DEVELOPMENT OF PROCESS TECHNIQUES FOR COMPOSITE BASED LEAF SPRING SYSTEMS

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by
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ABSTRACT

DEVELOPMENT OF PROCESS TECHNIQUES FOR COMPOSITE BASED LEAF SPRING SYSTEMS

Fiber reinforced composites have been utilized in automotive industry due to their superior mechanical performance and lower density as compared to conventional metallic materials. Leaf spring systems are the important parts of the automobiles, which effects the weight of the vehicle in addition to driving performance and security. In this study, composite based leaf spring systems were developed, manufactured and characterized.

Five different types of composite plates were manufactured with three different types of reinforcing material via resin transfer molding process and characterized in order to select the proper composite material for spring applications and design the composite leaf spring prototypes. Glass fiber reinforced epoxy, carbon fiber reinforced epoxy and glass/carbon hybrid fiber reinforced epoxy composite plates having unidirectional and [0^o/90^o] biaxial stacking sequences were fabricated. Tensile, flexural and thermo-mechanical properties of composite plates were determined within the study. Test results showed that unidirectional glass fiber reinforced epoxy composites are the most suitable materials for spring applications due to their higher strain energy capability as compared to carbon and hybrid fiber reinforced epoxy composites.

Composite leaf spring prototypes were manufactured based on two geometrical design by resin transfer molding procedure. Three different types of leaf spring prototypes with various fiber configuration were manufactured based on the first geometrical design and characterized by mechanical rig test. Mechanical rig test results showed that composite leaf spring which contains 56 layers of glass fiber and 4 layers of carbon fiber has the most suitable fiber configuration for leaf spring designed based on first geometrical design.

ÖZET

KOMPOZİT MALZEME ESASLI YAPRAK YAY SİTEMLERİNİN ÜRETİM TEKNİKLERİNİN GELİŞTİRİLMESİ

Son yıllarda fiber takviyeli kompozitler geleneksel metalik malzemere göre yüksek mekanik performansa ve düşük yoğunluğa sahip olduklarından dolayı otomotiv endüstrisinde kullanılmaktadırlar. Yaprak yay sistemleri aracın sürüş performansını ve güvenliğini etkilemesi yanında ağırlığına da etkiyen önemli bir parçasıdır. Bu çalışmada kompozit yaprak yay sistemleri geliştirilmiş, üretilmiş ve karakterize edilmiştir.

Yay uygulamaları için uygun kompozit malzeme seçimi ve kompozit yaprak yay pototiplerinin tasarımı amacıyla üç farklı takviye malzemesi içeren beş farklı tip kompozit plaka reçine transfer kalıplama yöntemi ile üretilmiş ve karakterize edilmiştir. Tek eksenli ve [0^o/90^o] iki eksenli elyaf dizilimlerine sahip cam elyaf takviyeli epoksi, karbon elyaf takviyeli epoksi ve cam/karbon hibrit elyaf takviyeli epoksi kompozit plakalar üretilmiştir. Çalışma kapsamında, üretilen bu plakaların çekme, eğme ve termomekanik özellikleri belirlenmiştir. Test sonuçları göstermiştir ki tek eksenli cam elyaf takviyeli epoksi kompozitler karbon ve cam/karbon hibrit elyaf takviyeli epoksi kompozitlerden daha yüksek gerinim enerjisi depolama kapasiteleri dolayısıyla yay uygulamaları için en uygun malzemelerdir.

Kompozit yaprak yay prototipleri iki farklı geometrik dizayn baz alınarak reçine transfer kalıplama prosesi ile üretilmiştir. Birinci geometrik dizayn baz alınarak farklı fiber konfigürasyonlarında üç farklı tip yaprak yay prototipinin üretimi gerçekleştirilmiş ve mekanik rig testi ile karakterizasyonları yapılmıştır. Mekanik rig test sonuçları göstermiştir ki 56 kat cam elyaf ve 4 kat karbon elyaf içeren yaprak yay prototipi birinci geometrik tasarım için en iyi elyaf konfigürasyonuna sahiptir.

Dedicated to;
My Mother

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CHAPTER 1

INTRODUCTION

Weight reduction is the main goal of automotive industry in the present scenario in order to conserve natural sources and economize energy. Weight reduction can be accomplished bu using better material, better manufacturing process an making design optimization (Raghavedra et al. 2012).

In recent years, composite materials are taking the place of metal parts in automotive and many industrial areas due to their high strength and low density (Shokrieh and Rezaei 2003, Hou et al. 2005). Applications of fiber-reinforced composites in automotive industry can be divided into three groups: body components, chassis components, and engine components. Among the chassis components, leaf spring is the first major application of fiber reinforced composites (Mahdi and Hamouda 2013). Leaf springs are structural elements on chassis that absorb the vertical vibrations and impacts due to road irregularities by variations in the spring deflection (Kumar and Vijayarangan 2007b). Therefore, strain energy capability of materials is the main design parameter for springs. Material having high tensile strength, low density and modulus have high strain energy are desired for this application (Al-Qureshi 2001).

Conventional leaf springs are usually formed by stacking leafs of steel, in progressively longer lengths on top of each other (Shokrieh and Rezaei 2003). Compared with this traditional material, composite materials are light and have high strength and stiffnes at the same time. The high capacity of energy storage, corrosion resistance and fatigue tolerance of composite materials over steel make them the ideal material for suspensions (Hou and Jeronimidis 2012, Subramanian and Senthilvelan 2011).

Dominant loading on leaf spring in its working condition is vertical force. Therefore, a leaf spring should have high strentgth and low modulus in the longitudinal direction (Shokrieh and Rezaei 2003). If fibers are oriented through the longitudinal direction, fiber reinforced composite materials provide these properties. The most commonly used fiber reinforced composites are glass or carbon fiber reinforced polymer for these applications. Although carbon fiber reinforced composites have superior static and dynamic mechanical properties as compared to glass fiber reinforced composites, glass fiber reinforced composites are usually selected with unidirectional lay-up due to their relatively lower cost for leaf spring applications. Thermoset resins, especially epoxy, have been utilized as matrix materials to provide desired mechanical properties.

There are several ways to manufacture a structural composite part. Among these process hand lay-up, filament winding, wet wrapping etc. process have been utilized to manufacture a leaf springs (Al-Qureshi 2001, Morris 1986, Mahdi and Hamouda 2013). Besides these, a close molding process, resin transfer molding (RTM), can be suggested for leaf springs. Main advantages of RTM are; being a low cost process, providing good finish surfaces, desired dimensions and to make complex parts over the other composite manufacture process (Mazumdar 2001).

The scope of this study is to manufacture composite monoleaf leaf springs via RTM process. For this purpose, a number of composite plates were manufactured with different configurations, and their mechanical and thermomechanical properties were determined to specify composite material's behaviour. By using these data, two geometrical design of composite leaf spring were studied. Composite monoleaf leaf spring prototypes designed in two different geometrical design were manufactured successfully via RTM process. The mechanical properties fo different leaf spring prototypes were evaluated based on experimental procedure.

CHAPTER 2

LEAF SPRINGS

Leaf springs are very important suspension elements for automotives to minimize the vertical vibrations, impacts and bumps due to road irregularities by the force of spring deflection and they provide a comfortable ride (Shokrieh and Rezaei 2003, Kumar and Vijayarangan 2007b). Leaf springs are desingn to absorb and store energy, and then release it like the other types of springs. This energy is stored as strain energy, so strain energy and shape of the material is main factor to design a spring (Mahdi et al. 2006, Al-Qureshi 2001, Kumar and Vijayarangan 2007b, Shankar and Vijayarangan 2006). Equation 2.1 shows the spesific strain energy,

$$U = \frac{\sigma^2}{\rho E} \tag{2.1}$$

In Eq. 2.1, σ illustrates the strength, ρ is the density and E is modulus of spring materials (Shankar and Vijayarangan 2006). Therefore, materials have high strength, and low density and modulus is a great candidate for a spring material.

2.1. Steel Leaf Springs

Steel springs have been used in vehicles for decades (Meatto and Pilpel 1999). Different types of steel can be used as leaf spring material such as SAE 1080, 1095, 5155-60, 6150-60 and 9850-60 (Al-Qureshi 2001). There are two types of steel leaf spring which are called monoleaf and multileaf leaf springs. Multileaf leaf springs contain several steel plates with variable length stacked together. On the other hand, monoleaf leaf springs contain just one steel plate. Steel that used for leaf springs are generally exposed a heat treatment and forming. After these process, steel gets greater strength and load capacity (Raghavedra et al. 2012). Figure 2.1 shows the geometry of a multileaf steel leaf spring (Shankar and Vijayarangan 2006).

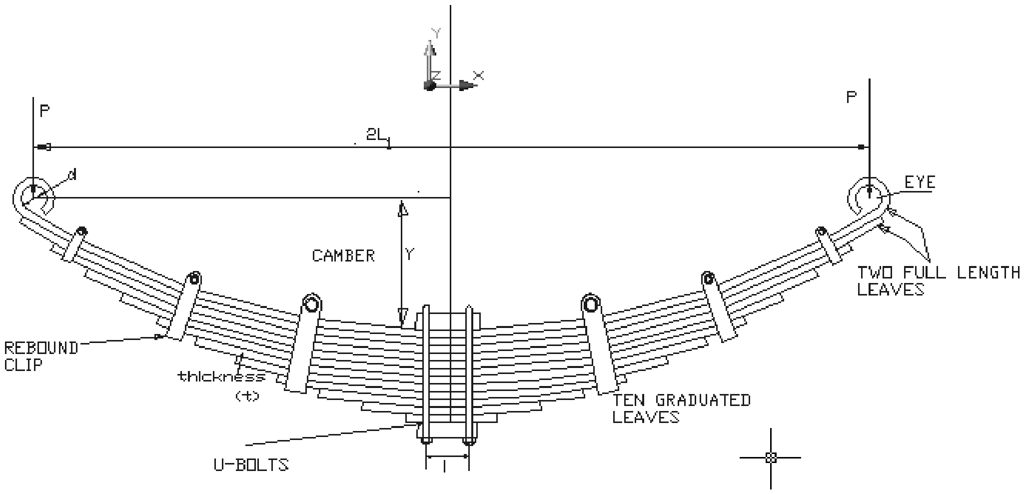

Figure 2. 1. Geometry of a steel multileaf leaf spring
(Source: Shankar and Vijayarangan 2006)

Steel leaf springs have been studied recent years. Shokrieh and Rezaei studied on four-leaf steel leaf spring (Shokrieh and Rezaei 2003). They applied both static and full bump loading to the leaf spring and record the deflection and stress that is generated on the spring. Leaf spring showed 120.4 mm deflection, and 483.2 MPa stress was generated on leaf spring against 2500 N static load. They also obtained 209.3 mm deflection, and 844.4 MPa stress on leaf spring against 4660 N full bump load. Besides these experimental data they also made stress analysis bu finite element method to the steel leaf spring (Shokrieh and Rezaei 2003). Kumar and Vijayarangan studied on seven leaf steel leaf spring (Kumar and Vijayarangan 2007a). They use experimental, analytical and FEA methods to characterize the leaf spring. They applied 3250 N load on leaf spring and determined maximum deflection, maximum stress on leaf spring and maximum stiffness of leaf spring by experimental, analytical and finite element analysis. Maximum stress on leaf spring was found as 680.05 MPa by experimental, 982.05 MPa by analytical and 744.32 MPa by FEA. Maximum deflection was found as 155 mm by experimental, 133.03 mm by analytical and 134.67 mm by FEA. Lastly, maximum stiffness of leaf spring was found as 20.96 N/mm by experimental, 24.43 N/mm by analytical and 24.13 by experimental (Kumar and Vijayarangan 2007a). Shiva Shankar and Vijayarangan found 107.5 mm maximum deflection by experimental and 90 mm maximum deflection by FEA against 3980 N static load, and 503.3 MPa maximum stress by experimental and 511 MPa maximum stress by FEA (Shankar and Vijayarangan 2006).

Although steel has a good performance as a spring material, researchers are tend to search new material technologies due to weight reduction.

2.2. Composite Leaf Springs

Weight reduction has been the main focus for automotive industry to save natural resources and energy in recent years. Leaf springs are one of the potential structure for weight reduction and this can be done by using better material, design and manufacture process (Gebremeskel 2013). Fiber reinforced polymers are a good candidate materials for leaf springs due to their weight saving potential. Other advantages of fiber reinforced polymers over conventional metallic leaf spring materials are; the possibility of reducing noise, vibrations and ride harshness due to their damping factors, the absence of corrosion problems and lower tooling cost (Talib et al. 2010). Besides, fiber reinforced polymers become prominent against conventional material with their strain energy that aforementioned in Eq. 2.1. Figure 2.2 shows compairing of strain energies of spring materials (Shokrieh and Rezaei 2003).

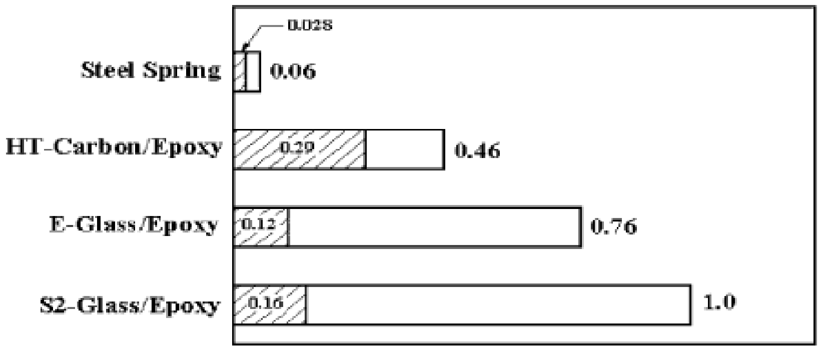

Figure 2.2. Strain energies of spring materials
(Source:Shokrieh and Rezaei 2003)

In Figure 2.2, hatced areas show the quantity of strain energy in dynamic loading (Shokrieh and Rezaei 2003). As shown in Figure 2.2, fiber reinforced composites’ strain energies are greater than steel’s both in dynamic loading and static loading. Due to their high strain energy, storage capacity, and high strength to weight ratio compared to steel, multi-leaf springs are being replaced by mono-leaf fiber reinforced springs. Fiber reinforced springs also have excellent fatigue resistance and durability (Rajendran and Vijayarangan 2001).

2.2.1. Materials for Fiber Reinforced Composite Leaf Spring Systems

2.2.1.1. Fiber Reinforced Composites

Composite materials are materials composed of two or more components on a macroscopic scale by chemical and mechanical effects. Two different phases combine in a composite material which are matrix phase and reinforcing phase. Reinforcing phases are generally fibers, sheets and particles, and these reinforcing phases are embedded in matrix phase (Raghavedra et al. 2012). Fiber reinforced polymer matrix composites are studied in this thesis.

2.2.1.1.1. Reinforcing Materials for Fiber Reinforced Composites

Reinforcing materials are aimed to provide superior levels of strength and stiffness to composite (Miracle and Donaldson 2001). Reinforcing elements can be fibers, whiskers or particles. Particles can not be oriented, so their effect on mechanical properties is so limited. Whiskers are extremely strong but it is so hard to disperse the homogenously in matrix. Fibers are long and circular. They are significantly stronger in the longer direction. Due to the strength and stiffness of fibers, they are used dominantly in composite structures as reinforcing materials (Campbell Jr 2003). Nowadays; carbon, aramid and glass fibers are widely used as reinforcing materials (Hull and Clyne 1996). Table 2.1 shows the comparison of mechanical properties of high strength fibers.

Table 2.1. Comparison of mechanical properties of high stregth fibers
(Source: Campbell Jr 2003)

Type of Fiber	Tensile Strength (Ksi)	Tensile Modulus (Msi)	Elongation at Failure (%)	Density (gm/cm^{3})	Coefficient of Thermal Expansion (10^{-6} ^{o}C)	Fiber Diameter (µm)
Glass						
E-Glass	500	11.0	4.7	2.58	4.9-6.0	5-20
S-2 Glass	650	12.6	5.6	2.48	2.9	5-10
Quartz	490	10.0	5.0	1.15	0.5	9
Organic						
Kevlar 29	525	12.0	4.0	1.44	-2.0	12
Kevlar 49	550	19.0	2.8	1.44	-2.0	12
Kevlar 149	500	27.0	2.0	1.47	-2.0	12
Spectra 1000	450	25.0	0.7	0.97	.....	27
PAN Based Carbon						
Standart Modulus	500-700	35-35	1.5-2.2	1.80	-0.4	6-8
Intermediate Modulus	600-900	40-43	1.3-2.0	1.80	-0.6	5-6
High Modulus	600-800	50-65	0.7-1.0	1.90	-0.75	5-8
Pitch Based Carbon						
Low Modulus	200-450	25-35	0.9	1.9	.....	11
High Modulus	275-400	55-90	0.5	2.0	-0.9	11
Ultra High Modulus	350	10-140	0.3	2.2	-1.6	10

2.2.1.1.1.1. Carbon Fibers

Carbon fibers are one of the most commonly used fibers in high performance structures. Carbon fibers exhibit high tensile, compressive strength, high toughness, have high module, excellent fatigue characteristic, low weigth and they are one of the most corrosion resistant materials available (Campbell Jr 2003, Miracle and Donaldson 2001). For example, Carbon fiber composites are five times stronger than 1020 steel for structural parts, and still five times lighter. In comparison to 6061 aluminum, carbon fiber composites are seven times stronger and two times stiffer, yet 1.5 times lighter These superior properties are results of fiber microstructure (Miracle and Donaldson 2001). Table 2.2 shows the properties of carbon fibers.

