zero.

- Hoop stress is the dominant stress in TSWI calculation (Fig. 3.43 - 3.46).

- Using ±55º instead of ±45º, increased the hoop stress in middle layers, where decreased the hoop stress in the outer layers (Fig. 3.44). This seems to be the main reason for having a lower TWSI for T-2.

- T-2 has a higher σ_{zz} and $\sigma_{\theta z}$ in layers 1-4 (Fig. 3.45 - 3.46).

Now, considering T-1 and T-3, analysis results and comparison of these patterns can be found in Fig. 3.48-3.53.

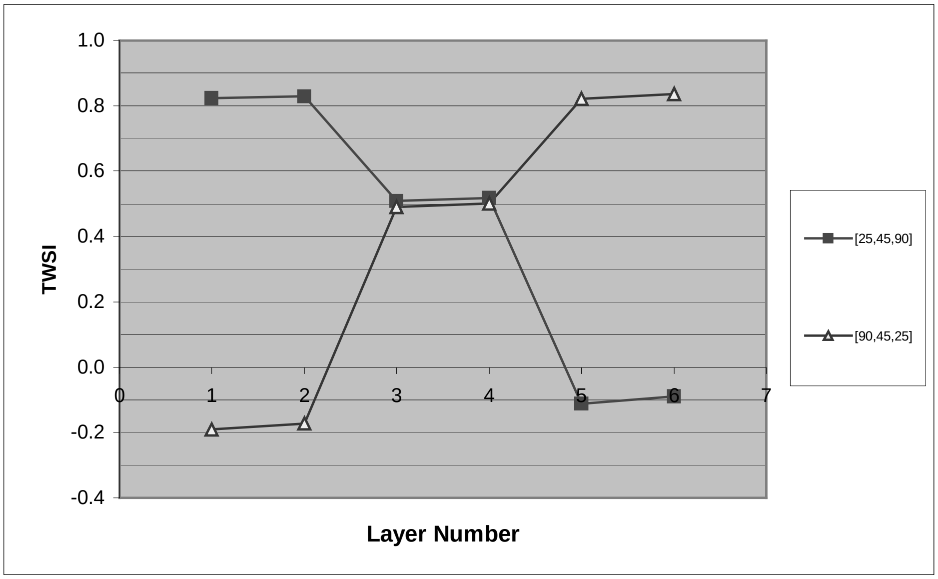

Figure 3.47 – Layer Number vs. TWSI, for T-1 and T-3

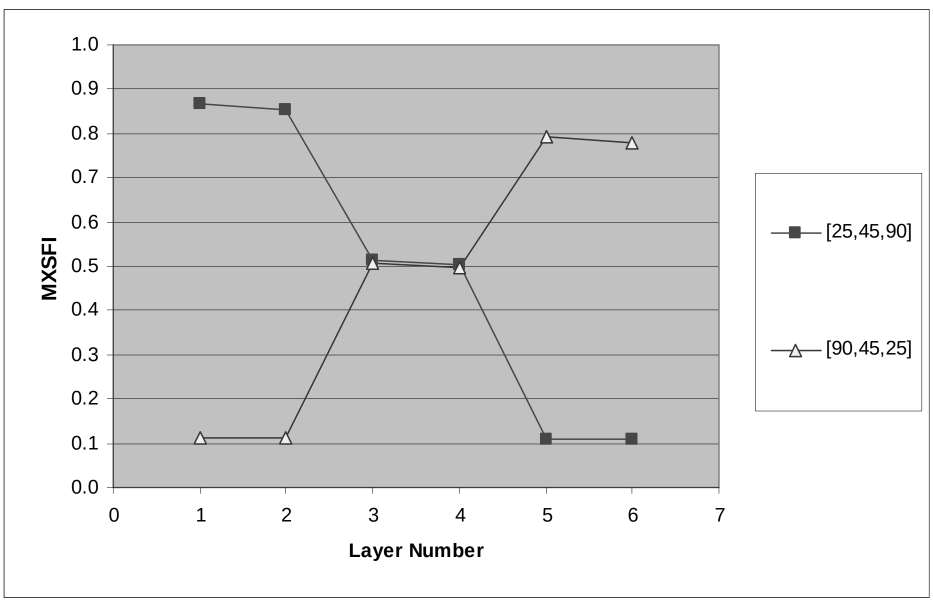

Figure 3.48 – Layer Number vs. MXSFI, for T-1 and T-3

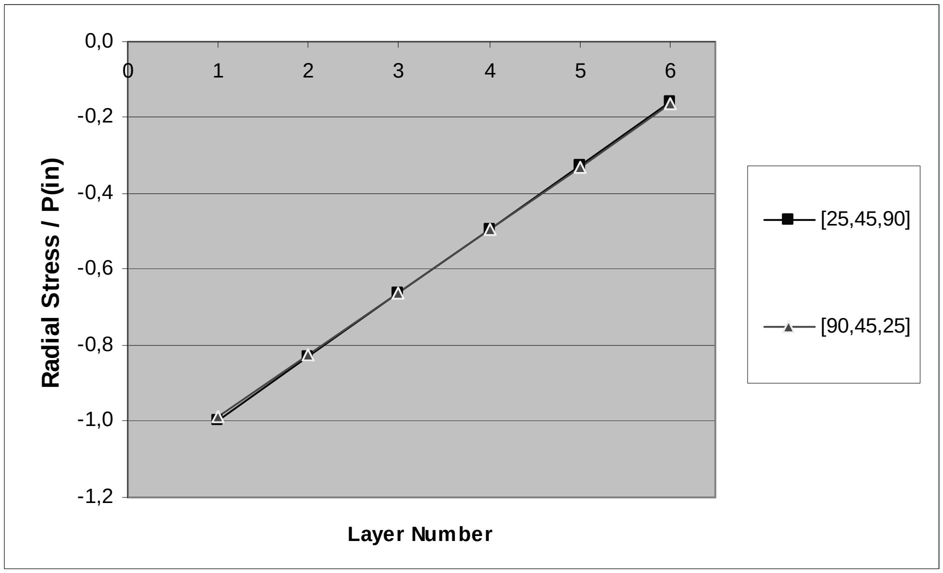

Figure 3.49 – Layer Number vs. σ_{rr}/P_{in}, for T-1 and T-3

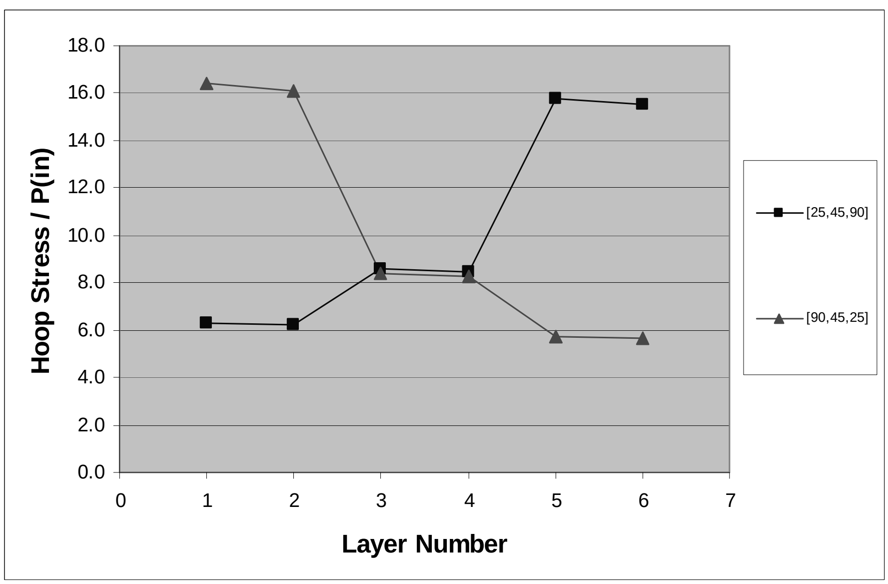

Figure 3.50 – Layer Number vs. $\sigma_{\theta\theta}/P_{in}$, for T-1 and T-3

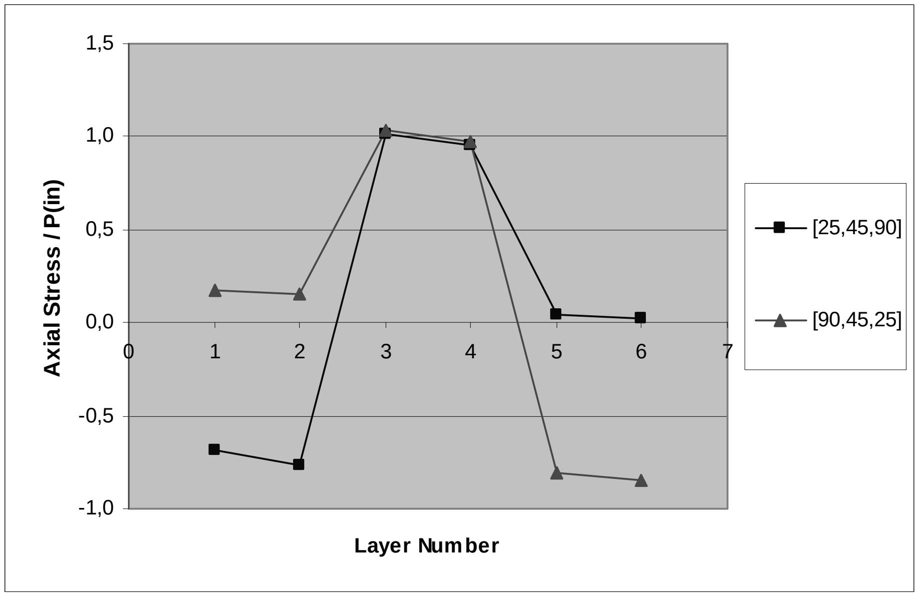

Figure 4.51 – Layer Number vs. σ_{zz}/P_{in}, for T-1 and T-3

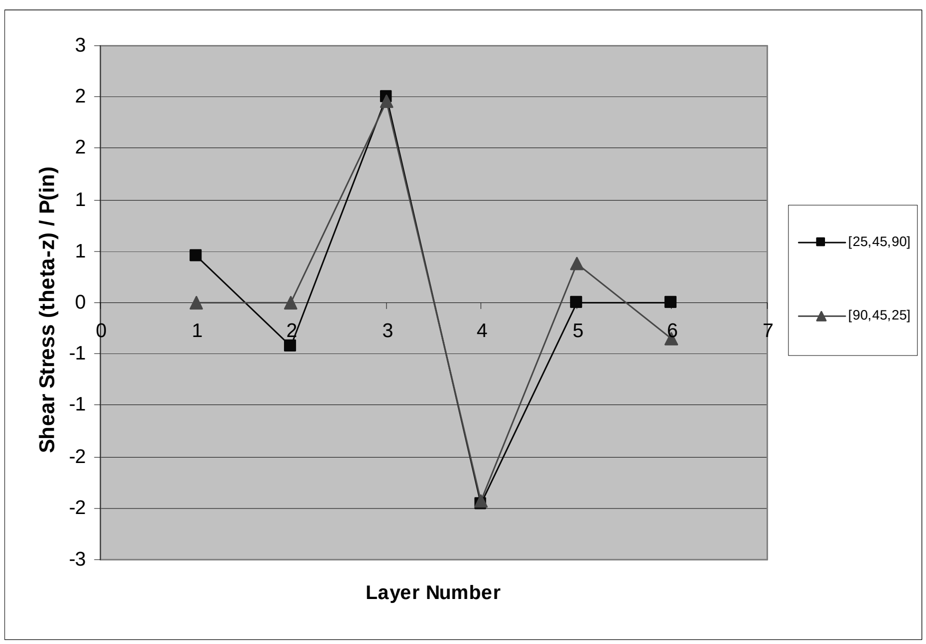

Figure 3.52 – Layer Number vs. $\sigma_{\theta z}/P_{in}$, for T-1 and T-3

Considering the analyses performed on T-1 and T-3, following conclusions can be drawn:

- If TWSI is considered, these patterns seem to have a similar performance (Fig. 3.47). However, if MXSFI is considered, T-3 has a better performance (Fig. 3.48).