Table 2.2. Properties of carbon fibers
(Source: Miracle and Donaldson 2001)

Property	Commercial, standart modulus	Aerospace		
		Standart modulus	Intermediate modulus	High modulus
Tensile modulus, GPa 8 (10^6 psi)	225 (33)	220-241 (32-35)	290-297 (42-43)	345-448 (50-65)
Tensile strength, MPa (ksi)	380 (550)	3450-4830 (500-700)	3450-6200 (600-900)	3450-5520 (600-800)
Elongation at break, %	1.6	1.5-2.2	1.3-2.0	0.7-1.0
Electrical resistivity, μΩ.cm	1650	1650	1450	900
Thermal conductivity W/m.K (Btu/ft.h.^{o}F)	20 (11.6)	20 (11.6)	20 (11.6)	50-80 (29-46)
Coefficient of thermal expansion, axial direction, 10^{-6} K	-0.4	-0.4	-0.55	-0.75
Density, g/cm^3 (lb/in^3)	1.8 (0.065)	1.8 (0.065)	1.8 (0.065)	1.9 (0.069)
Carbon content, %	95	95	95	99
Filament diameter, μm	6-8	6-8	5-6	5-8
Manufacturers	Zoltek, Fortafil, SGL	BPAmocco, Hexcel, Mitsubishi, Rayon, Toho, Toray, Tenax, Soficar, Formosa		

Carbon fibers are elastic to failure, creep resistant, and have excellent damping characteristics. On the other hand, carbon fibers have some disadvantages. They are brittle and have low impact resistance. They have low strains to failure, and they are relatively expensive in comparison to glass fibers (Campbell Jr 2003).

2.2.1.1.1.2. Aramid Fibers

Aramid fiber is an organic fiber that was invented by DuPont Corp. in early 1970s. Their properties of low weight, high strength, and high toughness ave led to the development of applications in composites, ballistics, tires, ropes, cables, asbestos replacement, and protective apparel. Three types of aramid fibers are commonly used. Kevlar 49 has higher modulus, and this form of aramid is mostly used today. Kevlar 29 is used in composites when higher toughness, damage tolerance, or ballistic stopping performance is desired. An ultrahigh-modulus fiber, Kevlar 149, is also available. Properties of aramid fibers are shown in Table 2.3 (Miracle and Donaldson 2001).

Table 2.3. Properties of aramid fibers
(Source: Miracle and Donaldson 2001)

Material	**Density, g/cm^3**	**Filament diameter**		**Tensile modulus**		**Tensile strength**		**Tensile elongation, %**	**Available yarn count, No. filaments**
		µm	**µin**	**GPa**	**10^6 psi**	**GPa**	**10^6 psi**		
Kevlar 29 (high toughness)	1.44	12	470	83	12	3.6	0.525	4.0	134-10000
						2.8$^{(b)}$	0.400$^{(b)}$		
Kevlar 49 (high modulus)	1.44	12	470	131	19	3.6-4.1	0.525-0.600	2.8	25-5000
Kevlar 149 (ultra high modulus	1.47	12	470	179	26	3.4	0.500	2.0	1000

The maximum temperature that aramid fibers can be used is limited about 350 ^{o}F due to its organic structure. Another disadvantages of this fiber is being extremely tough fiber that makes cutting this fiber hard, and cause some handling problem. Aramid fibers are often used for ballistic protection due to its toughness. They are also resistant to flame and most solvents except strong acids. Aramid fibers are hygroscopic and absorb moisture (Campbell Jr 2003).

2.2.1.1.1.3. Glass Fibers

Glass fibers are commonly used in composite applications due to their low cost, high tensile strength, high impact resistance and high chemical resistance (Campbell Jr 2003). They also exhibit useful bulk properties such as hardness, transperancy, stability and inertness (Miracle and Donaldson 2001). Three types of glass fiber are commonly used in composites. They are S type, E type and quartz. E glass is the most common type due to its low cost and good combination of tensile strength and modulus. S glass is more expensive than E glass, but is 40% stronger (Campbell Jr 2003). It is generally used for aircraft indsutry that high cost can be justified (Hull and Clyne 1996). Quartz fiber is the most expensive glass fiber type and it is used some specific electrical application due to low dielectirical properties (Campbell Jr 2003). Composition of different types of glass fiber pruducts are shown in Table 2.4.

Table 2. 4. Composition of different types of glass fibers
(Source: Miracle and Donaldson 2001)

Fiber	**Ref.**	**Composition, wt%**										
		SiO_2	**B_2O_3**	**Al_2O_3**	**CaO**	**MgO**	**TiO_2**	**Na_2O**	**K_2O**	**Li_2O**	**Fe_2O_3**	**F_2**
Boron containing E-glass	1.2	52-56	4-6	12-15	21-23	0.4-4	0.2-0.5	0-1	Trace	....	0.2-0.4	0.2-0.7
Boron-free E-glass	7	59	...	12.1	22.6	3.4	1.5	0.9	...	...	0.2	...
	8	60.1	...	13.2	22.1	3.1	0.5	0.6	0.2	...	0.2	0.1
ECR-glass	1.2	58.2	...	11.6	21.7	2.0	2.5	1.0	0.2	...	0.1	Trace
D-glass	1.2	74.5	22	0.3	0.5	...	...	1.0	<1.3	...	...	...
	2	55.7	26.5	13.7	2.8	1.0	...	0.1	0.1	0.1	...	...
S-,R-, and Te-glass	1.2	60-65.5	...	23-25	0-9	6-11	...	0-0.1	...	...	0-0.1	...
Silica/quaartz	1.2	99.9	....	....	...	...	...	...	...	...	...	...

Table 2.5 shows the properties of glass fiber products. As shown in Table 2.5 Tensile strength of glass fiber products varies from 3100 MPa to 4590 MPa, and young modulus of fibers varies from 69 MPa to 88 MPa. S glass fibers become prominent with its mechanical properties.

Table 2.5. Properties of glass fiber products
(Source: Miracle and Donaldson 2001)

Fiber	**Coeff. of linear expansion,**	**Specific heat,**	**Dielectric constant at room temp.**	**Weight loss in 24 h in 10%**	**Tensile Strength at 23 °C**	**Young's Modulus**	**Filament elongation at break**
	10^{-8}/°C	**cal/g/ °C**	**and 1 MHz**	**H_2SO_4 %**	**Mpa**	**GPa**	
General-purpose fibers							
Boron containing E-glass	7.9-6.0	0.192	5.86-6.6	41	3100-3800	76-78	4.5-4.9
Boron-free E-glass	6.0	....	7.0	6	3100-3800	80-81	4.6
Special-purpose fibers							
ECR-glass	5.9	....	....	5	3100-3800	80-81	4.5-4.9
D-glass	3.1	0.175	3.56-3.62	...	2410	....	....
S-glass	2.9	0.176	4.53-4.6	....	4380-4590	88-91	5.4-5.8
Silica/ quartz	0.54	...	3.78	...	3400	69	5

2.2.1.1.2. Matrix Materials

Both thermoplastic and thermoset resins can be used as matrix materials in fiber reinforced composites. A comparison between properties of thermoplastic and thermoset resins is giving in Table 2.6.

Table 2.6. Comparison between properties of thermoplastic and thermoset resins (Source: Miracle and Donaldson 2001).

Characteristic	Thermoplastic	Thermosets
Tensile properties	Excellent	Excellent
Stiffness properties	Excellent	Excellent
Compression properties	Good	Excellent
Compression strength after impact	Good to excellent	Fair to excellent
Bolted joint properties	Fair	Good
Fatigue resistance	Good	Excellent
Damage tolerance	Excellent	Fair to excellent
Durability	Excellent	Good to excellent
Maintainability	Fair to poor	Good
Service temperature	Good	Good
Dielectric properties	Good to excellent	Fair to good
Environmental weakness	None, or hydraulic fluid	Moisture
NBS smoke test performance	Good to excellent	Fair to good
Processing temp. ^{o}C (^{o}F)	343-427 (650-800)	121-315 (250-600)
Processing press. MPa (psi)	1.38-2.07 (200-300)	0.59-0.69 (85-100)
Lay-up characteristics	Dry, boardy, difficult	Tack, drape, easy
Debulking, fusing, or heat tacking	Every ply if part is not flat	Typically every 3 or more plies
In-process joining options	Co-fusion	Co-cure, Co-bond
Postprocess joining options	Fastening, bonding, fusion	Fastening, bonding
Manufacturing scrap rates	Low	Low
Ease of prepregging	Fair to poor	Good to excellent
Volatile-free prepreg	Excellent	Excellent
Prepreg shelf life and out time	Excellent	Good
Health/safety	Excellent	Excellent

2.2.1.1.2.1. Thermoset resins

Thermosetting resins are liquid resins which transform a hard brittle solid by chemical cross linking. Mechanical properties of thermoset resins depend on length and density of cross-links. The former is determined by initial chemicals used and the latter by the control of the cross-linking processes which are involed the cure. Curing can be done at room temperature, but optimum crosslinking and optimum propeties are obtained at an optimum temperature. A postcure treatment is often applied at a relatively high temeperature to minimise any further cure and change in properties during service. Most commonly thermoset resins are epoxy and polyester (Hull and Clyne 1996). Properties of epoxy and polyester resins are giving in Table 2.7.

Table 2.7. Properties of epoxy and polyester resins
(Source: Hull and Clyne 1996)

Property	Units	Epoxy resins	Polyester resins
Density	Mgm^{-3}	1.1-1.4	1.2-1.5
Young's modulus	GNm^{-3}	3-6	2-4.5
Poisson's ratio		0.38-0.4	0.37-0.39
Tensile strength	MNm^{-2}	35-100	40-90
Compressive strength	MNm^{-2}	100-200	90-250
Elongation to break	%	1-6	2
Thermal conductivity	$Wm^{-1}\ {}^{o}C$	0.1	0.2
Coeff. of thermal expansion	$10^{-6}\ {}^{o}C^{-1}$	60	100-200
Heat distortion temp.	^{o}C	50-300	50-110
Shirinkage on curing	%	1-2	4-8
Water absorption 24h to 20 ^{o}C	%	0.1-0.4	0.1-0.3

2.2.1.1.2.2. Thermoplastic resins

Thermoplastic resins are not cross-linked unlike thermosets. Their stiffness and strength properties come from their inherent properties of the monomer units and high molecular weigth.

Thermoplastic matrixes are normally used with short fiber reinforcements. Three common thermoplastic matrixes are polypropylene, nylon and polycarbonate. Table 2.8 shows the properties of the most commonly thermoplastics.

Table 2.8. Properties of commonly used thermoplastic resins.
(Source: Hull and Clyne 1996)

Property	**Units**	**Polypropylene**	**Nylon 6.6**	**Polycarbonate**
Density	Mgm^{-3}	0.90	1.14	1.06-1.20
Young's modulus	GNm^{-3}	1.0-1.4	1.4-2.8	2.2-2.4
Poisson's ratio		0.3	0.3	0.3
Tensile strength	MNm^{-2}	25-38	60-75	45-70
Elongation to break	%	>300	40-80	50-100
Thermal conductivity	$Wm^{-1}\ {}^{o}C$	0.2	0.2	0.2
Coeff. of thermal expansion	$10^{-6}\ {}^{o}C^{-1}$	110	90	70
Melting Point	^{o}C	175	264	-
Deflection temperature under load at 1.82 MNm^{-2}	%	60-65	75	110-140
Water absorption 24h to 20 ^{o}C	%	0.03	1.3	0.1

As shown in Table 2.8, thermoplastic resins have less mechanical performance than thermoset resins. Thus, that is the reason that thermoset resins are prefered in most structures that need high strength and stiffnes.

2.2.1.2. Materials Used for Composite Leaf Spring

Different types of reinforcing and matrix materials were used to manufacture composite leaf spring in the past. It was aforementioned that strain enery of the material is the main parameter to design a spring and composite materials have high strain energy. A leaf spring is exposured various kinds of external forces shown in Figure 2.3.

As shown in Figure 2.3, dominant loading on the leaf spring is vertical load. Thus, a material that have maximum load and minimum modulus of elasticity in longitudinal direction is the most suitable material for leaf spring (Shokrieh and Rezaei 2003).

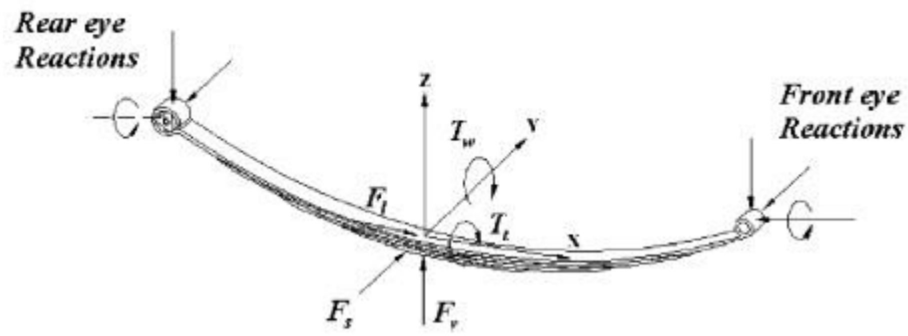

Figure 2.3. External forces that leaf spring exposured; F_v: Vertical load, F_s: Side load, F_t: Longitudinal load, T_t: Twisting torque, T_w: windup torque (Source: Shokrieh and Rezaei 2003)

In previous studies, a high number of reinforcing and matrix materials have been used with different lay-ups. One of these studies was made by Shokrieh and Rezaei (Shokrieh and Rezaei 2003). They considered two types of reinforcing material with epoxy resin. These reinforcing materials were glass fiber and carbon fiber, because these reinforcing materials have high strain energy capacity when combined epoxy resin. Carbon fibers have higher dynamic strain energy capability compared to glass fibers. Besides, glass fibers have lower strength and stiffness, higher density, better corrosion resistance, higher impact strength and lower cost. However, they choose glass fiber/epoxy system to manufacture leaf spring due to its good combination with cost and material properties. Glass fibers have two major types E and S2. They choose E glass fibers due to lower cost than S2 fibers. Thus, they used E-glass/epoxy system to fabricate composite leaf spring. After they chose material, they considered about lay-up of fabrics. Unidirectional lay-up along the longitudinal direction of spring was selected because leaf spring is loaded by longitudinal forces mainly (Shokrieh and Rezaei 2003). Sancaktar and Gratton used unidirectional E-glass as reinforcing materials due to its high extensibility, toughness and low cost. Epoxy resin is selected as matrix materials

(Sancaktar and Gratton 1999). Abu Talip et. al. designed an elliptical leaf spring by using woven E-glass reinforced epoxy composite. The reason of using woven E-glass is its widest range and the best control over thickness, weigth and strength of all forms of fiberglass textiles (Talib et al. 2010). Kumar and Vijayarangan chose unidirectional E-glass/epoxy system due to its high spesific strain energy in longitudinal direction (Kumar and Vijayarangan 2007a). Al-Qureshi used glassfiber/epoxy system for composite leaf spring. Reasons of his choises are glass fiber/epoxy has low sensivity to cracks, impact and wear damage. Besides, glass fiber/epoxy leaf springs are very smilar to metalic springs with regards to life requirements, since they have suficient impact strength, and their mechanical properties are nor greatly influced by the typical vehicle working condition (Al-Qureshi 2001). Morris utilized glass fiber/epoxy composite. The fiber volume fraction of composite was selected as 50%. Glass fiber epoxy eas chosen due to its great economic advantage over carbon fiber. 50% fiber volume fraction is close to the maximum attainable in practice (Morris 1986). Mahdi and Hamouda utilized three types of reinforcing with epoxy resin. They manufactured semi-elliptical composite leaf spring by using carbon/epoxy, glass/epoxy and glass-carbon/epoxy system (Mahdi and Hamouda 2013). Subramanian and Sentilevan studied on fiber reinforced thermoplastic leaf spring systems. They used discontinous, short glass fiber reinforced polypropylene and measure the fatigue performance (Subramanian and Senthilvelan 2010). Meatto and Pilpel utilized a different hybrid composite for monoleaf leaf springs. They used E-glass/epoxy system with steel (Meatto and Pilpel 1999). Hou et. al. used unidirectional glass fiber resinforced polyester with RTM process (Hou et al. 2005).

In summary, as shown in litarature search, E-glass fiber reinforced epoxy composite with unidirectional lay-up along the longitudinal direction of leaf spring is the most commonly used materials for leaf spring applications due to its high strain energy capability, superior strength and modulus, excellent corrosion ressitance and low cost. On the other hand, although its high cost, carbon fiber/epoxy composite is highly recommended as well. In this thesis, both glass and carbon fiber were used with different amounts when manufacturing composite leaf spring.

2.2.2. Manufacturing Processes of Composite Leaf Spring

Many techniques can be utilized to manufacture composite leaf spring. Al-Qureshi used hand lay-up vacuum bag process. In this process male and female mandrel was used. The glass fiber fabrics were cut to the desired lengths and laid-up to the mandrels. Then a releasing agent was applied to the mold. After this step, epoxy resin was applied throughout the layer. The impragnated fabrics were pressed until the desired thickness was obtained. Then fabrics cured at room temperature under vacuum for 12 h. Finally, cured laminate were remolded (Al-Qureshi 2001). Figure 2.4 shows the leaf springs that was manufactured by hand lay-up vacuum bag process.

As shown in Figure 2.4, leaf springs were exposed premature delamination. Thus, hand lay-up vacuum bag process is not successful enough to manufacture leaf spring (Al-Qureshi 2001).

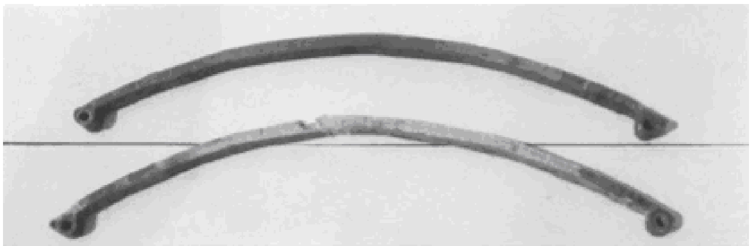

Figure 2.4. Composite leaf springs manufactured by hand lay-up vacuum bag process.
(Source: Al-Qureshi 2001)

Al Qureshi tried another technique to manufacture composite leaf spring is filament winding. According to this technique, a simple madrel was attached by a connecting rod to the winding machine for winding purpose. The operation was simply performed by depositing impragnated glass fiber with epoxy resin over the rotating mandrel in a hoop pattern. After the curing cycle was completed, a complete parabolic composite ring was manufactured. The ring was halved to produce the leaf spring. Figure 2.5 shows the ring and composite leaf spring that was manufactured by filament winding (Al-Qureshi 2001).

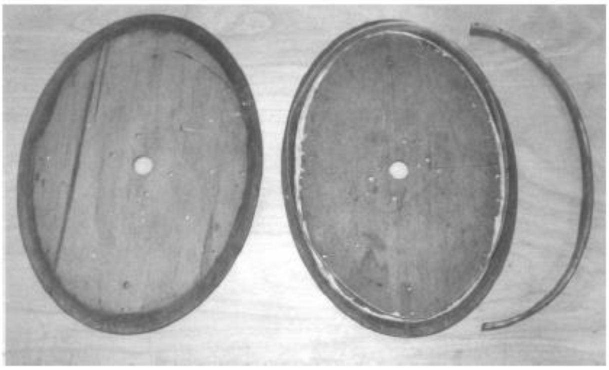

Figure 2.5. Composite leaf spring that manufactured by filament winding method.
(Source: Al-Qureshi 2001)

Sancaktar and Gratton used vacuum infusion technique to manufacture composite leaf spring. A mold was used instead of mandrel in this technique. The manufacturing of leaf spring was achieved in three steps in this process. Firstly, the mold was made from the sculpted pattern. After mold was prepared fabrics were cut to desired length and laid-up to the mold. After all required fibers were placed to the mold, a layer of peel-ply was applied to lay-up. Then the bleeder and braider plies applied (Sancaktar and Gratton 1999). The mold is inserted in a vacuum bag and laminates were cure under vacuum for 24 h. The pattern and mold that was used for this technique is shown in Figure 2.6.

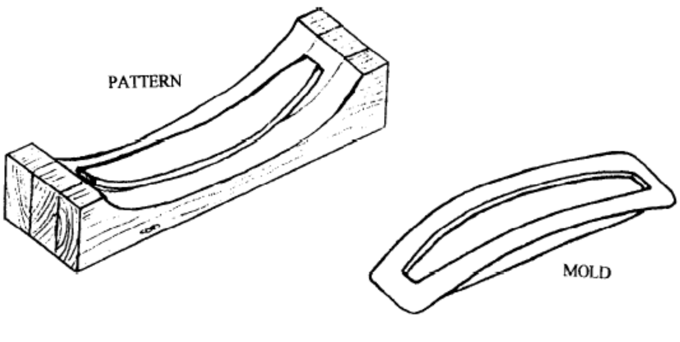

Figure 2.6. The pattern and mold that was used.
(Source: Sancaktar and Gratton 1999)

Morris utilized filment winding-compression molding process for composite leaf spring. Figure 2.7 is shown this manufacturing process (Morris 1986).

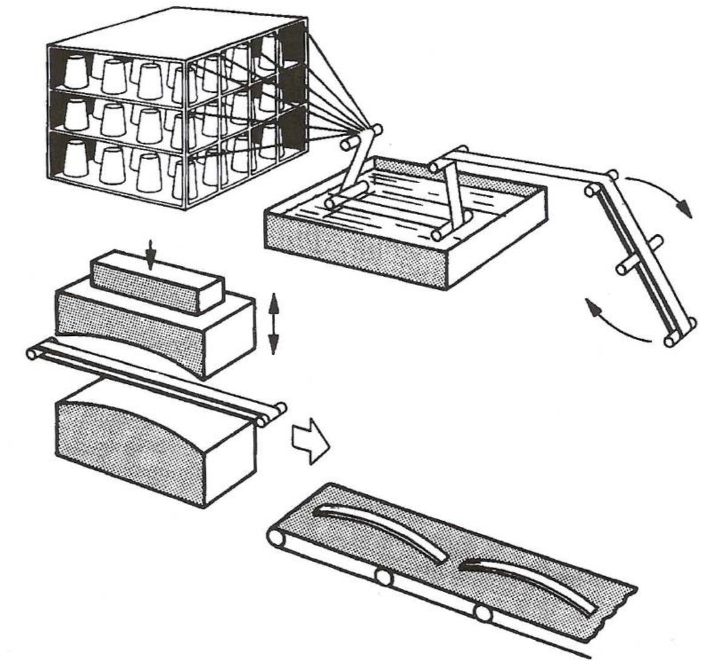

Figure 2.7. Filament winding-compression molding process.
(Source: Morris 1986)

As shown in Figure 2.7, the springs are fabricated by drawing a bundle of fibers through a bath of resin and winding them on spindles into a large bundle, longer than the finished spring, and laying this bundle into a female die. The male die is the pressed into the female and heat is applied to initiate the resin cure. After curing, the spring is removed from the die and trimmed to length (Morris 1986).

Mahdi and Homouda used wet wrapping process to manufacture semi elliptical springs. Initially, fabrics were impregnated in a resin bath. Then, wet fabrics were laid-up to the mandrel to form semi-elliptical leaf spring. Wet fabrics cured on the mandrel at room temperature for 24h (Mahdi and Hamouda 2013).

Gebremeskel used hand-lay up method, as well. First step of his process is preparing mould as shape of the leaf spring. Fibers were cut with desired dimension. Then releasing wax was applied to the mould to remold the leaf spring after curing. Mixture of epoxy resin and hardener was prepared and applied to mould. Then all layer of fibers were wet with epoxy. Then, composite leaf spring was cured at room temperature. Finally, composite leaf spring was removed from mould (Gebremeskel 2013). The mould setup that was used for this study and manufactured leaf spring are shown in Figure 2.8.

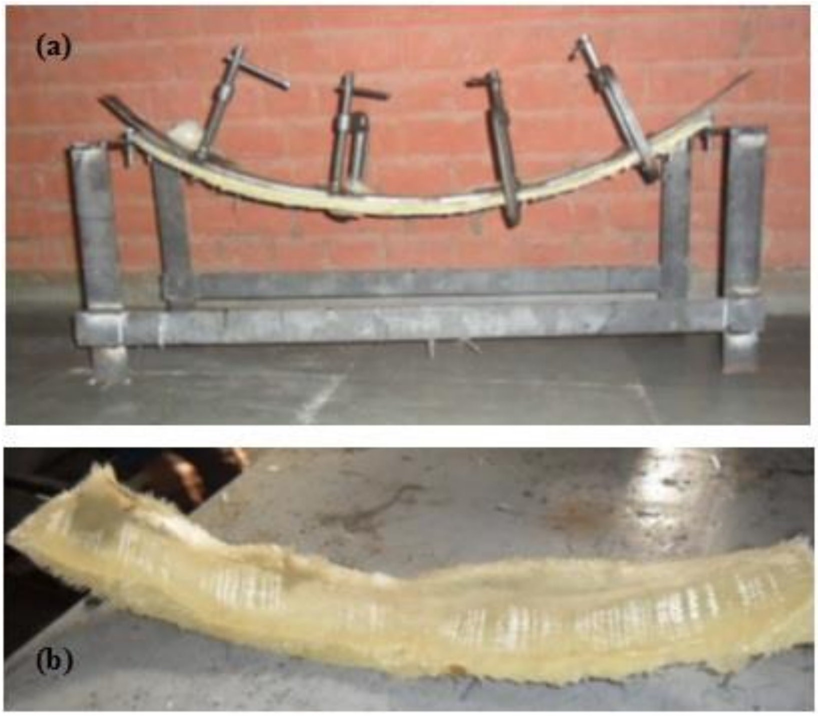

Figure 2.8. (a) mould setup for hand lay-up process, (b) manufactured composite leaf spring (Source: Gebremeskel 2013)

Different composite manufacturing techniques has been tried to manufacture composite leaf spring at previous research as mentioned. Although conventional hand lay-up technique was selected mostly in order to fabricate composite leaf spring, some problems like premature delamination, not to be in desired dimension etc. were observed at the leaf springs that fabricated by hand lay-up. In this thesis, another composite manufacturing technique that has not been studied in previous researches, resin transfer molding (RTM) with vacuum assistance, was selected.

2.2.2.1. Resin Transfer Molding (RTM) Process

Resin transfer molding process is one of the cost-effective system to manufacture high performance polymer composite components.RTM process was utilized in automotive industry, consumer products and, more recently marine and aviation markets (Akovali 2001).

In RTM, several layers of dry fabrics are placed in the bottom half of a two-part mold and the mold is closed, and liquid resin and its appropriate curing agent is injected into the mold. The injection pressure is genrally in the range of 0.7-7 bars. As the resin flows into the mold, it fills the space between the fiber yarns in the dry fiber preform, displaces air through the air vents in the mold, and coats the fibers. Process can be applied at room temperature or at an elevated temperature depending on the type on resin-curing agent system. After the cured part is pulled out of the mold, it is often necessary to trim the part at the outer edges to conform to the exact dimensions (Mallick 1993). Figure 2.9 shows the scheme of basic RTM process.

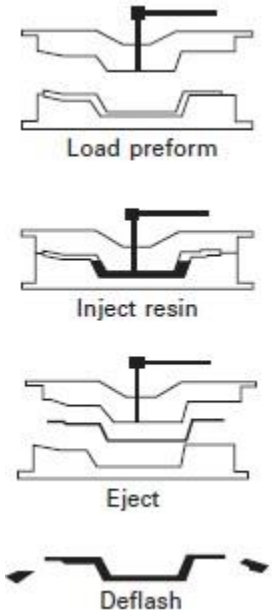

Figure 2.9. Photo of schematic RTM process.
(Source: Long 2005)

The process can be configured depending upon the application and the industrial environment. A pneumatic, reciprocating pump can deliver the resin and passed through a static mixer en route to the mould. The mould can be heated by resistance elements or fluid-carrying pipes; either may be embedded within the mould structure. Porting is essential to admit the resin and to vent the air. Multi-porting system can be used instead of single injection ports (Long 2005).

There are several variations of the RTM process that are used to fabricate composite structures. One of these variations is vacuum assisted resin transfer moulding (VARTM).

VARTM is an adaptation of the RTM process and is very cost-effective in making large structures. In this process, fabrics are placed in a one-sided mold and a cover, either rigid or flexible, is placed over the top to form a vacuum-tight seal.

Vacuum is used to the resin injection system to pull the liquid resin into fabrics. A high fiber volume fraction (70%) can be achieved by this process and therefore high structural performance is obtained in the part (Mazumdar 2001, Mallick 1993). Figure 2.10 shows the schematic VARTM process.

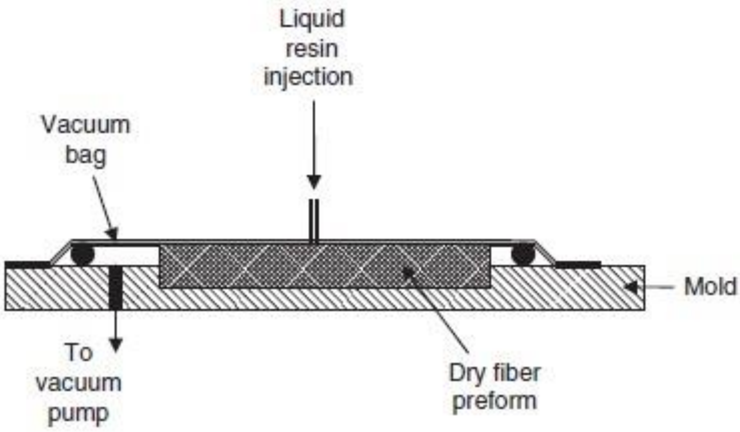

Figure 2.10. Schematic VARTM process.
(Source: Mallick 1993)

RTM process has potential to make small to large complex structures in a cost-effective manner. RTM also provides to use continuous fibers for the manufacture of structural components. Some of its major advantages over other composites manufacturing techniques listed below (Mazumdar 2001):

1. RTM is a low cost process due to reduced tooling costs and operating expenses as compared to compression molding and injection molding.

2. Composites can be manufactured close to dimensional tolerances due to mold structure.

3. RTM processing can make complex parts.

4. RTM provides a goof surface for manufactures.

5. RTM allows for production of structural parts with selective reinforcement and accurate fiber management.

6. Higher fiber volume fractions, up to 65%, can be achieved.

7. Various reinforcement materials can be used.

8. RTM is a close molding process, thus volatile emission during processing will be less.

9. RTM offers production of near-net-shape parts, hence low material wastage and reduced machining cost.

10. The process can be automated, resulting in higher production rates with less scrap (Mazumdar 2001).

Due to its advantages and availability to manufacture leaf spring, RTM process was selected as manufacturing tecnique for composite leaf spring in this thesis.

CHAPTER 3

EXPERIMENTAL

3.1. Materials

Fiber reinforced polymer matrix composites were selected to manufacture composite leaf spring in this study. Three type of non-crimp fabrics were used as reinforcement as listed below.

a) Unidirectional E-glass fabric
b) Unidirectional carbon Fabric
c) [+45^o/-45^o] biaxial carbon-glass hybrid fabric

Figure 3.1 shows fabrics used in this study. Unidirectional E-Glass fabric was purchased from Metyx Composites. Although it is defined as undirectional fabric, these fabrics contain filaments at 90^o direction. 2400 fibers exist at 0^o direction while 200 fibers exist at 90^o direction. Fibers at 0^o direction have 566 gr/m^2 areal weight, and fibers at 90^o direction have 47 gr/m^2 areal weight. Fabric also have tricot type stitches which have 10 gr/m^2 areal weight. Therefore, total areal weight of the fabric selected was about 623 gr/m^2.

Unidirectional carbon fabric was purchased from Spinteks Textile. All the fibers are oriented at 0^o direction and total areal weigh of this fabric was 300 g/m^2.

[+45^o/-45^o] biaxial carbon-glass hybrid fabric was purchased from Sönmez Advanced Textile. Both directions have glass fibers which have 267 gr/m^2 areal weight, and carbon fibers which have 178 gr/m^2 areal weight. Total areal weight of this fabric was 900 gr/m^2.

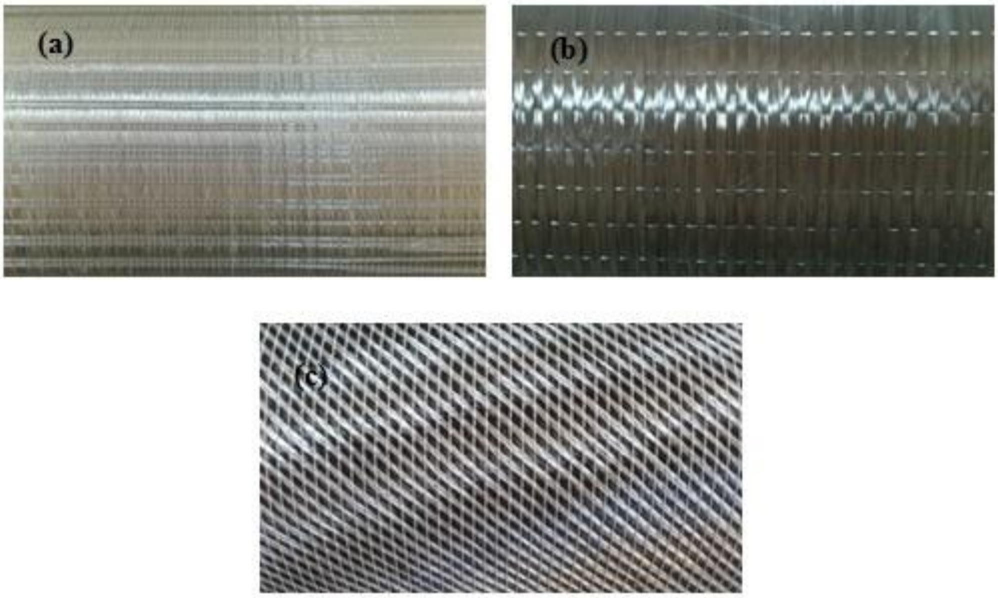

Figure 3.1. Fabrics used within this study. (a) unidirectional E-Glass fabric, (b) unidirectional carbon fabric, (c) [+45^o/-45^o] biaxial glass/carbon hybrid fabric

Duratek DTE 1200 epoxy resin, and DTS 1140 hardener were used as polymer matrix due to approximately 1 hour process time. The resin was selected as suitable for RTM process.

3.2. Manufacturing of Polymer Matrix Composite Plates via VARTM Process

In order to determine the mechanical and thermo-mechanical properties of composites, various type of composite plates were manufactured by resin transfer moulding (RTM) process. Vacuum was integreted into RTM process to enhance resin transfer into the mold. Figure 3.2 shows the stages RTM process that was used study to manufacture composite plates in this study.

In this process, fabrics were cut with a proper dimension as they fit in the mould. After that, fabrics were laid up to the mould, and mould was closed. Mould was moved to vertical position and 5.5 bar of vacuum was applied from four of the vacuum port that were located on the top of the mold via vacuum compressor before injection. After ensuring that the mould was completely under vacuum, epoxy and hardener were mixed with desired ratio in the RTM machine, and mixed resin was injected into the mould from the four port with 1 bar pressure. Figure 3.3 shows the vacuum pump and RTM machine that was used in the manufacturing stages respectively.