- σ_{rr} is not affected by winding pattern (Fig. 3.49). On the inner surface, σ_{rr} is equal to P_{in}. On the outer surface, σ_{rr} has a value, which is close to zero.

- Hoop stress is the dominant stress in TWSI calculation (Fig. 3.49- 3.52).

- Using 90º instead of ±25º in the first two layers, the hoop stress is increased in 90º layers, where the hoop stress in ±25º layers is decreased (Fig. 3.50). In both cases, the maximum hoop stress occurred in 90º layers. This is due to higher modulus in the hoop direction. However, since 90º layers have high strength in the hoop direction, they have a lower TWSI and MXSFI.

- ±25º layers have a higher σ_{zz} and $\sigma_{\theta z}$ (Fig. 3.51- 3.52).

Considering T-1 and T-3, the effect of interchanging the layer orientations is observed. Now consider two more analyses performed on Tube-4 (T-4) and Tube-5 (T-5), where layer orientations are interchanged.

An internal pressure and an axial force are applied to these tubes. The axial force is assumed to be caused by the pure internal pressure. Analyses are performed on these tubes in order to investigate the effect of interchange in layer orientations. Comparison of T-4 and T-5 results can be found in Fig. 3.53- 3.57.

TABLE 3.10 – Different Winding Patterns for T-4 and T-5

	Layer Orientation	
Layer Number	**T-4**	**T-5**
1	60	60
2	-60	-60
3	60	15
4	-60	-15
5	15	60
6	-15	-60
7	15	15
8	-15	-15

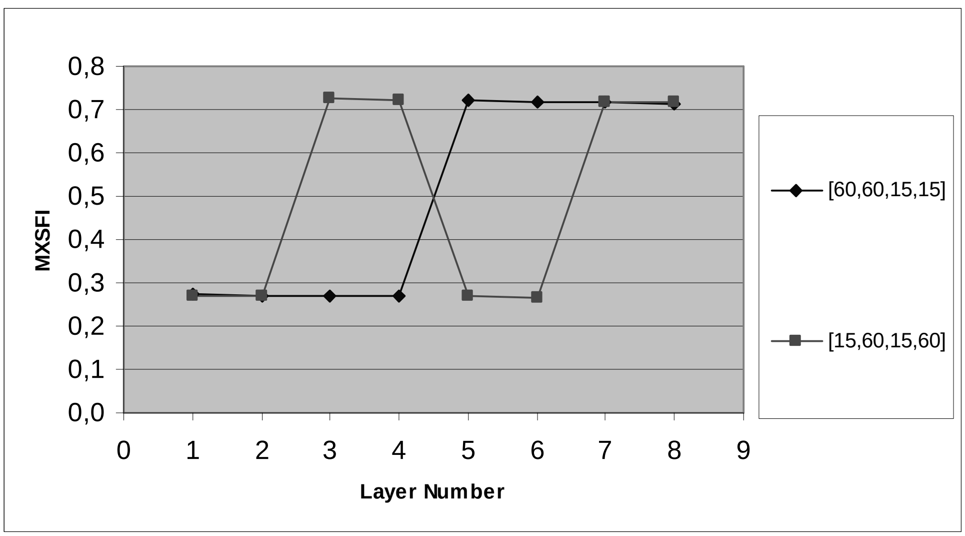

Figure 3.53 – Layer Number vs. MXSFI, for T-4 and T-5

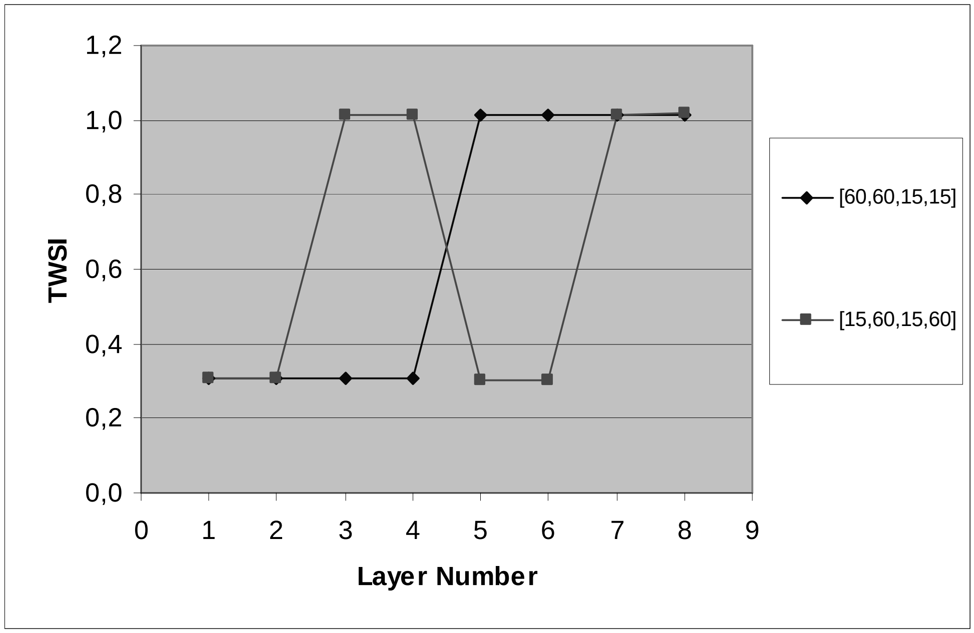

Figure 3.54 – Layer Number vs. TWSI, for T-4 and T-5

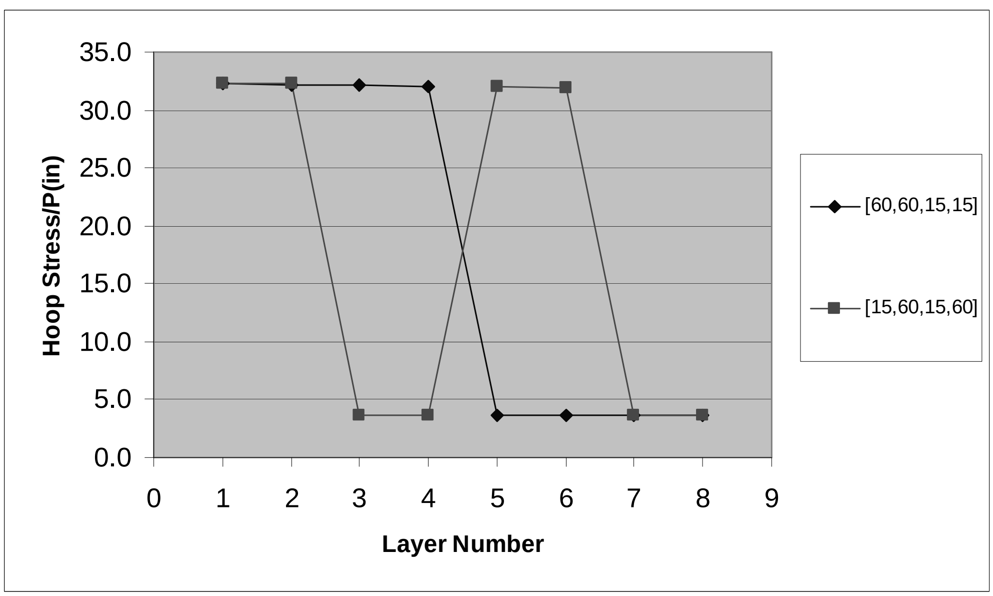

Figure 3.55 – Layer Number vs. Hoop Stress, for T-4 and T-5

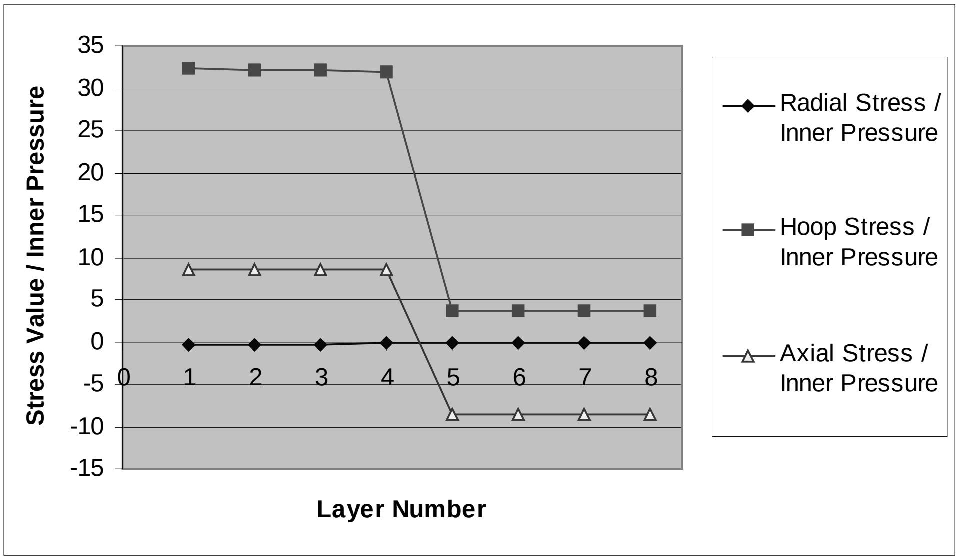

Figure 3.56 – Layer Number vs. stress value/inner pressure for T-4

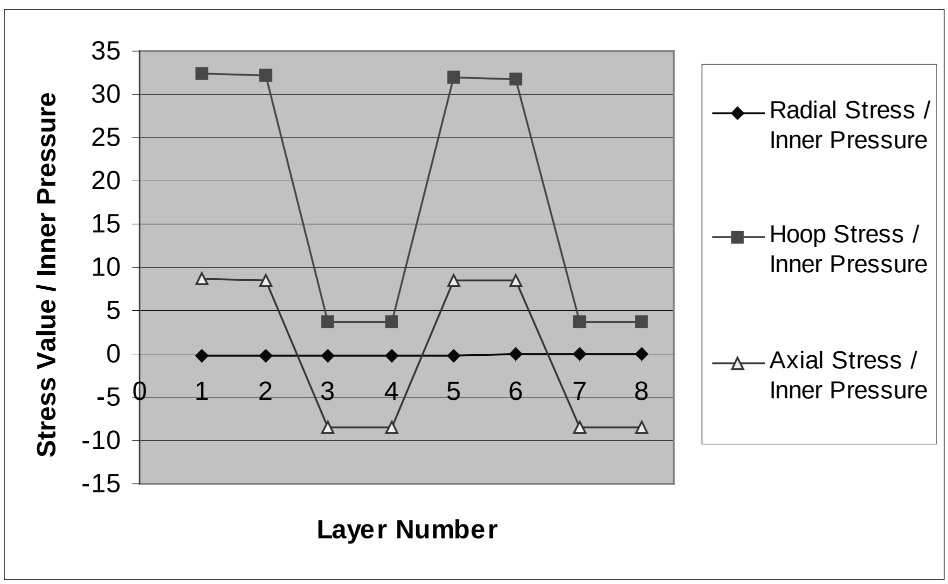

Figure 3.57 – Layer Number vs. stress value/inner pressure for T-5

Considering both analyses (T-4 and T-5), following conclusions can be drawn:

- Both TWSI and MXSFI show that, two tubes have a similar strength (Fig. 3.53 – 3.54). 60° layers have lower TWSI and MXSFI.

- TWSI and MXSFI values are dependent on layer orientation and independent of layer number.

- In both tubes, the maximum hoop stress occurred in 60° layers (Fig. 3.55). This is due to higher modulus in hoop direction, for ±60° layers. However, 60° layers have a higher strength in hoop direction and they have lower TWSI and MXSFI.

- Considering T-1, T-3, T-4 and T-5, the effect of interchange in layer orientations seems to be negligible.

CHAPTER 4

CONCLUSION AND FUTURE RECOMMENDATIONS

In the scope of the thesis, layered orthotropic tubes are analyzed under various loading conditions. Winding angle, level of orthotropy and various ratios of the loading conditions were the main concerns of the study. ANSYS Parametric Design Language (APDL) is used in order to perform several parametric analyses. Several analyses are performed and a huge amount of data is collected for the design of layered orthotropic tubes. The data is presented as series of graphs in order to enhance the evaluation process. Verification tests and tests for deciding on model parameters are also performed numerically.

The analyses performed showed that APDL is a powerful tool for the optimization of filament wound composite tubes. Using the APDL tool, the cost of repeated analyses are shown to be very low. Post processing can be performed or any required data can be obtained easily by using an APDL command.

In order to investigate the effect of combined loading, pure loading and combined loading analyses are performed separately. In the case of pure loading, the results of the analyses were in agreement with the ones given in the literature. For example, optimum winding angles for pure internal pressure loading, pure torsion and pure axial loading were very close to the experimental results mentioned in previous studies. The stress states on tube layers are also in agreement with these studies.

In the case of combined internal pressure and axial loading, the results of the current FEA analyses are important for design purposes. The most important result is that the ratio of applied loads and level of orthotropy has a significant effect on the optimum winding angle. For each winding angle, different loading conditions are examined. Tsai-Wu Failure Index versus loading ratio for several winding angles is plotted for two different levels of orthotropy. A certain loading condition, which simulates the loading on a pressure vessel, is particularly considered. Analyses results are consistent with the experimental ones in the literature.

For combined torsion and internal pressure loading, the effect of loading ratio and winding angle on Tsai-Wu Failure Index is investigated. By taking a loading ratio of zero, solution for the pure torsion is obtained for verification purposes. Optimum winding angles, critical layers and stress states in each layer is considered in this part.

Combined bending and axial loading is also considered in order to obtain required design data. Tsai-Wu Failure Index for various winding angles and various loading conditions are plotted. The results of combined bending and axial loading analyses were consistent with the previous results.

Variation of layer orientation, which is an important parameter in the optimization process, is also investigated. Moreover, the effect of the interchanging of layer orientations on tube strength is examined. The analysis results, on variation of layer orientation and interchanging of layer orientation are very important for the design of filament wound composite tubes. However, the design and optimization process of composites involve an enormous number of runs, which must be performed on each specific application of filament wound tubes.

As a future study, finite element analysis of the tubes under various loading conditions can be expanded to obtain three-dimensional surfaces of the failure indices. The surfaces can be obtained for each winding angle by a reduced number of variables, such as loading condition and level of orthotropy. Generating failure surfaces for each specific condition can help the research engineers to easily decide on design parameters of the filament wound composite tubes.

A series of APDL macros can be used in order to perform an optimization analysis. Optimization is specially required, if there is variation in winding angles. For each specific loading condition and for each material, optimized layer orientations or geometries can be found. It must be noted that, preparing an APDL macro for optimization is a lengthy process. However, once a macro is prepared, it is possible to perform design and optimization with a relatively low cost and effort.