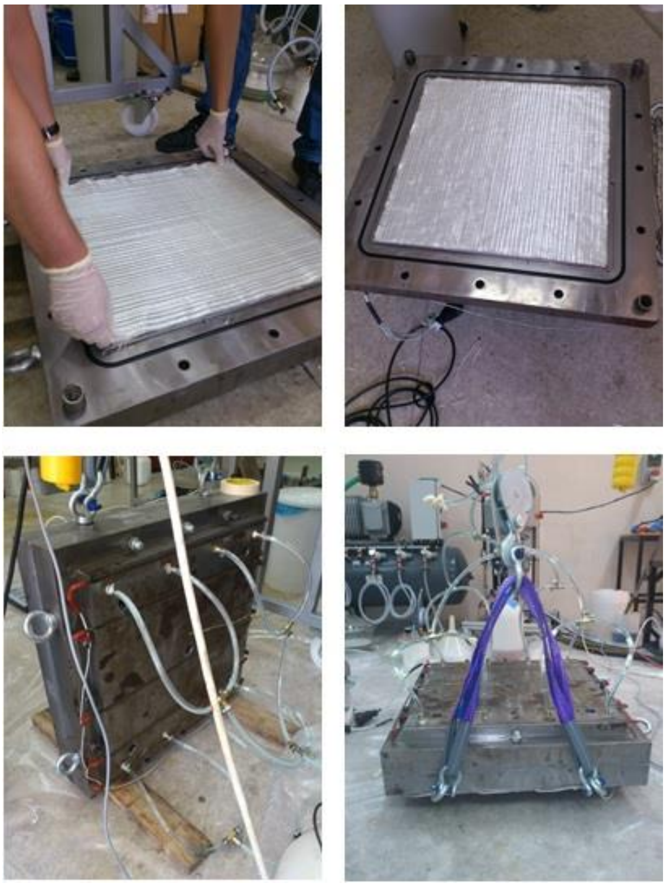

Figure 3.2. Photo showing the manufacturing scheme of composite plates via RTM process

Figure 3 3. Vacuum pump and RTM machine used in the manufacturing stages

After injection, composite plates were cured in the closed mould for 24 hours at room temperature, and then remolded. Post-curing was applied to all composite plates at 70 ^{o}C for 24 hour in order to obtain superior mechanical properties.

3.2.1. Manufactured Composite Plates Configurations

Five composite plates with five various fiber configurations were manufactured as listed below.

a) Unidirectional non-crimp E-glass fiber reinforced epoxy (Plate 1)
b) [0^{o}/90^{o}] non-crimp E-glass fiber reinforced epoxy (Plate 2)
c) Unidirectional non-crimp carbon fiber reinforced epoxy (Plate 3)
d) [0^{o}/90^{o}] non-crimp carbon fiber reinforced epoxy (Plate 4)
e) [$+45^{o}$/-45^{o}] non-crimp glass/carbon hybrid fiber reinforced epoxy (Plate 5)

Figure 3.4 shows composite plates that were manufactured within the study. Configurations of manufactured composite plates are given in Table 3.1.

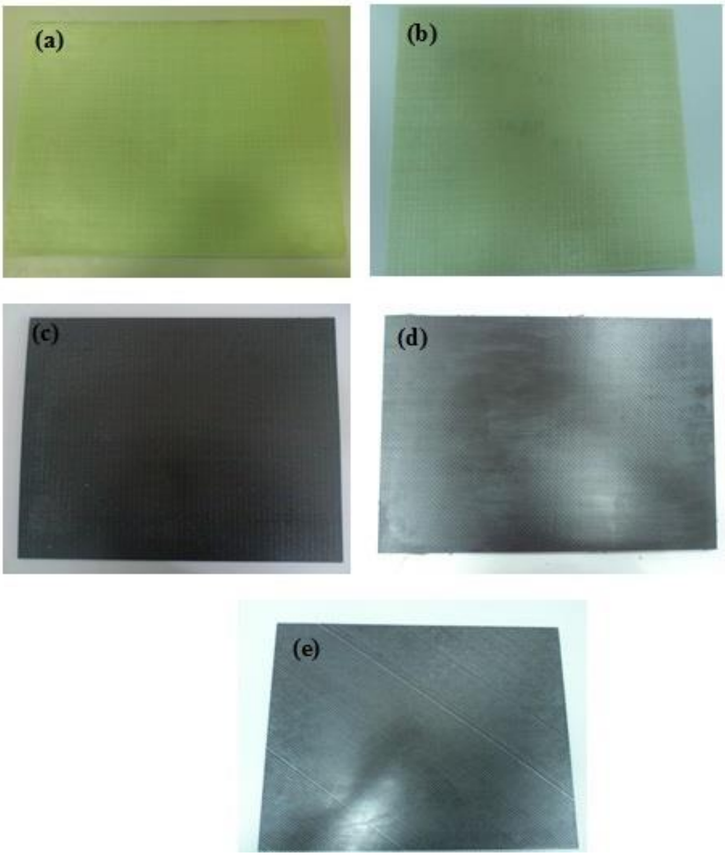

Figure 3.4. Manufactured composite plates, (a) unidirectional non-crimp E-Glass fiber reinforced epoxy plate, (b) [0^o/90^o] biaxial non-crimp E-Glass fiber reinforced epoxy plate, (c) unidirectional non-crimp carbon fiber reinforced epoxy plate, (d) [0^o/90^o] biaxial non-crimp carbon fiber reinforced epoxy plate, (e) [+45^o/-45^o] biaxial non-crimp glass/carbon hybrid fiber reinforced epoxy plate

Table 3.1. Manufactured Composite Plate Configurations

Composite Plate	**Fabric**	**# of Layers**	**Fabric Type**	**Orientation**
Plate 1	UD E-Glass	8	Non-Crimp	UD
Plate 2	UD E-Glass	8	Non-Crimp	[0^o/90^o]
Plate 3	UD Carbon	8	Non-Crimp	UD
Plate 4	UD Carbon	8	Non-Crimp	[0^o/90^o]
Plate 5	[+45/-45] Hybrid	6	Non-Crimp	[+45^o/-45^o]

3.3. Manufacturing of Composite Leaf Spring Prototypes

Composite leaf springs with two different geometrical designs (Design A and Design B) were manufactured by VARTM process. For this purpose, two different moulds were used.

3.3.1. Manufacturing Process for Design A

Figure 3.5 shows the first geometrical leaf spring design, called Design A.

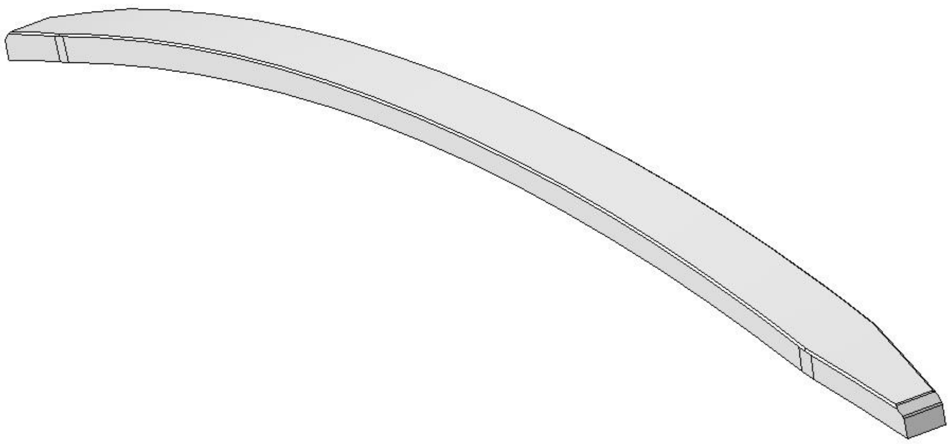

Figure 3.5. Schematic illustration of the first geometrical design of leaf spring, (Design A)

As shown in Figure 3.5, thickness of the composite leaf spring was held constant along the leaf spring for Design A. Althoug the width of the leaf spring is constant at the middle of the spring, it narrows through edges.

RTM process was used to manufacture the leaf spring designed within the study. In this process, fabrics were cut with respect to templates that was obtained from CAD data of the composite leaf spring. The cut Fabrics were laid-up into the mould, and mould was closed after completion of the fabric stacking process. Then, 3.5 bar of vacuum was applied from vacuum ports after the closing to mold. After ensuring that mould is under vacuum completely, resin injection was started with 1 bar pressure into the resin port by using RTM machine as shown in Figure 3.3. Resin flow was obtained by the force of injection pressure and vacuum. In order to ensure that all of the fabrics in the mould are wetted with epoxy resin, resin injection was maintained until resin flow was observed in all vacuum ports. Figure 3.6 shows the photo of manufacturing stages for composite leaf spring for Design A. The mould produced contains 6 vacuum ports and 1 resin injection port.

Figure 3.6. Photos showing the RTM stages to manufacture composite leaf spring for Design A

After completion of injection process, parts were kept in the mould for about 24 h at room temperature for completion of the curing. Then, leaf springs were remolded.

Three different types of composite monoleaf leaf springs that contains various fiber configurations were manufactured for Design A. These configurations are listed below, and shown in Figure 3.7.

- Design A-1, 60 layer of unidirectional glass fiber (Figure 3.7(a))
- Design A-2, 56 layer of unidirectional glass fiber + 4 layer of unidirectional carbon fiber (Figure 3.7(b))
- Design A-3, 56 layer of unidirectional glass fiber + 4 layer of [+45^o/-45^o] biaxial glass/carbon fiber (Figure 3.7(c))

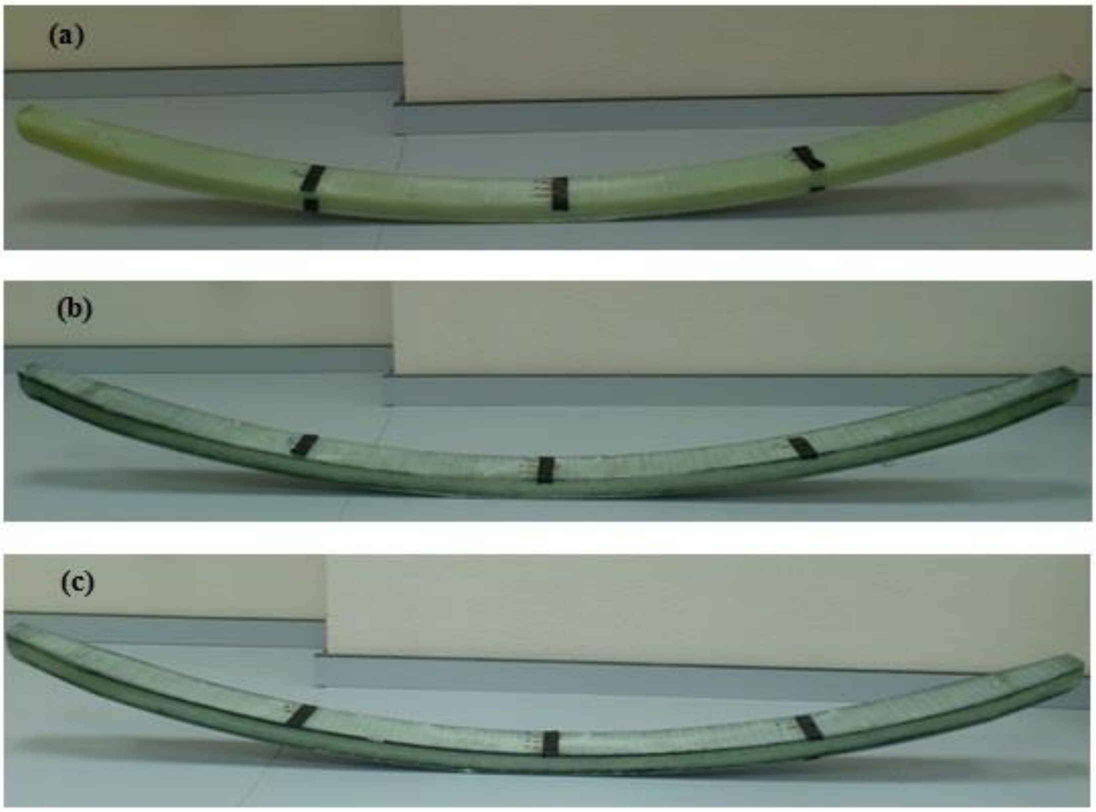

Figure 3.7. Manufactured composite monoleaf leaf springs for Design A.

3.3.2. Manufacturing Process for Design B

Figure 3.8 shows the geometrical desing of leaf spring named Design B. As shown in Figure 3.8, the width of the composite leaf spring was kept constant, however the thickness was changed along the leaf spring, and the edges were curved for Design B in contrast to Design A.

Similar to Design A, RTM procedure was applied to manufacture leaf spring for Design B. Fabrics were cut and laid up into the mould. Two cores at edges of mould was inserted into the mould to form curve edges of leaf springs. Fabrics were wrapped on these cores after laying-up. Once the fabric lay-up is completed, mould was closed, and 4.5 bar pressure of vacuum applied to the mould. Resin injection was started by RTM machine (Figure 3.3) once the mould was under vacuum completely. Composite leaf spring part was cured in the mould for 24 h. After completion of the curing, part was remolded. Figure 3.9 illustrates the photos showing the manufacturing stages for Design B.

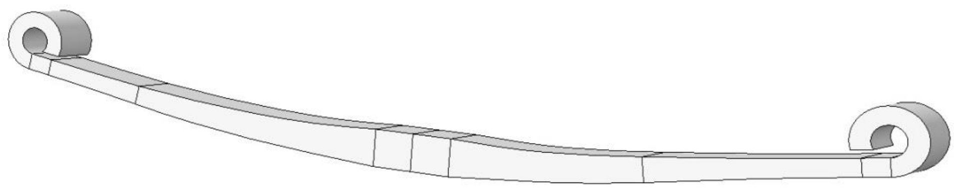

Figure 3.8. Schematic illustration of the leaf spring geometrical design, (Design B)

Figure 3.9. Photos showing the manufacturing stages for Design B

The mould that was used for Design B contains 11 vacuum port, and 1 resin injection port. Design B was manufactured using one fiber configuration that contains 167 layers of unidirectional E-Glass fiber. Leaf spring manufactured based on Desing B is shown in Figure 3.10.

Figure 3.10. Photo of manufactured composite leaf spring based on Design B.

3.4. Characterization of Composite Plates

3.4.1. Determining Fiber Volume Fraction of Composite Plates

Matrix burn-out test was applied to determine the fiber volume fraction of composite plates. In this method, small samples were cut from different parts of composite plates, and then they were burned off in a high temperature oven at high temperatures in which matrix materials burned completely. After cooling, the weight of the crucibles containing residues fibers was measured. Based on the density of matrix and fibers, fiber volume fraction of composite plates was calculated by Equation 3.1. Tests were performed at 700 ^{o}C for glass fiber reinforced composites, and 500 ^{o}C for carbon fiber reinforced composites.

$$V_f = \frac{v_f}{v_f + v_m} x100 = \frac{\frac{m_f}{\rho_f}}{\frac{m_f}{\rho_f} + \frac{m_m}{\rho_m}} \tag{3.1}$$

The equation above, v_f and v_m are the volumes of fiber and matrix, m_f and m_m are the mass of fiber and matrix, and ρ_f and ρ_m are the density of fiber and matrix, respectively.

Density method was utilized to measure the fiber volume fraction of biaxial glass/carbon hybrid fiber reinforced epoxy composite plate. The volume fraction of Plate 5 was calculated by measuring the density of Plate 5 in air and in distilled water.

Five samples were cut and weighted in air. Then, samples were immersed at distilled water and weigted. The density of Plate 5 was calculated by Archimedes principle using the equation below:

$$\rho_c = W_{air}\rho_{water}/(W_{air}W_{water})$$

In this equation; ρ_c is density of composite, W_{air} is the weigth of sample in air, ρ_{water} is density of distilled water and W_{water} is the weigth of sample in distilled water.

The fiber volume fraction of composite plate was measured by using the rule of mixtures as given below:

$$V_f = (\rho_c - \rho_{resin})/(\rho_{fiber} - \rho_{resin})$$

Glass/carbon hybrid fabric that utilized in this study contains equal amounts of glass and carbon fiber. Therefore, volume of carbon and glass fiber in this fabric were assumed as same.

3.4.2. Dynamic Mechanical Analysis (DMA)

Dynamic mechanical analysis was used to evaluate the changing of thermo mechnical properties of composite plates manufactured within this work. Analysis were performed using a TA Instuments Q800 (Figure 3.11) in dual centilever mode. In this procedure, storage modulus ($E^{'}$) and loss modulus ($E^{''}$) of the composite plates were determined. Tangent delta (δ) values gave the glass transition temperature (T_g) of the composite plates. Tests were applied from room temperature to 120 ^oC with 3 ^oC/minute heating rate.

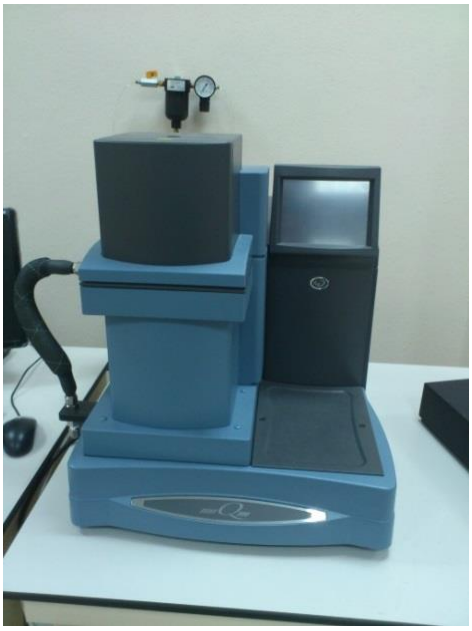

Figure 3.11. DMA equipment (TA Intruments Q800)

3.4.3. Tensile Test

Tensile test on composite plates were performed using Shimadzu AG-IC Universal Test Machine with 100 kN capacity load cell. Displacement values were obtained via video extensometer. Both axial and transversal mechanical properties were evaluated for unidirectional plates. For [0^o/90^o] plates, axial properties were evaluated only in one direction. Ultimate tensile strength (σ_{ult}), tensile modulus (E), strain at break (ε), possion ratios (ν), and strain energy capabilities in axial direction of each plates were obtained.

Test specimens were cut from composite plates with dimensions of 250 mm length and 25 mm width according to ASTM D 3039 test standart. Plate 5 was cut along fiber direction, so stacking sequences of Plate 5 became [0^o/90^o]. At least, 5 specimen for each composite plate were tested. Test speed was adjusted as 2 mm/minute. Figure 3.12 shows the tensile test configuration.