APPENDIX A.1

A MACRO WRITEN BY ANSYS PARAMETRIC DESIGN LANGUAGE - COMBINED LOADING OF LAYERED COMPOSITE TUBES

```
!                    THIS MACRO IS WRITEN BY
!                          BORA BALYA
!
!                     FOR HIS THESIS WORK
!        "DESIGN AND ANALYSIS OF COMPOSITE TUBES"
!                      COMBINED LOADING
!                 (SHORT VERSION-10 Layers)
/COM,
/COM, -------------------------------------------------------------------------------------I
/COM, I                                                                                    I
/COM, I                    ANALYSIS STARTS                                                 I
/COM, I                                                                                    I
/COM, -------------------------------------------------------------------------------------I
/COM,
fini                    !finish whatever active
/clear                  !clear the database
/title,Pi=%Pi% Po=%Po%MPa Fb=%BL%N Fa=%AF%N T=%T%Nm
/filname,Filament wound tube    !jobname
!---------- DATA OF GEOMETRY ------------------------------------------------------
multipro,'start',5
 *cset,1,3,LT,'enter length of tube  (mm)',400
 *cset,4,6,FL,'enter fixing length - A (mm)',20
```

```
 *cset,7,9,R,'enter average radius  (mm)',60.565
 *cset,10,12,LTH,'enter tube thickness  (mm)',1.13
 *cset,13,15,NL,'enter # of layers (min=3,max=30)',6
 *cset,61,62,'DIMENTIONAL',' PROPERTIES '
multipro,'end'
!---------- REPETATIVE ANALYSIS NOTE -------------------------------------------
!For repeated analyses deactivate the upper and activate
!the code below, to enter these values automaticly
!LT=250        !length of tube (mm)
!FL=7          !fixing length (mm)
!R=30          !average radius (mm)
!LTH=1.8     !tube thickness (mm)
!NL=4          !number of layers
! Fixing length is the distance from ends of the tube, where boundary conditions
! are applied within this distance. Average diameter is equal to average of inner
! and outer diameter. Total thickness of each shell element must be less than twice
! the radius of  curvature,and should be bigger than one-fifth of the radius of
!  curvature
!  SHELL99 allows up to 250 layers. If you have more than 250 layers use user
!  input constitutive matrix!
!----------ELASTIC CONSTANTS -------------------------------------------------------
multipro,'start',9
 *cset,1,3,EMX,'enter elastic modulus in x direction (MPa)',127700
 *cset,4,6,EMY,'enter elastic modulus in y direction (MPa)',7400
 *cset,7,9,EMZ,'enter elastic modulus in z direction (MPa)',7770
 *cset,10,12,PNRXY,'enter poisons ratio in xy',0.33
 *cset,13,15,PNRYZ,'enter poisons ratio in yz',0.188
 *cset,16,18,PNRXZ,'enter poisons ratio in xz',0.197
 *cset,19,21,GMXY,'enter shear modulus in xy direction (MPa)',6900
 *cset,22,24,GMYZ,'enter shear modulus in yz direction (MPa)',4300
 *cset,25,27,GMXZ,'enter shear modulus in xz direction (MPa)',4515
```

```
 *cset,61,62,'ELASTIC ',' CONSTANTS '
multipro,'end'
!--------- STRENGTH VALUES----------------------------------------------------------
!multipro,'start',9
! *cset,1,3,stx,'strain (t) - x ',
! *cset,4,6,sty,'strain (t) - y ',
! *cset,7,9,stz,'strain (t) - z ',
! *cset,10,12,scx,'strain (c) - x ',
! *cset,13,15,scy,'strain (c) - y ',
! *cset,16,18,scz,'strain (c) - z ',
! *cset,19,21,sxy,'strain - xy ',
! *cset,22,24,syz,'strain - yz ',
! *cset,25,27,sxz,'strain - xz ',
! *cset,61,62,'STRAIN STRENGTH ',' CONSTANTS '
!multipro,'end'
multipro,'start',9
 *cset,1,3,sstx,'stress (t) - x (MPa)',
 *cset,4,6,ssty,'stress (t) - y (MPa)',
 *cset,7,9,sstz,'stress (t) - z (MPa)',
 *cset,10,12,sscx,'stress (c) - x (MPa)',
 *cset,13,15,sscy,'stress (c) - y (MPa)',
 *cset,16,18,sscz,'stress (c) - z (MPa)',
 *cset,19,21,ssxy,'stress - xy (MPa)',
 *cset,22,24,ssyz,'stress - yz (MPa)',
 *cset,25,27,ssxz,'stress - xz (MPa)',
 *cset,61,62,'STRESS STRENGTH ',' CONSTANTS '
multipro,'end'
multipro,'start',3
 *cset,1,3,ccxy,'stress coupling xy',-1
 *cset,4,6,ccyz,'stress coupling yz',-1
 *cset,7,9,ccxz,'stress coupling xz',-1
```

```
 *cset,61,62,'STRESS COUPLING ',' COEFFICIENTS'
multipro,'end'
!---------- REPEATATIVE ANALYSIS NOTE ------------------------------------------
!For repeated analyses deactivate the upper and activate
!the code below, to enter the values automaticly
!EMX=45600     !elastic modulus in x direction (MPa)
!EMY=12230     !elastic modulus in y direction (MPa)
!EMZ=12230      !elastic modulus in z direction (MPa)
!PNRXY=0.278  !poisons ratio in xy
!PNRYZ=0.099  !poisons ratio in yz
!PNRXZ=0.099  !poisons ratio in xz
!GMXY=5500    !shear modulus in xy direction (MPa)
!GMYZ=2500     !shear modulus in yz direction (MPa)
!GMXZ=2820     !shear modulus in xz direction (MPa)
!---------- BOUNDARY CONDITIONS ------------------------------------------------
multipro,'start',5
 *cset,1,3,Pi,'enter inner pressure (MPa)',0.0
 *cset,4,6,Po,'enter outer pressure (MPa)',0.0
 *cset,7,9,BL,'enter bending load (N)',10000
 *cset,10,12,AF,'enter axial force (N)',
 *cset,13,15,T,'enter torsion (N)',0.0
 *cset,61,62,'BOUNDARY ','CONDITIONS'
multipro,'end'
!---------- REPETATIVE ANALYSIS NOTE -------------------------------------------
!For a repeated analyses deactivate the upper and activate
!the code below, to enter the values automaticly
!Pi=0       !inner pressure  (MPa)
!Po=0        !outer pressure  (MPa)
!BL=2500        !bending load    (N)
!AF=0        !axial force     (N)
!T=0         !torsion         (N)
```

```