Figure 3.12. Tensile test configuration

Force and displacement values were obtained during the test. Stress and strain values were calculated by using Equations 3.2 and 3.3.

$$\sigma = \frac{F}{A} \tag{3.2}$$

$$\varepsilon = \frac{(L-L_0)}{L_0} \tag{3.3}$$

The equation above, σ is tensile stress, F is the ultimate load, A is cross sectional area of the specimen. ε is tensile strain, L is the distance between gauge marks at any time and L_0 is the distance between gauge marks at initial position.

Tensile modulus (E) values were calculated from stress-strain graph. The slope of the stress-straim graph gave the tensile modulus.

Strain energy capabilities in axial direction of each plates were calculated by Equation 3.4.

$$U = \frac{1}{2}\frac{\sigma^2}{E} \tag{3.4}$$

3.4.4. Three Point Bending Test

Three point bending test was applied in order to determine the flexural properties of the composite plates. Test was carried out in accordance with ASTM D790 test standart. Width of specimens were 13 mm. At least, 5 specimens were cut from each composite plates and tested. Length of specimens were related to span ratio, and span ratio to length was selected as 16. Figure 3.13 shows test setup of the 3 point bending test.

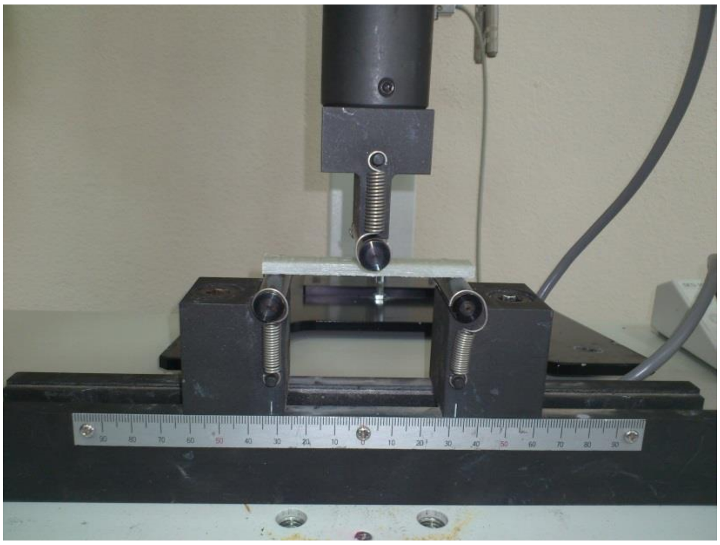

Figure 3.13. Three point bending test setup

Load and deflection values were obtained during the test. Flexural stress, flexural strain and flexural modulus values were calculated based on equations below. Equation 3.5 was used to calculate flexural stress.

$$\sigma_f = \frac{3PL}{2bd^2} \tag{3.5}$$

In this equation, σ_f is the stress in outer fibers at midpoint, P is load that applied on specimen, L is span length, b is width of the specimen tested and d is thickness of the specimen. Flexural strain was calculated by using Equation 3.6.

$$\varepsilon_f = \frac{6Dd}{L^2} \tag{3.6}$$

In Eq. 3.5, ε_f is flexural strain, D is maximum deflection in the center of beam, d is thickness of the specimen and L is span length. Flexural modulus was calculated by using Equation 3.7.

$$E_b = \frac{L^3 m}{4bd^3} \tag{3.7}$$

In Eq. 3.6, E_b is flexural modulus of elasticity, L is span length, m is slope of the tangent to the initial straigh-line portion of the load deflection curve, b is width of the specimen and d is thickness of the specimen.

3.5. Characterization of Composite Monoleaf Leaf Spring

3.5.1. Rig Test

Rig test was applied to composite monoleaf leaf springs manufactured in Design A. Rig test setup is shown in Figure 3.14. As shown in Figure 3.14, composite leaf spring was placed simply supported. A vertical load was applied to the center of the leaf spring by a square metal plate with dimensions of 150x150 mm. The distance between two supports is 1160 mm. Figure 3.15 shows the loading conditions and dimensions schematically.

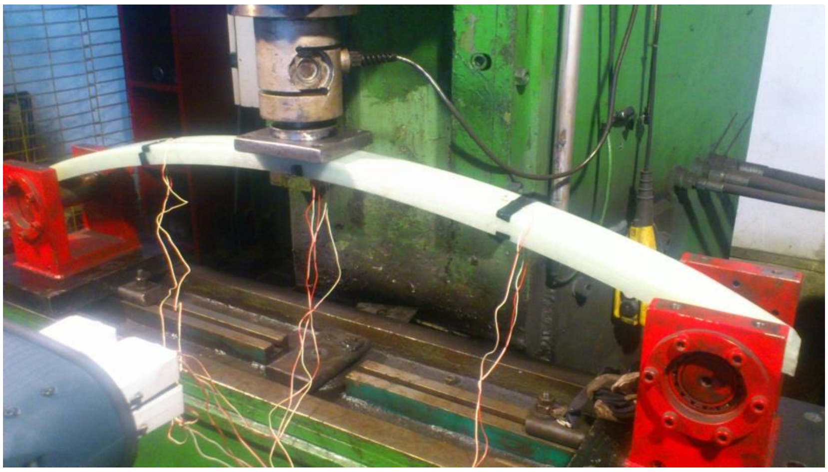

Figure 3.14. Rig test setup for measuring performance of composite leaf spring

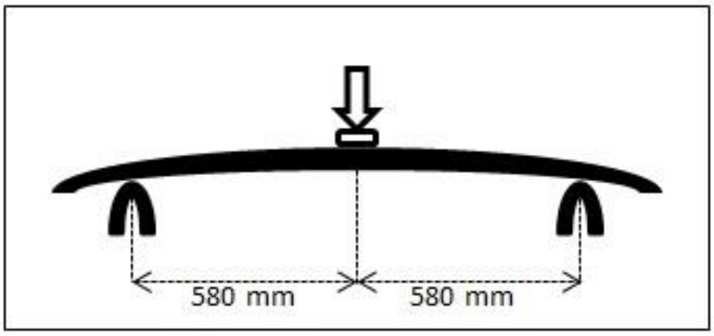

Figure 3.15. Schematic of loading configuration for in Rig test

Strain gauges total of 7 were attached to each leaf springs in order to evaluate the strain values on specific parts of the leaf springs due to applied load. A data acquisition device connected a computer was used to record data obtained from strain gauges. Figure 3.16 shows strain gauge positions on leaf spring, schematically.

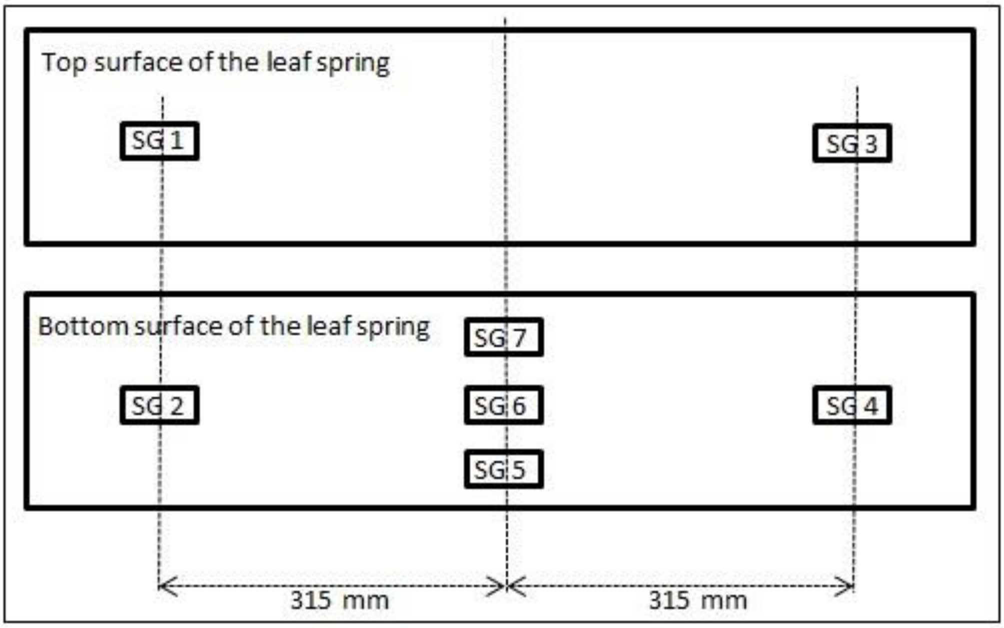

Figure 3.16. Strain gauge positions on composite leaf spring

During testing, load was applied up to 1631 kgf in 9 steps. Deflection of center of the leaf spring and strain values were recorded for each load step. Strain values were converted to stress values through data acquisition system, so stress values at specifies position on leaf springs were obtained.

CHAPTER 4

RESULTS AND DISCUSSIONS

In this chapter, both results of tests applied on composite plates and composite leaf springs were given.

4.1. Test Results of Composite Plates

4.1.1. Fiber Volume Fraction of Composite Plates

In fiber reinforced polymeric composite materials, great amount of load are beared by fibers. Thus, fiber volume fraction of the material affects mechanical and physical properties of material directly. As fiber volume fraction of materials increases, mechanical properties of material enhances.

Fiber volume fraction of Plate 1, Plate 2, Plate 3 and Plate 4 was measured by burn-out test and results are given in Table 4.1 to 4.4. Density method was utilized to measure the fiber volume fraction of Plate 5 and result is given in Table 5.

Table 4.1. Fiber weight and fiber volume fraction of Plate 1

Sample No	**Fiber Weight Fraction**	**Fiber Volume Fraction**
1	67.49	48.47
2	68.27	49.36
3	68.11	49.18
4	68.21	49.30
5	67.93	48.98
6	67.68	48.69
Average	**67.95**	**49.00**
Std. Dev.	**0.31**	**0.36**

Table 4. 2. Fiber weight and fiber volume fraction of Plate 2

Sample No	Fiber Weight Fraction	Fiber Volume Fraction
1	65.97	45.06
2	67.40	46.66
3	67.00	46.21
4	67.66	46.95
5	66.53	45.68
6	66.86	46.05
Average	**66.90**	**46.10**
Std. Dev.	**0.61**	**0.68**

Table 4.3. Fiber weight and fiber volume fraction of Plate 3

Sample No	Fiber Weight Fraction	Fiber Volume Fraction
1	52.14	41.52
2	49.68	39.15
3	49.14	38.64
4	54.27	43.61
5	56.77	46.11
6	57.36	46.71
Average	**53.23**	**42.63**
Std. Dev.	**3.50**	**3.43**

Table 4.4. Fiber weight and fiber volume fraction of Plate 4

Sample No	Fiber Weight Fraction	Fiber Volume Fraction
1	49.71	39.45
2	51.14	40.83
3	50.05	39.77
4	52.25	41.90
5	50.72	40.42
6	48.28	38.09
Average	**50.36**	**40.07**
Std. Dev.	**1.35**	**1.30**

Table 4.5. Fiber volume fraction of Plate 5

Sample No	W_{air} (gr)	W_{water} (gr)	Composite Density (gr/cm^3)	Fiber Volume Fraction
1	0.955	0.351	1.581	41.69
2	1.312	0.5021	1.619	45.54
3	1.1267	0.446	1.646	48.09
4	1.1123	0.4245	1.617	45.26
5	1.004	0.3803	1.613	44.88
Average	**1.103**	**0.421**	**1.615**	**45.09**
Std. Dev.	**0.14**	**0.06**	**0.02**	**2.28**

Fiber volume fraction of composite plates that were manufacture in this study was found between % 40 and % 49. Although all plates except Plate 5 contain 8 layers, fiber volume fraction of carbon fiber reinforced composites plates are relatively lower. The reason of this situation can be considered as carbon fabrics that was used within this study contain relatively lower density and thinner fibers.

4.1.2. Thermo-mechanical Properties

Thermo-mechanical properties of composite plates were obtained by Dynamic Mechanical Analysis (DMA). Mechanical properties of polymeric materials changes dramatically at glass transition temperature (T_g). Thus, Glass transition temperature is the main criteria for polymeric materials to determine the maximum working temperature. Glass transition temperature of composite plates were obtained by DMA. In this test, storage modulus ($E^{'}$) and loss modulus ($E^{''}$) of material were determined as a function of temperature. Tangent of storage modulus and loss modulus ratio gives Tan Delta function. Glass transition temperature (T_g) is the temperature that Tan Delta function peaks. Figure 4.1 shows the graph of storage modulus, loss modulus and Tan Delta as a function of temperature as an example.

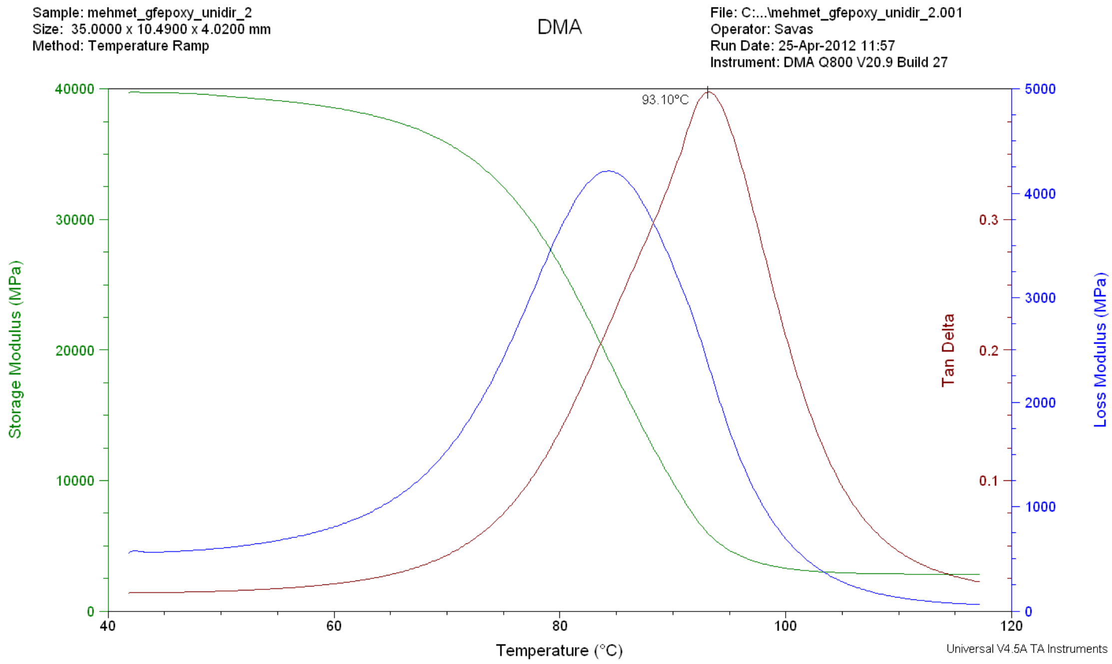

Figure 4.1. Graph of storage and loss modulus as a result of DMA analysis

At least 2 samples were analysed for each composite plate. Avarage of each plate's results were calculated and T_g of composite plates were determined. Table 4.5 shows glass transition temperature for each plate.

Table 4.6. Glass transition temperature of composite plates

Sample No / Plate No	**1**	**2**	**Average**	**Std. Dev.**
Plate 1	93.10	93.66	**93.38**	**0.39**
Plate 2	98.42	98.98	**98.70**	**0.39**
Plate 3	114.14	114.69	**114.41**	**0.38**
Plate 4	97.30	96.54	**96.92**	**0.54**
Plate 5	110.79	110.69	**110.74**	**0.07**

Glass transition temperature (T_g) limits working temperature of polymeric materials. A structural composite may not work above glass transition temperature. Five different composite structures' glass transition temperature are shown in Table 4.5. These results demonstrate that glass transition temperature of plates fabricated in this study varies from 90 ^{o}C to 110 ^{o}C. These values are above the working temperature of leaf springs. Thus, epoxy matrix composites' thermo-mechanical properties are convenient for leaf spring applications.

4.1.3. Tensile Properties

Tensile properties of each plates are discussed by stress-strain curves shown in Figure 4.2 to 4.8, and test results are given in Table 4.7 to Table 4.11.