!--------- LAYER ORIENTATION -------------------------------------------------------
*IF,NL,EQ,3,THEN
        multipro,'start',3
         *cset,1,3,xtet1,'enter theta1',0.0
         *cset,4,6,xtet2,'enter theta2',0.0
         *cset,7,9,xtet3,'enter theta3',0.0
         *cset,61,62,'BOUNDARY ','CONDITIONS'
      multipro,'end'
        *ELSEIF,NL,EQ,4,THEN
        multipro,'start',4
         *cset,1,3,xtet1,'enter theta1',45
         *cset,4,6,xtet2,'enter theta2',-45
         *cset,7,9,xtet3,'enter theta3',45
         *cset,10,12,xtet4,'enter theta4',-45
         *cset,61,62,'BOUNDARY ','CONDITIONS'
      multipro,'end'
        *ELSEIF,NL,EQ,5,THEN
        multipro,'start',5
         *cset,1,3,xtet1,'enter theta1',0.0
         *cset,4,6,xtet2,'enter theta2',0.0
         *cset,7,9,xtet3,'enter theta3',0.0
         *cset,10,12,xtet4,'enter theta4',0.0
         *cset,13,15,xtet5,'enter theta5',0.0
         *cset,61,62,'BOUNDARY ','CONDITIONS'
      multipro,'end'
        *ELSEIF,NL,EQ,6,THEN
        multipro,'start',6
         *cset,1,3,xtet1,'enter theta1',60
         *cset,4,6,xtet2,'enter theta2',-60
         *cset,7,9,xtet3,'enter theta3',60
         *cset,10,12,xtet4,'enter theta4',-60
```

```
     *cset,13,15,xtet5,'enter theta5',60
     *cset,16,18,xtet6,'enter theta6',-60
     *cset,61,62,'BOUNDARY ','CONDITIONS'
multipro,'end'
    *ELSEIF,NL,EQ,7,THEN
    multipro,'start',7
     *cset,1,3,xtet1,'enter theta1',0
     *cset,4,6,xtet2,'enter theta2',0.0
     *cset,7,9,xtet3,'enter theta3',0.0
     *cset,10,12,xtet4,'enter theta4',0.0
     *cset,13,15,xtet5,'enter theta5',0.0
     *cset,16,18,xtet6,'enter theta6',0.0
     *cset,19,21,xtet7,'enter theta7',0.0
     *cset,61,62,'BOUNDARY ','CONDITIONS'
multipro,'end'
    *ELSEIF,NL,EQ,8,THEN
    multipro,'start',8
     *cset,1,3,xtet1,'enter theta1',0.0
     *cset,4,6,xtet2,'enter theta2',0.0
     *cset,7,9,xtet3,'enter theta3',0.0
     *cset,10,12,xtet4,'enter theta4',0.0
     *cset,13,15,xtet5,'enter theta5',0.0
     *cset,16,18,xtet6,'enter theta6',0.0
     *cset,19,21,xtet7,'enter theta7',0.0
     *cset,22,24,xtet8,'enter theta8',0.0
     *cset,61,62,'BOUNDARY ','CONDITIONS'
multipro,'end'
    *ELSEIF,NL,EQ,9,THEN
    multipro,'start',9
     *cset,1,3,xtet1,'enter theta1',0.0
     *cset,4,6,xtet2,'enter theta2',0.0
```

```
    *cset,7,9,xtet3,'enter theta3',0.0
    *cset,10,12,xtet4,'enter theta4',0.0
    *cset,13,15,xtet5,'enter theta5',0.0
    *cset,16,18,xtet6,'enter theta6',0.0
    *cset,19,21,xtet7,'enter theta7',0.0
    *cset,22,24,xtet8,'enter theta8',0.0
    *cset,25,27,xtet9,'enter theta9',0.0
    *cset,61,62,'BOUNDARY ','CONDITIONS'
  multipro,'end'
   *ELSEIF,NL,EQ,10,THEN
   multipro,'start',10
    *cset,1,3,xtet1,'enter theta1',0.0
    *cset,4,6,xtet2,'enter theta2',0.0
    *cset,7,9,xtet3,'enter theta3',0.0
    *cset,10,12,xtet4,'enter theta4',0.0
    *cset,13,15,xtet5,'enter theta5',0.0
    *cset,16,18,xtet6,'enter theta6',0.0
    *cset,19,21,xtet7,'enter theta7',0.0
    *cset,22,24,xtet8,'enter theta8',0.0
    *cset,25,27,xtet9,'enter theta9',0.0
    *cset,28,30,xtet10,'enter theta10',0.0
    *cset,61,62,'BOUNDARY ','CONDITIONS'
  multipro,'end'
*ENDIF
!---------- CHANGE ANGLES --------------------------------------------
!Change angles by 90 degrees into filament winding convention
teta1=90-xtet1
teta2=90-xtet2
teta3=90-xtet3
teta4=90-xtet4
teta5=90-xtet5
```

```
teta6=90-xtet6
teta7=90-xtet7
teta8=90-xtet8
teta9=90-xtet9
teta10=90-xtet10
!---------- MESH OPTIONS ---------------------------------------------------------------
multipro,'start',1
 *cset,1,3,xMESHSx,'enter mesh density!',7
 *cset,61,62,'Mesh Density defines how fine ',' will be the meshing done'
 *cset,63,64,'ref: 2-course , 5 -fine',' , 7-superior',
multipro,'end'
!MESHS=5.8     !mesh density
!---------- STRUCTURAL ANALYSIS ---------------------------------------------------
/NOPR
/PMETH,OFF,0
KEYW,PR_SET,1
KEYW,PR_STRUC,1
KEYW,PR_THERM,0
KEYW,PR_FLUID,0
KEYW,PR_MULTI,0
/GO
!----------- ANGLE UNIT -----------------------------------------------------------------
*AFUN,DEG
!------------ LOCAL COORDINATE SYSTEM -----------------------------------------
/PREP7
LOCAL,11,1,0,0,0,0,0,0
!local cylindrical coordinate system is defined at the origin.
ESYS,11
!---------- ELEMENT TYPE ---------------------------------------------------------------
ET,1,SHELL99 !Set keyoptions of shell 99
KEYOPT,1,2,0
```

```
KEYOPT,1,3,0
KEYOPT,1,4,0
KEYOPT,1,5,0
KEYOPT,1,6,0
KEYOPT,1,8,1
!storage of layer data:first-last/all layers in order to store layer result and display
!them keyoption 8 should be '1'.
KEYOPT,1,9,0
KEYOPT,1,10,0
KEYOPT,1,11,1 !nodes at:middle layer/bottom face/top face
TYPE,   1
MAT,       1
REAL,       1
ESYS,      11
SECNUM,
TSHAP,QUAD
/PSF,DEFA, ,1,0,1
/PBF,DEFA, ,1
/PIC,DEFA, ,1
/PSYMB,CS,0
/PSYMB,NDIR,0
/PSYMB,ESYS,11
/PSYMB,LDIV,0
/PSYMB,LDIR,0
/PSYMB,ADIR,0
/PSYMB,ECON,0
/PSYMB,XNODE,0
/PSYMB,DOT,1
/PSYMB,PCONV,
/PSYMB,LAYR,1
/PSYMB,FBCS,0
```

```
!---------- REAL CONSTANTS -----------------------------------------------------------
*IF,NL,EQ,3,THEN
	R,1
	RMODIF,1,1,3,0,0,0,0,0
	RMODIF,1,13,1,teta1,LTH/NL,1,teta2,LTH/NL,
	RMODIF,1,19,1,teta3,LTH/NL,
	*ELSEIF,NL,EQ,4,THEN
	R,1
	RMODIF,1,1,4,0,0,0,0,0
	RMODIF,1,13,1,teta1,LTH/NL,1,teta2,LTH/NL,
	RMODIF,1,19,1,teta3,LTH/NL,1,teta4,LTH/NL,
	*ELSEIF,NL,EQ,5,THEN
	R,1
	RMODIF,1,1,5,0,0,0,0,0
	RMODIF,1,13,1,teta1,LTH/NL,1,teta2,LTH/NL,
	RMODIF,1,19,1,teta3,LTH/NL,1,teta4,LTH/NL,
	RMODIF,1,25,1,teta5,LTH/NL,
	*ELSEIF,NL,EQ,6,THEN
	R,1
	RMODIF,1,1,6,0,0,0,0,0
	RMODIF,1,13,1,teta1,LTH/NL,1,teta2,LTH/NL,
	RMODIF,1,19,1,teta3,LTH/NL,1,teta4,LTH/NL,
	RMODIF,1,25,1,teta5,LTH/NL,1,teta6,LTH/NL,
	*ELSEIF,NL,EQ,7,THEN
	R,1
	RMODIF,1,1,7,0,0,0,0,0
	RMODIF,1,13,1,teta1,LTH/NL,1,teta2,LTH/NL,
	RMODIF,1,19,1,teta3,LTH/NL,1,teta4,LTH/NL,
	RMODIF,1,25,1,teta5,LTH/NL,1,teta6,LTH/NL,
	RMODIF,1,31,1,teta7,LTH/NL,
	*ELSEIF,NL,EQ,8,THEN
```

```
    R,1
    RMODIF,1,1,8,0,0,0,0,0
    RMODIF,1,13,1,teta1,LTH/NL,1,teta2,LTH/NL,
    RMODIF,1,19,1,teta3,LTH/NL,1,teta4,LTH/NL,
    RMODIF,1,25,1,teta5,LTH/NL,1,teta6,LTH/NL,
    RMODIF,1,31,1,teta7,LTH/NL,1,teta8,LTH/NL,
    *ELSEIF,NL,EQ,9,THEN
    R,1
    RMODIF,1,1,9,0,0,0,0,0
    RMODIF,1,13,1,teta1,LTH/NL,1,teta2,LTH/NL,
    RMODIF,1,19,1,teta3,LTH/NL,1,teta4,LTH/NL,
    RMODIF,1,25,1,teta5,LTH/NL,1,teta6,LTH/NL,
    RMODIF,1,31,1,teta7,LTH/NL,1,teta8,LTH/NL,
    RMODIF,1,37,1,teta9,LTH/NL,
    *ELSEIF,NL,EQ,10,THEN
    R,1
    RMODIF,1,1,10,0,0,0,0,0
    RMODIF,1,13,1,teta1,LTH/NL,1,teta2,LTH/NL,
    RMODIF,1,19,1,teta3,LTH/NL,1,teta4,LTH/NL,
    RMODIF,1,25,1,teta5,LTH/NL,1,teta6,LTH/NL,
    RMODIF,1,31,1,teta7,LTH/NL,1,teta8,LTH/NL,
    RMODIF,1,37,1,teta9,LTH/NL,1,teta10,LTH/NL,
*ENDIF
!-------------MATERIAL PROPERTIES --------------------------------------------------
MPTEMP,,,,,,,
MPTEMP,1,0
MPDATA,EX,1,,EMX
MPDATA,EY,1,,EMY
MPDATA,EZ,1,,EMZ
MPDATA,PRXY,1,,PNRXY
MPDATA,PRYZ,1,,PNRYZ
```

```
MPDATA,PRXZ,1,,PNRXZ
MPDATA,GXY,1,,GMXY
MPDATA,GYZ,1,,GMYZ
MPDATA,GXZ,1,,GMXZ
!----------- CONSTRUCTING GEOMETRY ---------------------------------------------
CYL4,0,0,R, , , ,LT
/VIEW, 1 ,1,1,1
/ANG, 1
/REP,FAST
FLST,3,2,5,ORDE,2
FITEM,3,3
FITEM,3,-4
AGEN,2,P51X, , , , , , ,0
VDELE,       1, , ,1
/REPLOT
APLOT
!----------- CREATE AN OBLIQUE VIEW -----------------------------------------------
/VIEW, 1 ,1,2,3
/ANG, 1
/REP,FAST
GPLOT
!----------- DIVIDE AREAS OF BC'S -------------------------------------------------------
wpstyle,1,0.1,-1,1,0.003,0,2,,5
wpoff,0,0,LT-FL
FLST,2,2,5,ORDE,2
FITEM,2,5
FITEM,2,-6
ASBW,P51X
GPLOT
FLST,2,4,5,ORDE,2
FITEM,2,1
```

```
FITEM,2,-4
AGLUE,P51X
!----------- MESHING -----------------------------------------------------------------------
TYPE,   1
MAT,       1
REAL,       1
ESYS,      11
SECNUM,
/UI,MESH,OFF
ESIZE,xMESHSx,0,
MSHAPE,0,2D
MSHKEY,0
FLST,5,4,5,ORDE,2
FITEM,5,1
FITEM,5,-4
CM,_Y,AREA
ASEL, , , ,P51X
CM,_Y1,AREA
CHKMSH,'AREA'
CMSEL,S,_Y
AMESH,_Y1
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2  !mesh density can be changed.
!----FIXING ALL DOF'S AT THE ENDS OF TUBE ----------------------------------
FLST,2,4,4,ORDE,4
FITEM,2,11
FITEM,2,-12
FITEM,2,17
FITEM,2,-18
DL,P51X, ,ALL,0  ! Fix one end of the tube in all DOF's.
```

```
!---- CREATE NODE COMPONENT SET----------------------------------------------
FLST,5,2,5,ORDE,2
FITEM,5,2
FITEM,5,4
ASEL,S, , ,P51X
NSLA,S,1
CM,n1,NODE  !Create a component set for torsion.
!----- APPLY TORSION-----------------------------------------------------------------
FLST,2,1,9,ORDE,1
FITEM,2,1
F,P51X,MZ,T
GPLOT
ALLSEL,ALL !Apply torsion to created component set.
!------ SHOW PRESSURE ARROWS ----------------------------------------------------
/PSF,PRES,NORM,2,0,1
/PBF,DEFA, ,1
/PIC,DEFA, ,1
/PSYMB,CS,1
/PSYMB,NDIR,0
/PSYMB,ESYS,11
/PSYMB,LDIV,0
/PSYMB,LDIR,0
/PSYMB,ADIR,0
/PSYMB,ECON,0
/PSYMB,XNODE,0
/PSYMB,DOT,1
/PSYMB,PCONV,
/PSYMB,LAYR,0
/PSYMB,FBCS,0
/PBC,ALL, ,1
```

```
/REP !Showing pressure arrows will easen to see whether there exist an error or not.
!-------SHOW THICKNESS OF THE SHELL--------------------------------------------
/ESHAPE,1
EPLOT
!-------CREATE COMPONENT FOR PRESSURE--------------------------------------
FLST,5,4,5,ORDE,2
FITEM,5,1
FITEM,5,-4
ASEL,S, , ,P51X
ESLA,S
CM,EC1,ELEM
GPLOT
ALLSEL,ALL
!Select all nodes in order to create a node component for inner and outer pressure.
!-------- APPLY INNER PRESSURE -----------------------------------------------------
FLST,2,1,9,ORDE,1
FITEM,2,1
SFE,P51X,1,PRES, ,Pi, , ,  !inner pressure is applied to all nodes.
!------- APPLY OUTER PRESSURE------------------------------------------------------
FLST,2,1,9,ORDE,1
FITEM,2,1
SFE,P51X,2,PRES, ,Po, , ,  !outer pressure is applied to all nodes.
!------- COUNT NUMBER OF NODES ---------------------------------------------------
*GET,NONF,NODE,0,COUNT,,,,
!-------- APPLY BENDING LOAD--------------------------------------------------------
FLST,2,1,9,ORDE,1
FITEM,2,2
F,P51X,FY,-BL/NONF !Force per node is applied to the nodes within fixing length.
!--------- APPLY AXIAL LOAD ---------------------------------------------------------
```

```
FLST,2,1,9,ORDE,1
FITEM,2,2
F,P51X,FZ,AF/NONF
!Force per node is applied to the nodes within fixing length.
FINISH
!----- INPUT FAILURE CRITERIA -----------------------------------------------------
/POST1
FC,1,S,XTEN,sstx
FC,1,S,YTEN,ssty
FC,1,S,ZTEN,sstz
FC,1,S,XCMP,sscx
FC,1,S,YCMP,sscy
FC,1,S,ZCMP,sscz
FC,1,S,XY,ssxy
FC,1,S,YZ,ssyz
FC,1,S,XZ,ssxz
FC,1,S,XYCP,ccxy
FC,1,S,YZCP,ccyz
FC,1,S,XZCP,ccxz
!FC,1,EPEL,XTEN,stx
!FC,1,EPEL,YTEN,sty
!FC,1,EPEL,ZTEN,stz
!FC,1,EPEL,XCMP,scx
!FC,1,EPEL,YCMP,scy
!FC,1,EPEL,ZCMP,scz
!FC,1,EPEL,XY,sxy
!FC,1,EPEL,YZ,syz
!FC,1,EPEL,XZ,sxz
FINISH
!---------- SOLVE ------------------------------------------------------------------------------
/SOL
```

```
/STATUS,SOLU
SOLVE
FINISH
!--------- POST PROCESS -------------------------------------------------------------------
/POST1
RSYS,11
/POST1
AVPRIN,0,0,
PLNSOL,S,TWSI,0,1
FINISH
/EOF
```