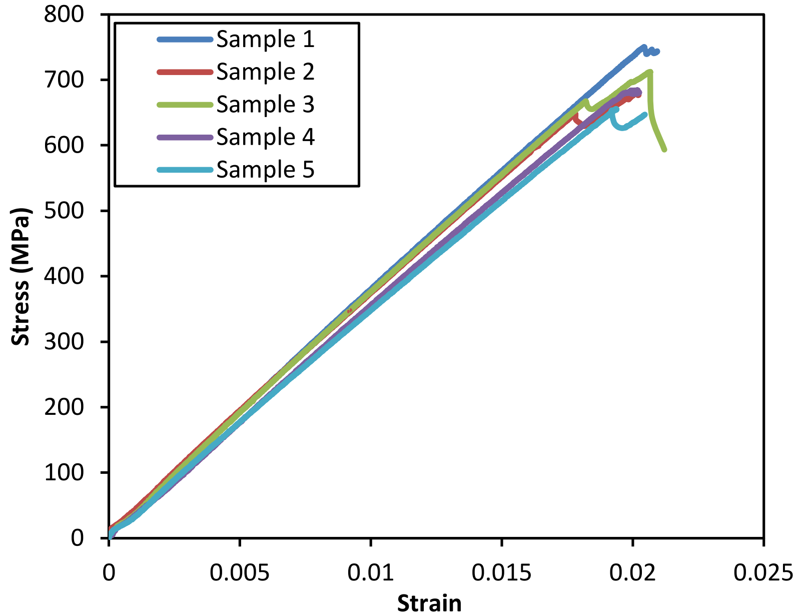

Figure 4.2. Axial tensile stress-strain curve of composite Plate 1

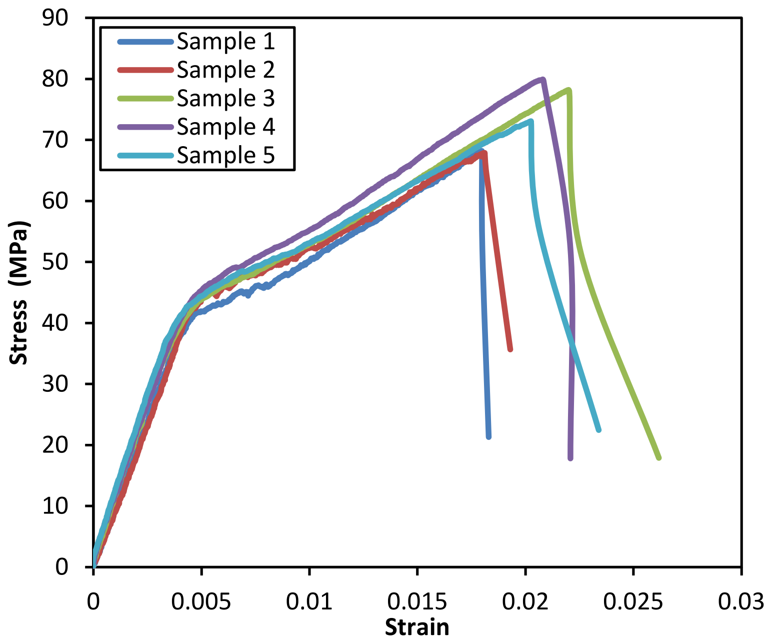

Figure 4.3. Transverse tensile stress-strain curves of Plate 1

Table 4.7. Tensile test results for Plate 1

Sample No	**Ult. Axial Tensile Strength (σ_{11})(MPa)**	**Axial Tensile Modulus (E_{11})(MPa)**	**Ult. Transversal Tensile Strength (σ_{22})(MPa)**	**Transversal Tensile Modulus (E_{22})(MPa)**	**Poisson Ratio (ν_{12})**	**Axial Break Strain (ε_{11}) (%)**	**Trans. Break Strain (ε_{22})(%)**
1	750.23	37051	68.21	9856	0.29	2.08	1.8
2	646.02	36561	67.88	9849	0.24	1.77	1.8
3	712.21	36268	78.20	9762	0.28	2.07	2.2
4	684.24	34606	79.92	9570	0.32	2.10	2.08
5	655.53	35463	73.08	10320	0.28	1.92	2.03
Average	**689.65**	**35990**	**73.46**	**9871**	**0.28**	**1.99**	**1.98**
Std. Dv.	**42.65**	**964.65**	**5.55**	**276.04**	**0.029**	**0.14**	**0.18**

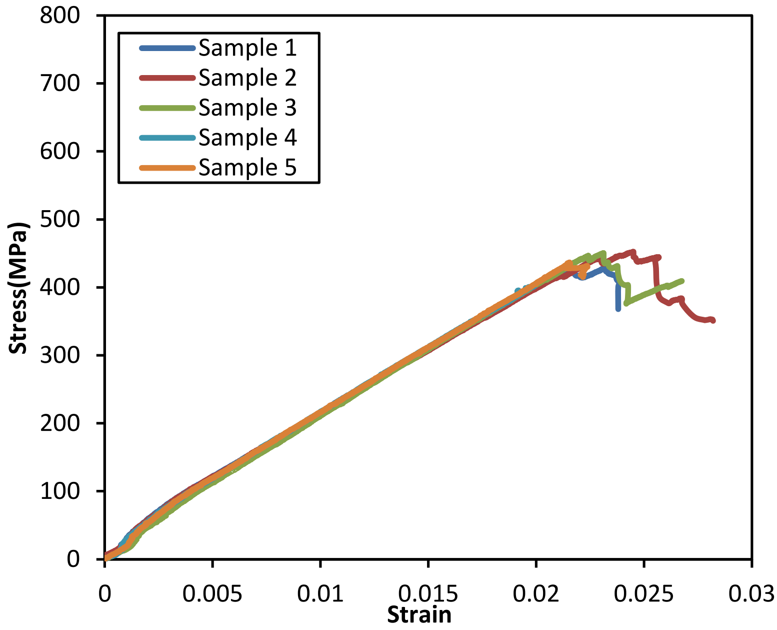

Figure 4.4. Tensile stress-Strain curve of composite Plate 2

Table 4.8. Tensile test results for composite Plate 2

Sample No	**Ult. Tensile Strength (σ_{11}, σ_{22})(MPa)**	**Tensile Modulus (E_{11}, E_{22})(MPa)**	**Poisson Ratio (ν_{12})**	**Break Strain ($\varepsilon_{11}, \varepsilon_{22}$)(%)**
1	430.60	29746.3	0.29	2.37
2	452.47	33564.7	0.28	2.55
3	450.44	30697.9	0.25	2.31
4	403.02	27001.4	0.33	1.94
5	436.68	31839.1	0.22	2.22
Average	**434.64**	**30569.88**	**0.27**	**2.27**
Std. Dev.	**19.92**	**2449.9**	**0.04**	**0.22**

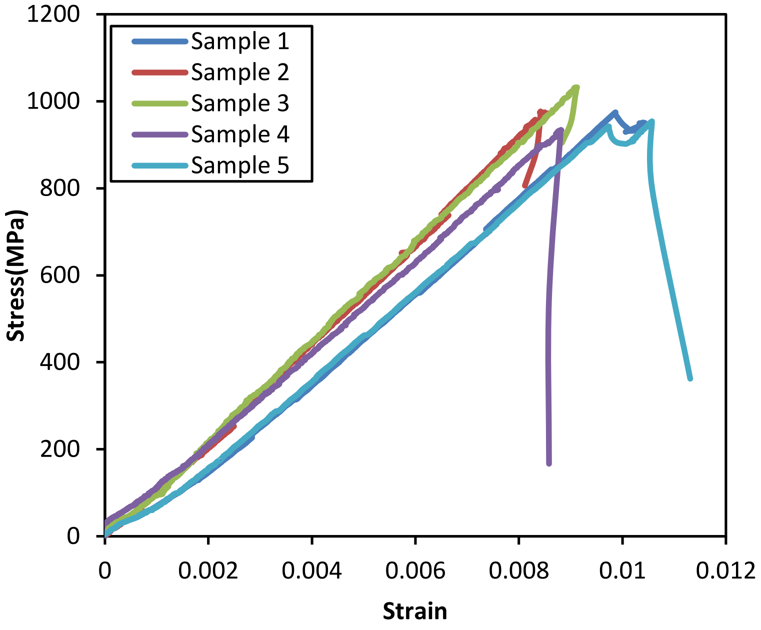

Figure 4.5. Axial tensile stress-strain curve of composite Plate 3.

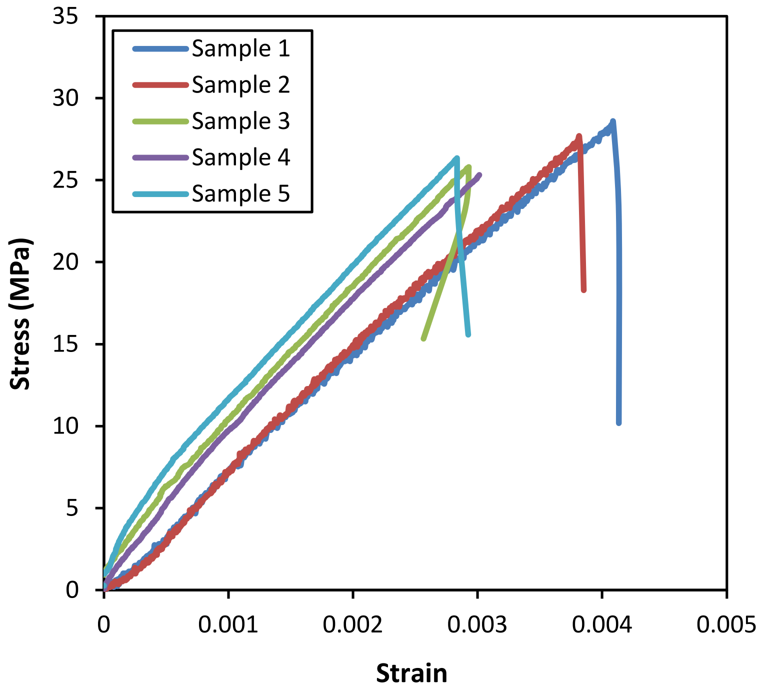

Figure 4.6. Transverse tensile stress-strain curve of composite Plate 3

Table 4.9. Tensile test results for composite Plate 3

Sample No	Ult. Axial Tensile Strength (σ_{11})(MPa)	Axial Tensile Modulus (E_{11})(MPa)	Ult. Transversal Tensile Strength (σ_{22})(MPa)	Transversal Tensile Modulus (E_{22})(MPa)	Poisson Ratio (ν_{12})	Axial Break Strain (ε_{11}) (%)	Transversal Break Strain (ε_{22})(%)
1	974.7	102100	28.5	7900	0.42	0.98	0.41
2	1027.4	106000	27.6	8200	0.58	0.84	0.38
3	1032.1	115100	25.8	9000	0.37	0.91	0.29
4	933.8	102800	31.4	9200	0.25	0.88	0.38
5	954.0	102800	26.3	9800	0.44	1.05	0.28
Average	**984.4**	**105700**	**27.9**	**8800**	**0.41**	**0.93**	**0.34**
Std. Dev.	**43.89**	**5436.27**	**2.22**	**769.41**	**0.12**	**0.08**	**0.06**

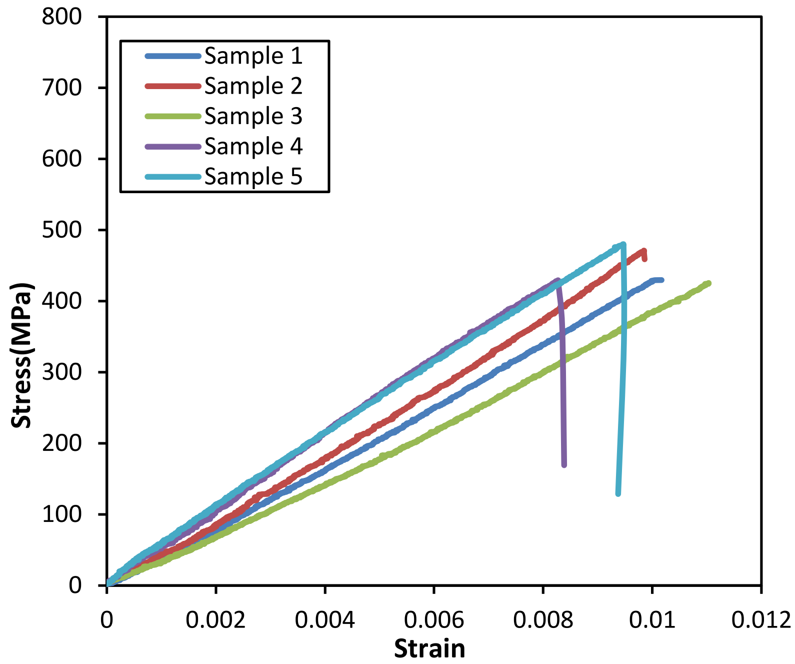

Figure 4.7. Tensile stress-Strain curve of composite Plate 4

Table 4.10. Tensile test results of composite Plate 4

Sample No	Ult. Tensile Strength (σ_{11}, σ_{22})(MPa)	Tensile Modulus (E_{11}, E_{22})(MPa)	Poisson Ratio (ν_{12})	Break Strain (ε_{11}, ε_{22})(%)
1	429.49	42605	0.22	1.00
2	470.95	44467	0.28	0.98
3	443.89	39767	0.20	1.10
4	429.21	51707	0.18	0.83
5	479.80	53656	0.23	0.90
Average	**450.67**	**46440**	**0.22**	**0.97**
Std. Dev.	**23.53**	**5977.89**	**0.038**	**0.102**

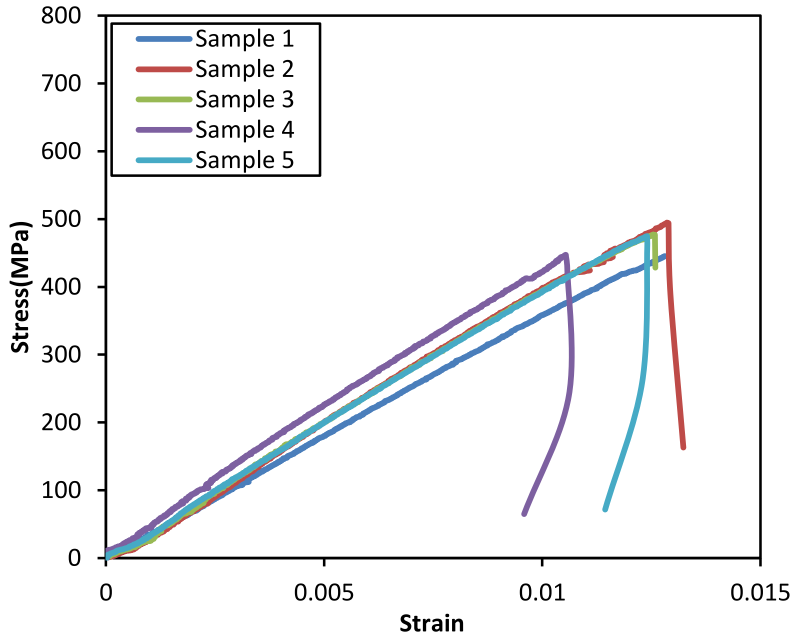

Figure 4.8. Tensile stress-strain curve of composite Plate 5

Table 4.11. Tensile test results for composite Plate 5

Sample No	Ult. Tensile Strength (σ_{11}, σ_{22})(MPa)	Tensile Modulus (E_{11}, E_{22})(MPa)	Poisson Ratio (ν_{12})	Break Strain ($\varepsilon_{11}, \varepsilon_{22}$)(%)
1	445.39	39447	0.23	1.19
2	495.19	40283	0.22	1.28
3	477.02	38558	0.26	1.25
4	447.30	43604	0.32	1.05
5	456.98	39518	0.28	1.24
Average	**464.37**	**40282**	**0.26**	**1.20**
Std. Dev.	**21.31**	**1955.04**	**0.040**	**0.091**

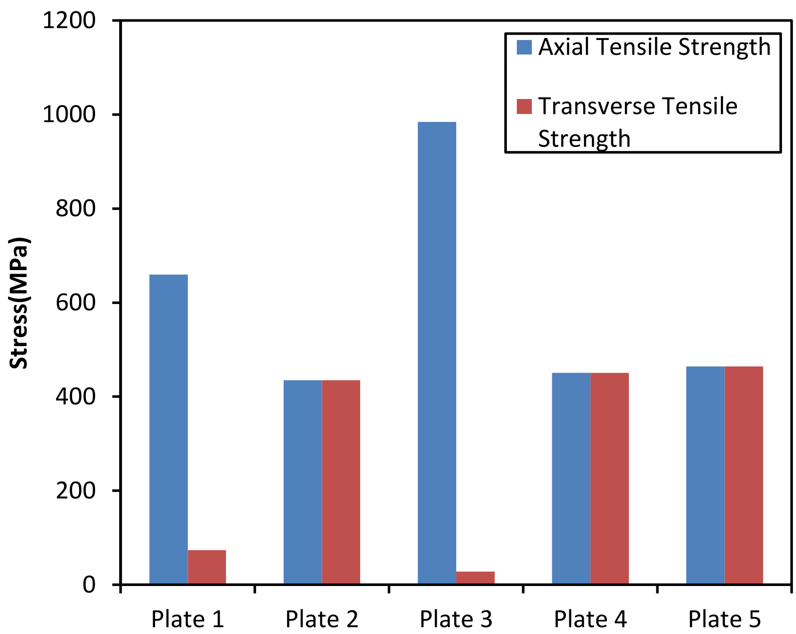

Figure 4.9. Graph of axial and transverse tensile strength of composite plates

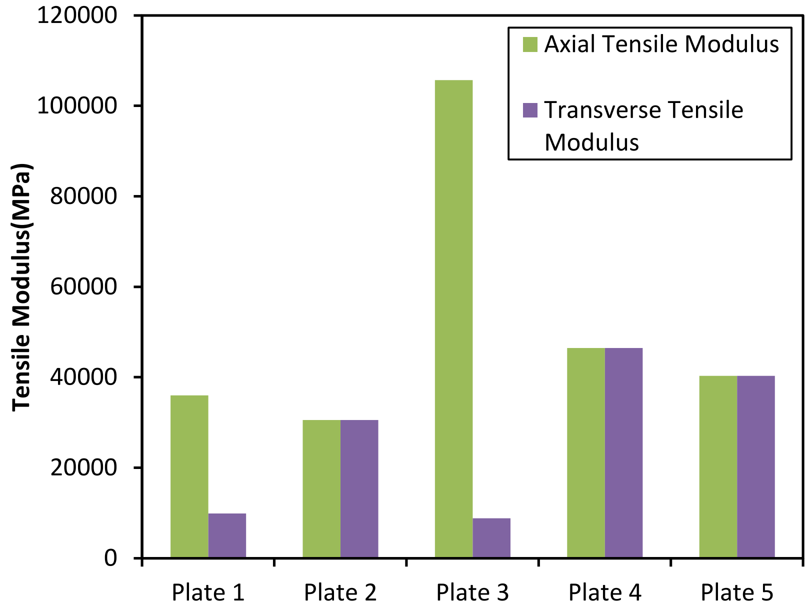

Figure 4.10. Graph of axial and transverse tensile modulus of composite plates

Figures 4.9 and 4.10 illustrate the comparing tensile strength and modulus of composite plates. Unidirectional plates demonstrated high tensile strength along fiber direction as expected. Fibers are predominant load-bearing elements in unidirectional plates if load is applied along fiber direction. That's the reason that unidirectional composites have superior tensile strength along fiber direction. On the other hand, unidirectional composites have low mechanical properties at 90^{o} direction. In this case, matrix are predominant load-bearing element in the structure, and under loading conditions, matrix micro cracking begins initially. Delamination occurs at lower stress as a result of matrix crack propagation.