APPENDIX A.2

A MACRO WRITEN BY ANSYS PARAMETRIC DESIGN LANGUAGE - INTERNAL PRESSURE LOADING OF LAYERED COMPOSITE TUBES

```
!                         THIS MACRO IS WRITTEN BY
!                                BORA BALYA
!
!                           FOR HIS THESIS WORK
!              "DESIGN AND ANALYSIS OF COMPOSITE TUBES"
!                INNER PRESSURE LOADING – (OPEN ENDED)
!                  (SHORT VERSION – UP TO 10 Layers)
!
/COM,
/COM, ---------------------------------------------------------------------------------------I
/COM, I                                                                                      I
/COM, I                        ANALYSIS STARTS                                               I
/COM, I                                                                                      I
/COM, ---------------------------------------------------------------------------------------I
/COM,
fini                           !finish whatever active
/clear                         !clear the database
/title,P(in)=%Pi% #Layers=%NL% LengthOfTube=%LT% r(average)=%R%
/filname,Filament wound tube    ! jobname
!---------- DATA OF GEOMETRY -------------------------------------------------------
multipro,'start',4
 *cset,1,3,LT,'enter length of tube  (mm)',400
```

```
 *cset,4,6,NL,'enter # of layers (min=3,max=10)',10
 *cset,7,9,R,'enter average radius  (mm)',30.565
 *cset,10,12,LTH,'enter tube thickness  (mm)',1.13
 *cset,61,62,'DIMENTIONAL',' PROPERTIES '
multipro,'end'
!---------- REPETITIVE ANALYSIS NOTE --------------------------------------------
! For a repeated analysis deactivate the upper part and activate
! the code below, in order to enter the values automatically
! LT=250        !length of tube (mm)
! R=30          !average radius (mm)
! LTH=1.8       !tube thickness (mm)
! NL=4          !number of layers
!  Average diameter is equal to average of inner and outer diameter.
!  Total thickness of each shell element must be less than twice the radius of
!  curvature, and should be bigger than one-fifth of the radius of curvature.
!  SHELL99 allows up to 250 layers. If you have more than 250 layers use user
!  input constitutive matrix!
!----------ELASTIC CONSTANTS -------------------------------------------------------
multipro,'start',9
 *cset,1,3,EMX,'enter elastic modulus in x direction (MPa)',
 *cset,4,6,EMY,'enter elastic modulus in y direction (MPa)',
 *cset,7,9,EMZ,'enter elastic modulus in z direction (MPa)',
 *cset,10,12,PNRXY,'enter poisons ratio in xy',
 *cset,13,15,PNRYZ,'enter poisons ratio in yz',
 *cset,16,18,PNRXZ,'enter poisons ratio in xz',
 *cset,19,21,GMXY,'enter shear modulus in xy direction (MPa)',
 *cset,22,24,GMYZ,'enter shear modulus in yz direction (MPa)',
 *cset,25,27,GMXZ,'enter shear modulus in xz direction (MPa)',
 *cset,61,62,'ELASTIC ',' CONSTANTS '
multipro,'end'
!--------- STRENGTH VALUES------------------------------------------------------------
```

```
multipro,'start',9
*cset,1,3,stx,'strain (t) - x ',
*cset,4,6,sty,'strain (t) - y ',
*cset,7,9,stz,'strain (t) - z ',
*cset,10,12,scx,'strain (c) - x ',
*cset,13,15,scy,'strain (c) - y ',
*cset,16,18,scz,'strain (c) - z ',
*cset,19,21,sxy,'strain - xy ',
*cset,22,24,syz,'strain - yz ',
*cset,25,27,sxz,'strain - xz ',
*cset,61,62,'STRAIN STRENGTH ',' CONSTANTS '
!multipro,'end'
multipro,'start',9
 *cset,1,3,sstx,'stress (t) - x (MPa)',
 *cset,4,6,ssty,'stress (t) - y (MPa)',
 *cset,7,9,sstz,'stress (t) - z (MPa)',
 *cset,10,12,sscx,'stress (c) - x (MPa)',
 *cset,13,15,sscy,'stress (c) - y (MPa)',
 *cset,16,18,sscz,'stress (c) - z (MPa)',
 *cset,19,21,ssxy,'stress - xy (MPa)',
 *cset,22,24,ssyz,'stress - yz (MPa)',
 *cset,25,27,ssxz,'stress - xz (MPa)',
 *cset,61,62,'STRESS STRENGTH ',' CONSTANTS '
multipro,'end'
multipro,'start',3
 *cset,1,3,ccxy,'stress coupling xy',
 *cset,4,6,ccyz,'stress coupling yz',
 *cset,7,9,ccxz,'stress coupling xz',
 *cset,61,62,'STRESS COUPLING ',' COEFFICIENTS'
multipro,'end'
!---------- REPETITIVE ANALYSIS NOTE --------------------------------------------
```

```
! For a repeated analysis deactivate the upper part and activate
! the code below, in order to enter the values automatically
!EMX=45600     !elastic modulus in x direction (MPa)
!EMY=12230     !elastic modulus in y direction (MPa)
!EMZ=12230      !elastic modulus in z direction (MPa)
!PNRXY=0.278  !poisons ratio in xy
!PNRYZ=0.099  !poisons ratio in yz
!PNRXZ=0.099  !poisons ratio in xz
!GMXY=5500    !shear modulus in xy direction (MPa)
!GMYZ=2500     !shear modulus in yz direction (MPa)
!GMXZ=2820     !shear modulus in xz direction (MPa)
!---------- BOUNDARY CONDITIONS --------------------------------------------------
multipro,'start',1
 *cset,1,3,Pi,'enter inner pressure (MPa)',
multipro,'end'
!---------- REPETITIVE ANALYSIS NOTE ---------------------------------------------
! For a repeated analysis deactivate the upper and activate
! the code below, to enter these values automatically
! Pi=0        !inner pressure  (MPa)
!--------- LAYER ORIENTATION -------------------------------------------------------
*IF,NL,EQ,3,THEN
          multipro,'start',3
           *cset,1,3,xtet1,'enter theta1',
           *cset,4,6,xtet2,'enter theta2',
           *cset,7,9,xtet3,'enter theta3',
           *cset,61,62,'BOUNDARY ','CONDITIONS'
       multipro,'end'
          *ELSEIF,NL,EQ,4,THEN
          multipro,'start',4
           *cset,1,3,xtet1,'enter theta1',
           *cset,4,6,xtet2,'enter theta2',
```

```
    *cset,7,9,xtet3,'enter theta3',
    *cset,10,12,xtet4,'enter theta4',
    *cset,61,62,'BOUNDARY ','CONDITIONS'
multipro,'end'
   *ELSEIF,NL,EQ,5,THEN
   multipro,'start',5
    *cset,1,3,xtet1,'enter theta1',
    *cset,4,6,xtet2,'enter theta2',
    *cset,7,9,xtet3,'enter theta3',
    *cset,10,12,xtet4,'enter theta4',
    *cset,13,15,xtet5,'enter theta5',
    *cset,61,62,'BOUNDARY ','CONDITIONS'
multipro,'end'
   *ELSEIF,NL,EQ,6,THEN
   multipro,'start',6
 *cset,1,3,xtet1,'enter theta1',
 *cset,4,6,xtet2,'enter theta2',
 *cset,7,9,xtet3,'enter theta3',
 *cset,10,12,xtet4,'enter theta4'
 *cset,13,15,xtet5,'enter theta5',
 *cset,16,18,xtet6,'enter theta6',
    *cset,61,62,'BOUNDARY ','CONDITIONS'
multipro,'end'
   *ELSEIF,NL,EQ,7,THEN
   multipro,'start',7
    *cset,1,3,xtet1,'enter theta1',0.0
    *cset,4,6,xtet2,'enter theta2',0.0
    *cset,7,9,xtet3,'enter theta3',0.0
    *cset,10,12,xtet4,'enter theta4',0.0
    *cset,13,15,xtet5,'enter theta5',0.0
    *cset,16,18,xtet6,'enter theta6',0.0
```

```
     *cset,19,21,xtet7,'enter theta7',0.0
     *cset,61,62,'BOUNDARY ','CONDITIONS'
multipro,'end'
    *ELSEIF,NL,EQ,8,THEN
    multipro,'start',8
     *cset,1,3,xtet1,'enter theta1',0.0
     *cset,4,6,xtet2,'enter theta2',0.0
     *cset,7,9,xtet3,'enter theta3',0.0
     *cset,10,12,xtet4,'enter theta4',0.0
     *cset,13,15,xtet5,'enter theta5',0.0
     *cset,16,18,xtet6,'enter theta6',0.0
     *cset,19,21,xtet7,'enter theta7',0.0
     *cset,22,24,xtet8,'enter theta8',0.0
     *cset,61,62,'BOUNDARY ','CONDITIONS'
multipro,'end'
    *ELSEIF,NL,EQ,9,THEN
    multipro,'start',9
     *cset,1,3,xtet1,'enter theta1',0.0
     *cset,4,6,xtet2,'enter theta2',0.0
     *cset,7,9,xtet3,'enter theta3',0.0
     *cset,10,12,xtet4,'enter theta4',0.0
     *cset,13,15,xtet5,'enter theta5',0.0
     *cset,16,18,xtet6,'enter theta6',0.0
     *cset,19,21,xtet7,'enter theta7',0.0
     *cset,22,24,xtet8,'enter theta8',0.0
     *cset,25,27,xtet9,'enter theta9',0.0
     *cset,61,62,'BOUNDARY ','CONDITIONS'
multipro,'end'
    *ELSEIF,NL,EQ,10,THEN
    multipro,'start',10
     *cset,1,3,xtet1,'enter theta1',0.0
```

```
        *cset,4,6,xtet2,'enter theta2',0.0