Unidirectional composite materials are linear-elastic systems. Thus, stress-strain curves of these systems only contain elastic region and failure occurs before yielding. However, as shown in Figure 4.3, stress-strain curve of unidirectional glass fiber epoxy composite contains plastic region and yield point. The reason of this case is that glass fabric utilized to manufacture Plate 1 contains a small amount of fiber at 90^{o} direction although it's described as unidirectional. In this case, matrix micro-cracking begins as well yet fibers at 90^{o} direction inhibit matrix crack propagation. As a result of this circumstances, Plate A shows plastic behavior and higher tensile strength and modulus than expected at 90^{o} direction.

Mechanical properties of biaxial composite plates were assumed as same at both at 0^{o} and 90^{o} direction. Tensile strenght values of each biaxial plates were not found in wide range as shown in Figure 4.9 by contrast with unidirectional plates. Plate 5 which is [0^o/90^o] biaxial glass/carbon hybrid fiber reinforced epoxy has the highest tensile stregth unexpectedly. Two possible case can be considered. (a) fiber-resin interface was not tough enough due to poor fiber sizing coat, so fibers could not be wetted by resin sufficiently, (b) fiber volume fraction of Plate 4 was lower with compared to Plate 5. However, stiffnes value of three biaxial plates; Plate2, Plate 4 and Plate 5, are 30569.88 MPa, 46440 MPa and 40282 MPa respectively. Among three biaxial composite plates, [0^o/90^o] biaxial carbon fiber reinforced epoxy has highest stiffness value as expected. Biaxial composites have lower mechanical properties with compared to unidirectional composite plates at longitudinal direction. On the other hand, they are isotropic materials at longitudinal and transverse direction, so have higher mechanical performance at transverse direction with compared to unidirectional plates.

The dominant loading on the leaf spring is vertical load as indicated in Chapter 2. Vertical loads generate tensile stress on longitudinal direction of leaf spring. Thus, leaf springs should have high strength at longitudinal direction. Test results illustrate that unidirectional composites are convenient materials for leaf springs due to their high strength at longitudinal direction.

Strain energy capability is the main parameter to select material for leaf spring applications as aforementioned in Chapter 2. Strain energies that were absorbed in axial direction by each plates were given in Table 4.12.

Table 4.12. Amount of strain energies that were absorbed by composite plates

Number of Plate	**Amount of strain energy absorbed by comp. plate (MPa)**
Plate 1	6.6075
Plate 2	3.0895
Plate 3	4.5835
Plate 4	2.1865
Plate 5	2.6765

As shown in Table 4.12, unidirectional glass fiber reinforced epoxy has the highest strain energy capability in longitudinal direction among five plates observed in this study. Therefore, unidirectional glass fiber reinforced epoxy was considered as the most suitable material for leaf spring application with respect to its high strength and low tensile modulus at longitudinal direction.

4.1.4. Flexural Properties

Flexural properties of composite plates were determined by 3 point bending test and bending stress-bending strain curves were given in Figure 4.11 to 4.15. Obtained stress, strain and modulus values were given in Table 4.13 to 4.17.

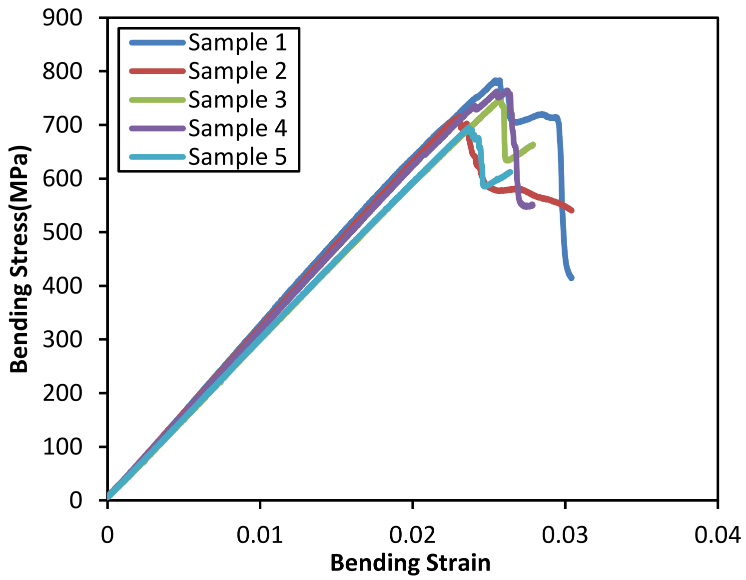

Figure 4.11. Bending stress-strain curves of specimens from Plate 1

Table 4.13. Flexural properties of Plate 1

Sample No	Bending Stress (MPa)	Bending Modulus (MPa)	Bending Strain (%)
1	783.367	30840.7	2.54
2	718.269	30229.0	2.31
3	781.624	29603.3	2.58
4	784.913	30636.3	2.62
5	719.990	29581.4	2.36
Average	**757.633**	**30178.1**	**2.48**
Std. Dev.	**35.17**	**578.36**	**0.14**

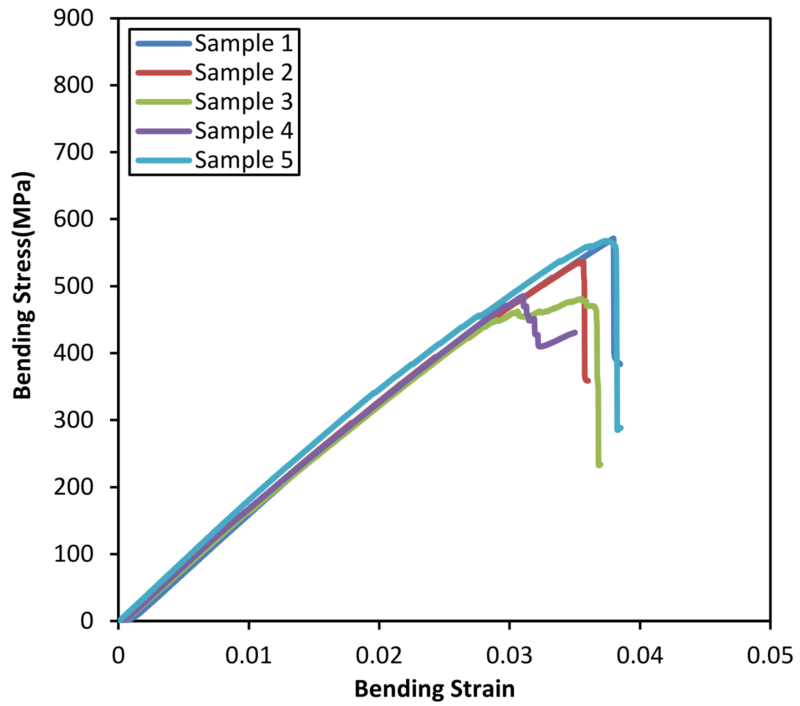

Figure 4.12. Bending stress-strain curves of specimens from Plate 2

Table 4.14. Flexural properties of Plate 2

Sample No	Bending Stress (MPa)	Bending Modulus (MPa)	Bending Strain (%)
1	571.27	17784	3.72
2	536.71	17545	3.56
3	480.71	17402	3.54
4	485.23	17954	3.10
5	567.48	18290	3.74
Average	**528.28**	**17795**	**3.53**
Std. Dev.	**43.51**	**349.06**	**0.26**

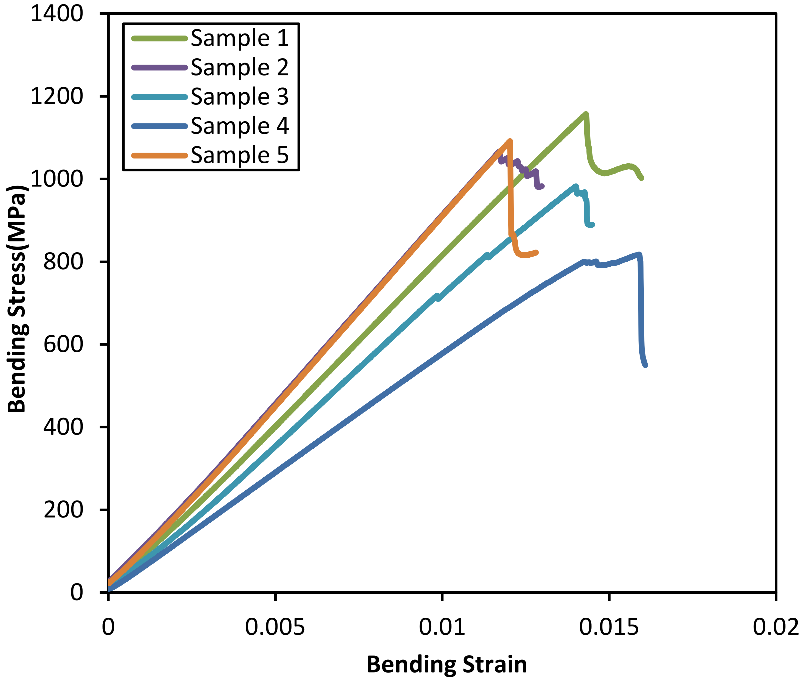

Figure 4.13. Bending stress-strain curves of specimens from Plate 3

Table 4.15. Flexural properties of Plate 3

Sample No	Bending Stress (MPa)	Bending Modulus (MPa)	Bending Strain (%)
1	1157.2	80546	1.43
2	1067.1	88855	1.17
3	982.5	72252	1.39
4	814.9	52196	1.58
5	1091.9	90758	1.21
Average	**1023.22**	**80462.4**	**1.36**
Std. Dev.	**131.95**	**15653.66**	**0.168**

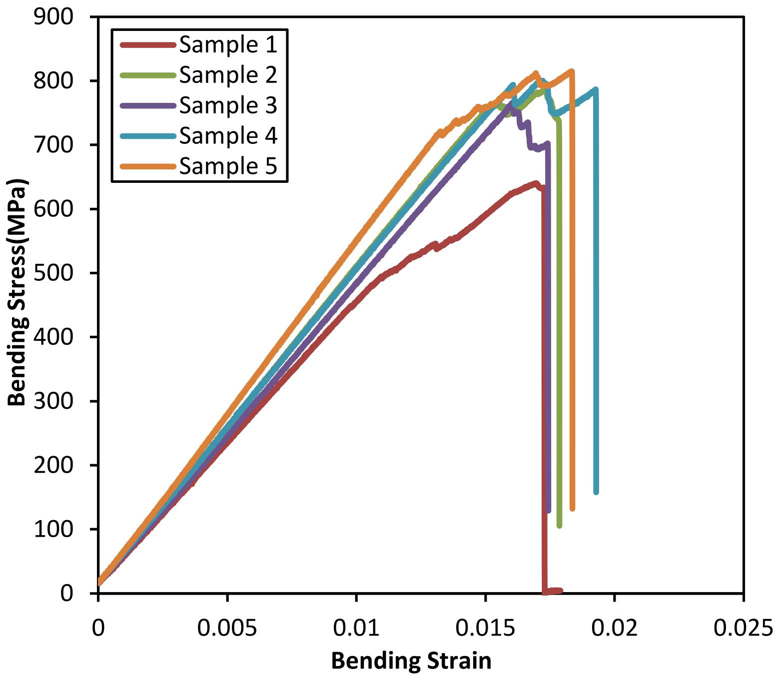

Figure 4.14. Bending stress-strain curves of specimens from Plate 4

Table 4.16. Flexural properties of Plate 4

Sample No	Bending Stress (MPa)	Bending Modulus (MPa)	Bending Strain (%)
1	640.0	40281	1.74
2	618.2	33871	1.70
3	697.2	40206	1.61
4	673.3	37003	1.70
5	603.4	33615	1.83
Average	**646.4**	**36995**	**1.72**
Std. Dev.	**38.69**	**3251.62**	**0.079**

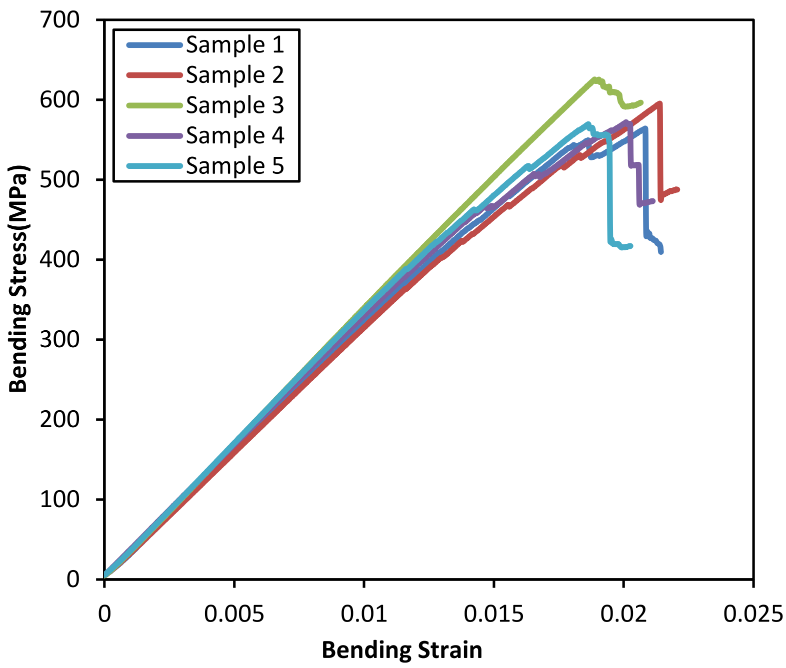

Figure 4.15. Bending stress-strain curves of specimens from Plate 5

Table 4.17. Flexural properties of Plate 5

Sample No	Bending Stress (MPa)	Bending Modulus (MPa)	Bending Strain (%)
1	546.2	31585	2.08
2	595.4	31236	2.13
3	625.5	33397	1.88
4	571.9	32957	2.01
5	569.6	33263	1.86
Average	**585.3**	**32487**	**1.99**
Std. Dev.	**30.037**	**1003.71**	**0.1194**

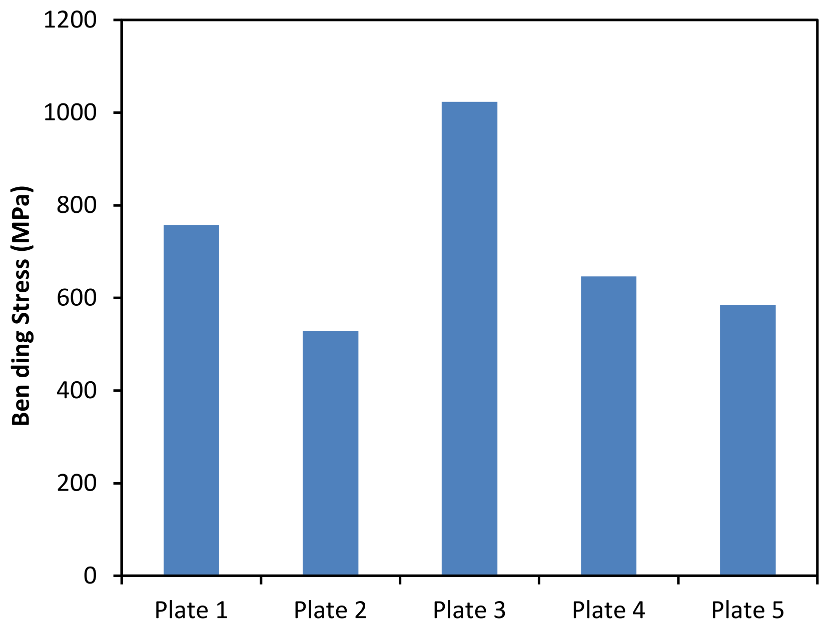

Figure 4.16. Graph of bending stress values of all composite plates

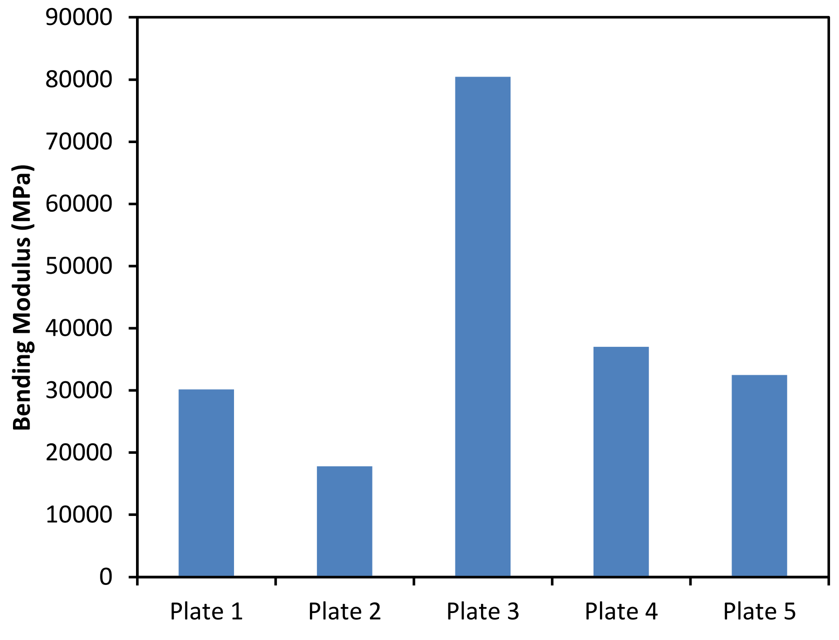

Figure 4.17. Graph of bending modulus values of all composite plates

3 point bending test results are similar with tensile test results. Unidirectional plates (Plate 1 and Plate 3) have maximum bending strenght, as tensile loads are generated along longitudinal direction of material when the specimen are loaded by an external bending load. As shown in Figure 4.17, bending modulus of Plate 3 is much more higher than Plate 1. Modulus effects the rigidity of plates. Rigid bodies are

undesired structures for spring applications because higher modulus restricts the spring deflection. Therefore, energy capability of spring decreases with higher modulus.

Among biaxial plates, Plate 4, carbon reinforced, has both the highest bending strength and bending modulus as expected.

4.2. Test Results of Composite Leaf Spring

4.2.1. Rig Test Results

Manufactured composite leaf springs are characterized by rig test. Load was applied in 9 steps from 0 kgf to 1630 kgf. Deflection and strain gauge values were recorded by each step. Figure 4.18 illustrates load-deflection curves of each leaf springs.

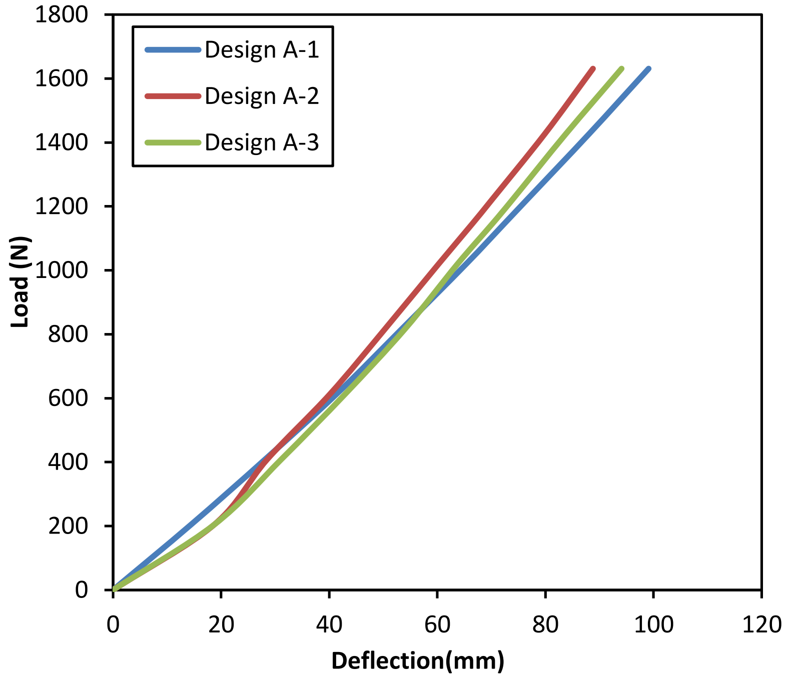

Figure 4.18. Load-deflection curve of leaf springs

Load-deflection curves of leaf springs are linear as shown in Figure 4.18. It was aimed to obtain 89.9 mm deflection for 1630 kgf load. Deflection of Design A-1 was measured as 99.1 mm under 1630 kgf loading. This deflection value means that leaf spring designed based on Design A-1 is more flexible than desired. In order to enhance the rigidity of leaf spring, Design A-2 and Design A-3 were developed with carbon and hybrid fiber addition. Test results demonstrate that deflectiom of leaf spring under 1630 kgf load is 88.8 mm for Design A-2 which contains 4 layers of carbon fiber, and 94.1 mm for Design A-3 which contains 4 layers of hybrid fiber. Among three desings, Desing A-2 has the closest deflection value to aimed value, 89.9 mm.

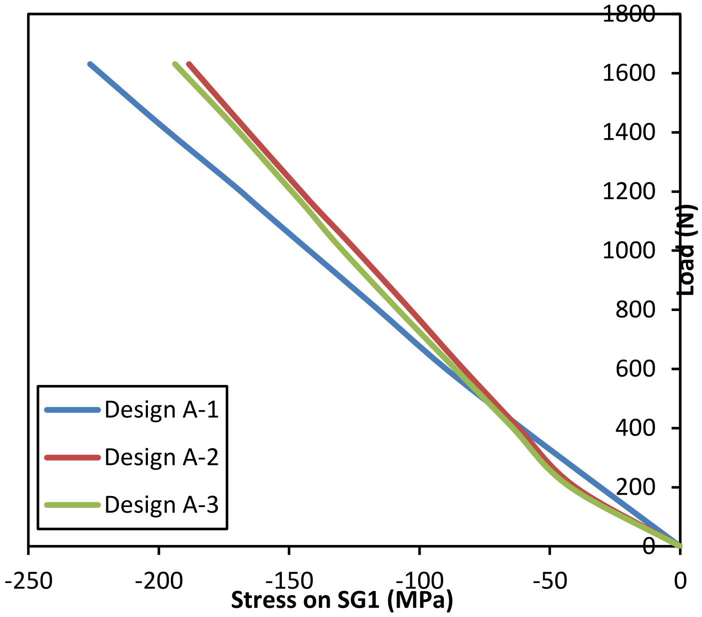

Figure 4.19. Load-SG1 curves of leaf springs

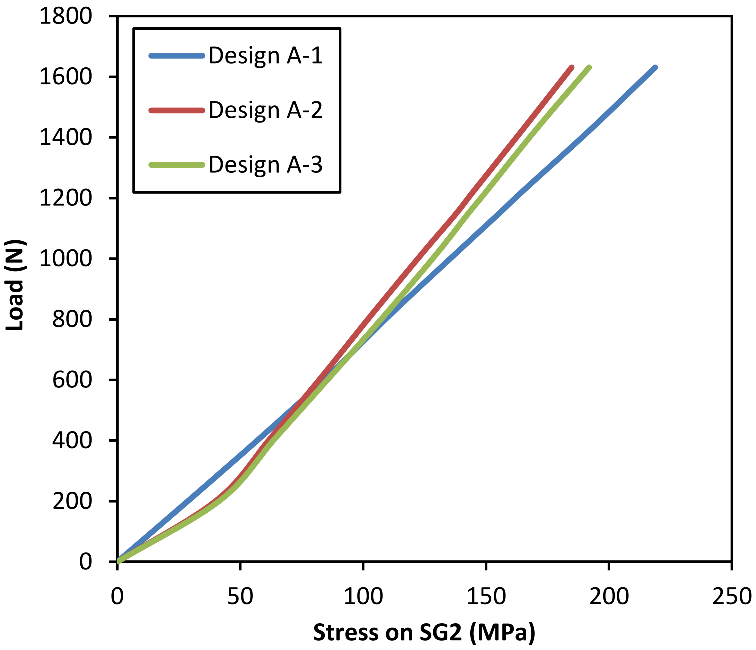

Figure 4.20. Load-SG2 curves of leaf springs

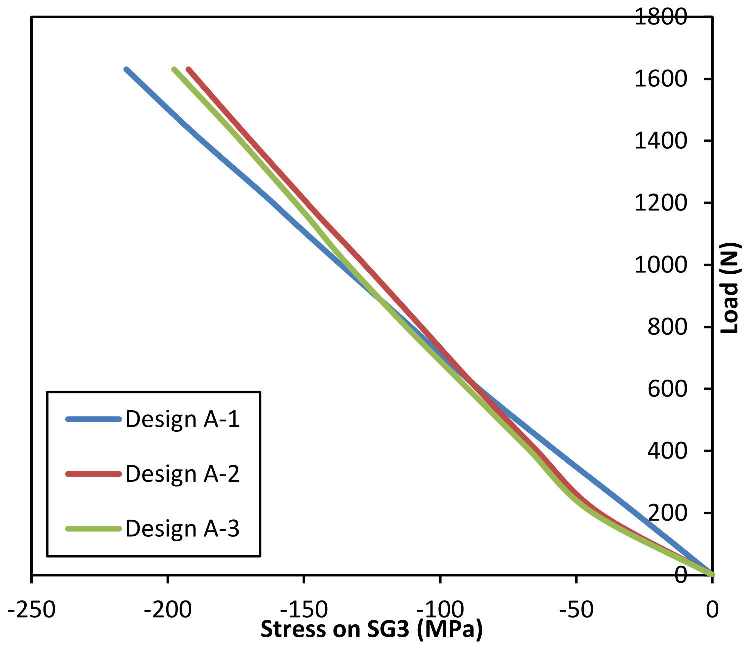

Figure 4.21. Load-SG3 curves of leaf springs

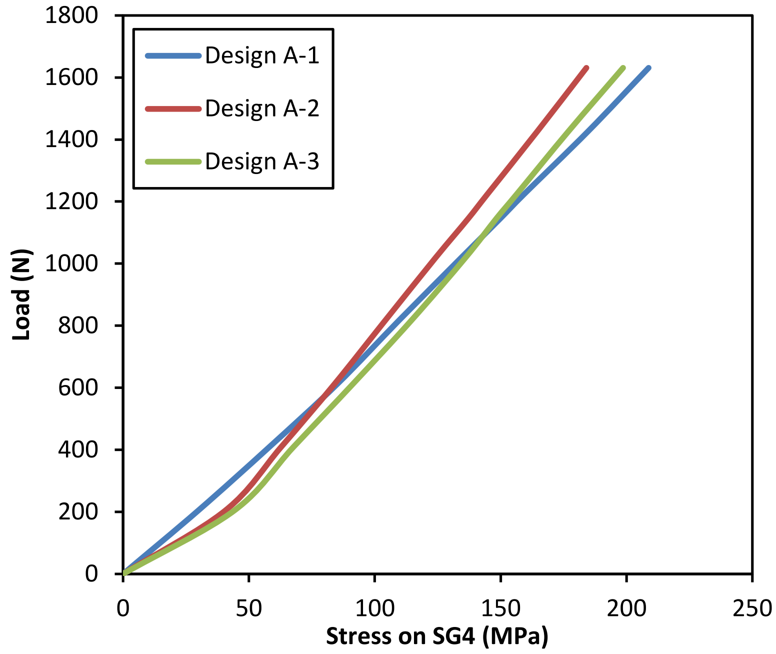

Figure 4.22. Load-SG4 curves of leaf springs

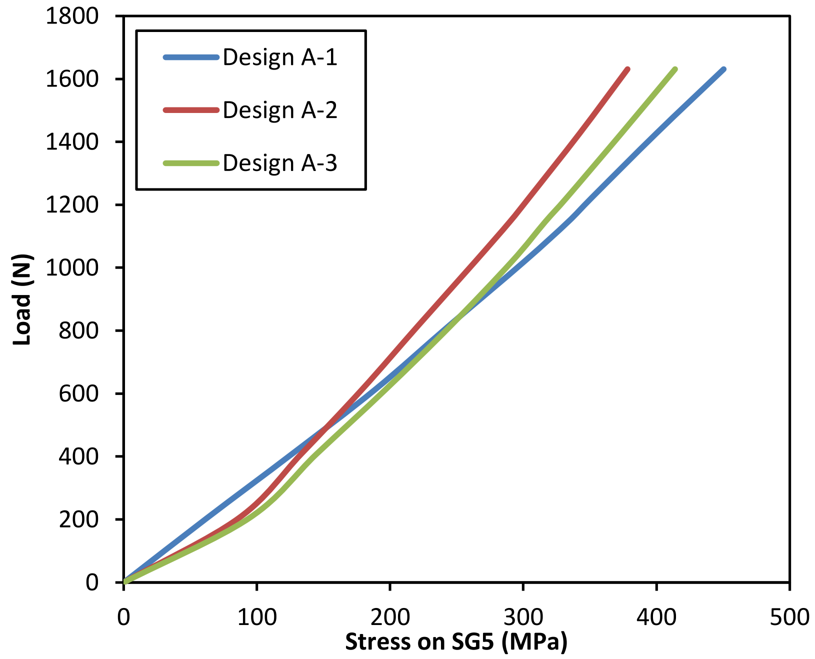

Figure 4.23. Load-SG5 curves of leaf springs

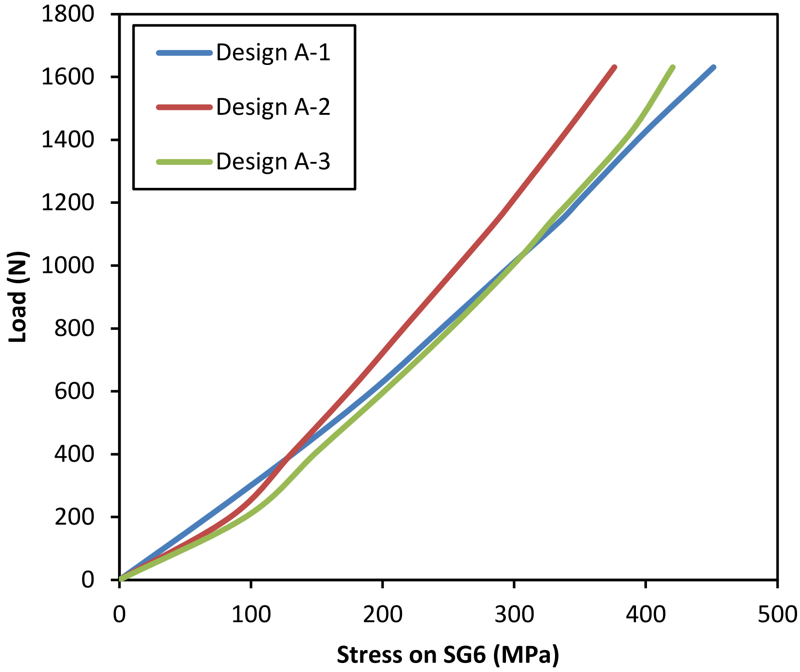

Figure 4. 24. Load-SG6 curves of leaf springs

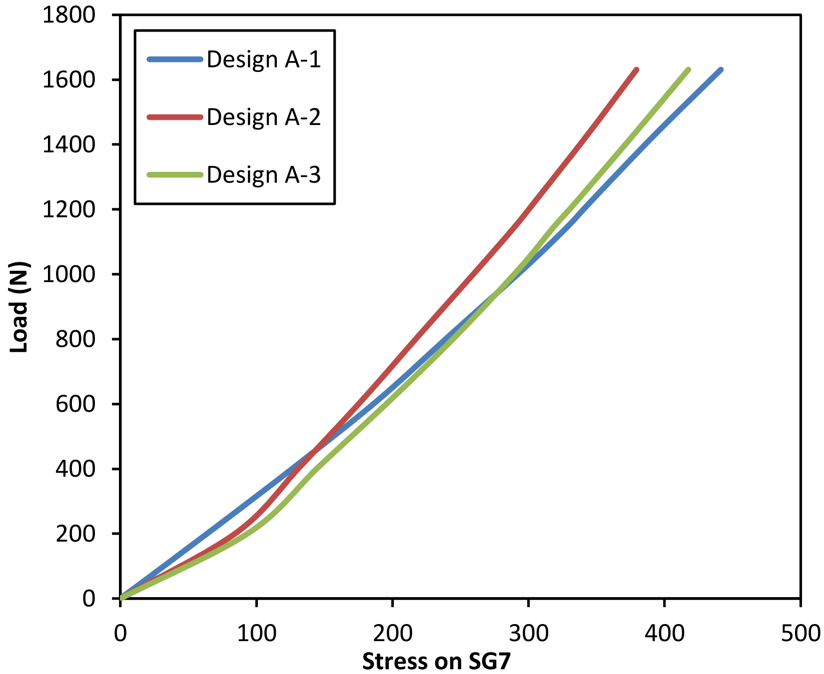

Figure 4.25. Load-SG7 curves of leaf springs

Seven strain gauges attached to leaf springs. Position of strain gauges were given in Section 3. Data acquisition device (DAQ) is utilized to collect data form each strain gauge in each load step. Computer program which conducted to DAQ converted strain data to stress values. Figure 4.19 to 4.20 demonstrates stress values on the surface where strain gauges were attached by the force of external load.

As shown in Figure 4.19 to 4.25, compressive forces were generated at the upper surface of the leaf spring whereas tensile forces were generated at the bottom surface of leaf spring. Maximum stress was generated at the center of the spring for all designs. The stress on SG6 in Design A-1 was the highest stress values that measured, 451.46 MPa. As compared to determined tensile strength of Plate 1, 689 MPa, maximum stress that generated on leaf spring is lower. Among three designs, the lowest stress was generated on surface of Design A-2 due to higher stiffness of this spring as compared to the others.

Moreover, weight of springs that manufactured in this thesis were measured. Weigth of leaf spring was designed based on Design A-1, Design A-2 and Design A-3 were measured as 5182 gr, 5190 gr and 5324 gr respectively. An equivalent steel leaf spring in this geometry is nearly 25000 gr. Weigth of leaf spring was designed based on Design B was measured as 18592 gr whereas weight of an equivalent steel leaf sprinf is nearly 100000 gr. Thus, a significant weigth reduction was gained for both leaf spring prototype.

CHAPTER 5

CONCLUSION

In this study, composite leaf spring prototypes were manufactured successfully based on two geometrical design via resin transfer molding process. Composite leaf springs were characterized by mechanical rig test. Moreover, various type of composite plates with different fabric configurations were manufactured via RTM process to determine the mechanical and themo-mechanical behaviour of composite structures considered in the leaf spring designs.

Flexural properties, tensile properties, glass transition temperature and fiber volume fraction of composite were determined within the study. Test results illustrates that both tensile and flexural strength of unidirectional composite structures are higher than biaxial composite structures along longitudinal direction. Among unidirectional composites, carbon fiber reinforced structures have higher tensile and flexural strength as compared to glass fiber reinforced composites. Moreover, unidirectional carbon fiber reinforced composite also exhibited higher modulus than those for glass fiber reinforced composites. It was observed that the carbon fiber reinforced composites are very rigid structures, and therefore their strain energy storage capabilities are insuffiecient for spring applications. Biaxial composite structures do not show appropriate mechanical properties along longitudinal direction. However, they exhibit higher mechanical performance at transverse direction as compared to unidirectional structures.

Materials that have low density, high strength, and low modulus and in longitudinal direction are convenient systems for spring applications. Test results illustrated that unidirectional glass fiber reinforced composites are the most suitable material for spring applications.

Three different types of composite leaf spring prototypes with various fiber configuration were manufactured based on the first geometrical design. It was found that stiffness of the leaf spring prototypes varies depend on fabric configuration. Stiffness of the leaf spring that contains merely glass fibers was found as lower than the desired value. Addition of carbon or glass/carbon hybrid fabric to the structure enhanced the stiffness of leaf spring. It was investigated that Design A-2 which contains

56 layers of glass fabric and 4 layers of carbon fabrics has the closest stiffness feature to desired value. Besides these, stress that generated on the surface of the leaf spring due to an external load depends on stiffness of the leaf spring. It was observed that, generated stress due to an external load is lower in surface of stiffer leaf springs.

Moreover, it was found that composite leaf springs developed within this study are 80% lighter than a conventional steel leaf spring for both geometrical design.

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