        *cset,7,9,xtet3,'enter theta3',0.0
        *cset,10,12,xtet4,'enter theta4',0.0
        *cset,13,15,xtet5,'enter theta5',0.0
        *cset,16,18,xtet6,'enter theta6',0.0
        *cset,19,21,xtet7,'enter theta7',0.0
        *cset,22,24,xtet8,'enter theta8',0.0
        *cset,25,27,xtet9,'enter theta9',0.0
        *cset,28,30,xtet10,'enter theta10',0.0
        *cset,61,62,'BOUNDARY ','CONDITIONS'
    multipro,'end'
*ENDIF
!---------- CHANGE ANGLES --------------------------------------------
!Change angles by 90 degrees into filament winding convention
teta1=90-xtet1
teta2=90-xtet2
teta3=90-xtet3
teta4=90-xtet4
teta5=90-xtet5
teta6=90-xtet6
teta7=90-xtet7
teta8=90-xtet8
teta9=90-xtet9
teta10=90-xtet10
!---------- MESH OPTIONS ---------------------------------------------------------------
/nop            ! Suppress printout for this macro
multipro,'start',1
 *cset,1,3,MESHSD,'enter mesh density!',7
 *cset,61,62,'Mesh Density defines how fine ',' will be the meshing done'
 *cset,63,64,'ref: 2-course , 5 -fine',' , 7-superior',
multipro,'end'
```

```
!---------- REPETITIVE ANALYSIS NOTE ---------------------------------------------
! For a repeated analysis deactivate the upper part and activate
! the code below, in order to enter these values automatically
!MESHS=7     !mesh density
!---------- STRUCTURAL ANALYSIS -------------------------------------------------
/NOPR
/PMETH,OFF,0
KEYW,PR_SET,1
KEYW,PR_STRUC,1
KEYW,PR_THERM,0
KEYW,PR_FLUID,0
KEYW,PR_MULTI,0
/GO
!----------- ANGLE UNIT ---------------------------------------------------------
*AFUN,DEG
!------------ LOCAL COORDINATE SYSTEM -----------------------------------------
/PREP7
LOCAL,11,1,0,0,0,0,0,0
! Local cylindrical coordinate system is defined at the origin.
ESYS,11
!---------- ELEMENT TYPE --------------------------------------------------------
ET,1,SHELL99! Set key options of Shell 99
KEYOPT,1,2,0
KEYOPT,1,3,0
KEYOPT,1,4,0
KEYOPT,1,5,0
KEYOPT,1,6,0
KEYOPT,1,8,1
! Storage of layer data: first-last/all layers in order to store layer result and display
! them key option 8 should be '1'.
KEYOPT,1,9,0
```

```
KEYOPT,1,10,0
KEYOPT,1,11,1   ! Nodes at: middle layer/bottom face/top face
TYPE,   1
MAT,       1
REAL,       1
ESYS,      11
SECNUM,
TSHAP,QUAD
/PSF,DEFA, ,1,0,1  ! element cord. system set as 'on'
/PBF,DEFA, ,1
/PIC,DEFA, ,1
/PSYMB,CS,0
/PSYMB,NDIR,0
/PSYMB,ESYS,11
/PSYMB,LDIV,0
/PSYMB,LDIR,0
/PSYMB,ADIR,0
/PSYMB,ECON,0
/PSYMB,XNODE,0
/PSYMB,DOT,1
/PSYMB,PCONV,
/PSYMB,LAYR,1
/PSYMB,FBCS,0
!---------- REAL CONSTANTS ------------------------------------------------------------
*IF,NL,EQ,3,THEN
	R,1
	RMODIF,1,1,3,0,0,0,0,0
	RMODIF,1,13,1,teta1,LTH/NL,1,teta2,LTH/NL,
	RMODIF,1,19,1,teta3,LTH/NL,
	*ELSEIF,NL,EQ,4,THEN
	R,1
```

```
RMODIF,1,1,4,0,0,0,0,0
RMODIF,1,13,1,teta1,LTH/NL,1,teta2,LTH/NL,
RMODIF,1,19,1,teta3,LTH/NL,1,teta4,LTH/NL,
*ELSEIF,NL,EQ,5,THEN
R,1
RMODIF,1,1,5,0,0,0,0,0
RMODIF,1,13,1,teta1,LTH/NL,1,teta2,LTH/NL,
RMODIF,1,19,1,teta3,LTH/NL,1,teta4,LTH/NL,
RMODIF,1,25,1,teta5,LTH/NL,
*ELSEIF,NL,EQ,6,THEN
R,1
RMODIF,1,1,6,0,0,0,0,0
RMODIF,1,13,1,teta1,LTH/NL,1,teta2,LTH/NL,
RMODIF,1,19,1,teta3,LTH/NL,1,teta4,LTH/NL,
RMODIF,1,25,1,teta5,LTH/NL,1,teta6,LTH/NL,
*ELSEIF,NL,EQ,7,THEN
R,1
RMODIF,1,1,7,0,0,0,0,0
RMODIF,1,13,1,teta1,LTH/NL,1,teta2,LTH/NL,
RMODIF,1,19,1,teta3,LTH/NL,1,teta4,LTH/NL,
RMODIF,1,25,1,teta5,LTH/NL,1,teta6,LTH/NL,
RMODIF,1,31,1,teta7,LTH/NL,
*ELSEIF,NL,EQ,8,THEN
R,1
RMODIF,1,1,8,0,0,0,0,0
RMODIF,1,13,1,teta1,LTH/NL,1,teta2,LTH/NL,
RMODIF,1,19,1,teta3,LTH/NL,1,teta4,LTH/NL,
RMODIF,1,25,1,teta5,LTH/NL,1,teta6,LTH/NL,
RMODIF,1,31,1,teta7,LTH/NL,1,teta8,LTH/NL,
*ELSEIF,NL,EQ,9,THEN
R,1
```

```
    RMODIF,1,1,9,0,0,0,0,0
    RMODIF,1,13,1,teta1,LTH/NL,1,teta2,LTH/NL,
    RMODIF,1,19,1,teta3,LTH/NL,1,teta4,LTH/NL,
    RMODIF,1,25,1,teta5,LTH/NL,1,teta6,LTH/NL,
    RMODIF,1,31,1,teta7,LTH/NL,1,teta8,LTH/NL,
    RMODIF,1,37,1,teta9,LTH/NL,
    *ELSEIF,NL,EQ,10,THEN
    R,1
    RMODIF,1,1,10,0,0,0,0,0
    RMODIF,1,13,1,teta1,LTH/NL,1,teta2,LTH/NL,
    RMODIF,1,19,1,teta3,LTH/NL,1,teta4,LTH/NL,
    RMODIF,1,25,1,teta5,LTH/NL,1,teta6,LTH/NL,
    RMODIF,1,31,1,teta7,LTH/NL,1,teta8,LTH/NL,
    RMODIF,1,37,1,teta9,LTH/NL,1,teta10,LTH/NL,
*ENDIF
!-------------MATERIAL PROPERTIES ----------------------------------------------------
MPTEMP,,,,,,,
MPTEMP,1,0
MPDATA,EX,1,,EMX
MPDATA,EY,1,,EMY
MPDATA,EZ,1,,EMZ
MPDATA,PRXY,1,,PNRXY
MPDATA,PRYZ,1,,PNRYZ
MPDATA,PRXZ,1,,PNRXZ
MPDATA,GXY,1,,GMXY
MPDATA,GYZ,1,,GMYZ
MPDATA,GXZ,1,,GMXZ
!----------- CONSTRUCTING GEOMETRY ---------------------------------------------
CYL4,0,0,R, , , ,LT
/VIEW, 1 ,1,1,1
/ANG, 1
```

```
/REP,FAST
FLST,3,2,5,ORDE,2
FITEM,3,3
FITEM,3,-4
AGEN,2,P51X, , , , , , ,0
VDELE,       1, , ,1
/REPLOT
APLOT
!----------- CREATE AN OBLIQUE VIEW ----------------------------------------------
/VIEW, 1 ,1,2,3
/ANG, 1
/REP,FAST
GPLOT
!----------- DIVIDE AREAS OF BC'S ----------------------------------------------------
!wpstyle,1,0.1,-1,1,0.003,0,2,,5
!wpoff,0,0,LT-FL
!FLST,2,2,5,ORDE,2
!FITEM,2,5
!FITEM,2,-6
!ASBW,P51X
!GPLOT
!FLST,2,4,5,ORDE,2
!FITEM,2,1
!FITEM,2,-4
!AGLUE,P51X
!----------- MESHING -------------------------------------------------------------------
TYPE,   1
MAT,       1
REAL,       1
ESYS,      11
SECNUM,
```

```
/UI,MESH,OFF
ESIZE,MESHSD,0,
MSHAPE,0,2D
MSHKEY,0
FLST,5,2,5,ORDE,2
FITEM,5,5
FITEM,5,-6
CM,_Y,AREA
ASEL, , , ,P51X
CM,_Y1,AREA
CHKMSH,'AREA'
CMSEL,S,_Y
AMESH,_Y1
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2  ! Mesh density can be changed.
!----FIXING ONE NODE AT THE END OF TUBE ------------------------------------
FLST,2,1,1,ORDE,1
FITEM,2,2
D,P51X, ,0, , , ,ALL, , , , ,
!---- CREATE NODE COMPONENT SET-----------------------------------------------
FLST,5,2,5,ORDE,2
FITEM,5,2
FITEM,5,4
ASEL,S, , ,P51X
NSLA,S,1
CM,n1,NODE   ! Create a component set for torsion.
!------ SHOW PRESSURE ARROWS ----------------------------------------------------
/PSF,PRES,NORM,2,0,1
/PBF,DEFA, ,1
/PIC,DEFA, ,1
```

```
/PSYMB,CS,1
/PSYMB,NDIR,0
/PSYMB,ESYS,11
/PSYMB,LDIV,0
/PSYMB,LDIR,0
/PSYMB,ADIR,0
/PSYMB,ECON,0
/PSYMB,XNODE,0
/PSYMB,DOT,1
/PSYMB,PCONV,
/PSYMB,LAYR,0
/PSYMB,FBCS,0
/PBC,ALL, ,1
/REP
! Showing pressure arrows will ease to see whether there exists an error or not.
!-------SHOW THICKNESS OF THE SHELL------------------------------------------
/ESHAPE,1
EPLOT
!-------CREATE COMPONENT FOR PRESSURE--------------------------------------
FLST,5,2,5,ORDE,2
FITEM,5,5
FITEM,5,-6
ASEL,S, , ,P51X
ESLA,S
CM,EC1,ELEM
GPLOT
ALLSEL,ALL
! Select all nodes in order to create a node component for inner and outer pressure.
!-------- APPLY INNER PRESSURE ----------------------------------------------------
FLST,2,1,9,ORDE,1
FITEM,2,1
```

```
SFE,P51X,1,PRES, ,Pi, , ,
/USER,  1   ! Inner pressure is applied to all nodes.
FINISH
!----- INPUT FAILURE CRITERIA -------------------------------------------------------
/POST1
FC,1,S,XTEN,sstx
FC,1,S,YTEN,ssty
FC,1,S,ZTEN,sstz
FC,1,S,XCMP,sscx
FC,1,S,YCMP,sscy
FC,1,S,ZCMP,sscz
FC,1,S,XY,ssxy
FC,1,S,YZ,ssyz
FC,1,S,XZ,ssxz
FC,1,S,XYCP,ccxy
FC,1,S,YZCP,ccyz
FC,1,S,XZCP,ccxz
!FC,1,EPEL,XTEN,stx
!FC,1,EPEL,YTEN,sty
!FC,1,EPEL,ZTEN,stz
!FC,1,EPEL,XCMP,scx
!FC,1,EPEL,YCMP,scy
!FC,1,EPEL,ZCMP,scz
!FC,1,EPEL,XY,sxy
!FC,1,EPEL,YZ,syz
!FC,1,EPEL,XZ,sxz
FINISH
!---------- SOLVE --------------------------------------------------------------------------
/SOL
/STATUS,SOLU
SOLVE
```

```
FINISH
!--------- POST PROCESS ------------------------------------------------------------------
/POST1
RSYS,11   ! Solutions will be displayed in the local coordinate system
AVPRIN,0, ,
PLESOL,S,TWSI,0,1
FINISH
/EOF
```

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