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Natural Silkworm Silk-Epoxy Resin Composite for High Performance Application

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1. Introduction

Synthetic (man-made) fibres are important reinforcement materials in modern composites for high performance applications primarily due to their high specific strength and high specific modulus. However, the environmental unfriendly production method of synthetic fibres is an area of concern. Amid the growing global awareness and push for environmentally friendly products, the need to seek viable alternatives materials for synthetic fibres has been rising. As such, natural animal-based fibres are looked into as potential candidates. Modification of natural fibres to rival the mechanical performance of synthetic fibres has been looked into by many research. In this chapter, we will also explore the use of a low cost method to enhance the mechanical properties of silkworm silk during the sericulture stage. In addition, the feasibility to fabricate natural silkworm silk-epoxy composite will be evaluated.

2. Synthetic fibres as reinforcements in composites for high performance applications

The development of composites accelerated in mid 20th century, where the occurrences of the World Wars and Cold War rapidly pushed for the development of synthetic fibres like fibreglass, carbon fibres, boron fibres and aramid fibres, as countries vied for aerospace dominance. Since then, high performance industries including aerospace, automobile, protective gear and sports equipments are the major users of synthetic fibres. Fibre-reinforced composites have also found their way into consumer items like bicycles and golf clubs. This has empowered cyclists to cycle faster and golfers to swing further with less effort than before. However, the manufacturing process of common synthetic fibres like aramid and carbon creates environmental problems. Synthesis of aramid fibres utilise petroleum-based precursors with hot, concentrated sulphuric acid as solvent, while the synthesis of carbon fibres also require petroleum-based precursors and a series of high temperatures processing steps. Moreover, due to rising costs of energy, transportation, and raw materials, production costs of synthetic fibres have increased.

3. Natural fibres as an alternative

To tackle this imminent problem, the development and use of "greener" natural alternatives is gaining momentum to replace synthetic fibres in composite fabrication. Currently, the

Germans used a total of 30,000 tonnes of natural fibre reinforced polymers in their automotive industry in 2005. (Karus et al., 2006, as cited in Mussig, 2010). The use of natural fibres in composites is nothing new to human. Evidence of natural fibre reinforced composites could be found in pottery containing hemp fibre which dated back to as early as 10 000BC. (Rowell, 2008, as cited in Mussig, 2010).

3.1 Different types of natural fibres

Natural fibres can be categorised into plant fibres and animal fibres. Plant fibres include flax, hemp, jute, abaca, sisal, coir and cotton. Animal fibres include silk and wool. Numerous silk spinning animals like caterpillars, silkworms and spiders exist in nature, but spider silk is the strongest of them all. Silk is spun by animals for various reasons, but most of which are for the strength that their silk provides. Silkworm spins silk for protection of the larvae during pupation, while spider spins silk for shelter, protection of young spiders and trapping of prey. The high tensile strength of spider silk rivals that of high grade steel and aramid fibres such as Kevlar. Spider silk is also lighter than steel and elongates more than aramid. Thus spider silk seems to be the perfect candidate to replace synthetic fibres. However, the carnivorous and cannibalistic nature of spider makes harvesting of its silk difficult to be implemented on a large scale. Since *Bombyx Mori* silkworm silk also possesses a high tensile strength after spider silk, silk harvesting from this highly domesticated silkworm is an easier alternative. The mechanical properties of some common natural and synthetic fibres are shown below. (Table 1).

Types of Fibre	Material	Density (g/cm3)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Failure (%)
Natural Fibres	Spider Silk	1.3	1300-2000	30	19-30
	Enhanced *B.Mori* Silk	1.3-1.38	600-700	12.2	30-35
	B. Mori Silk	1.3-1.38	500	8.5-8.6	15
	Flax	1.45	500-900	50-70	1.5-4.0
	Hemp	1.48	350-800	30-60	1.6-4.0
Synthetic Fibres	Kevlar 49	1.44	3600-4100	130	2.8
	Carbon	1.4	4000	235	2
	E-glass	2.5	3100-3800	76-79	4.8
	Dyneema	0.97	2300-3500	550	2.7-4.5
	High Grade Steel	7.8	1000	200	30

Table 1. Mechanical Properties of Common Natural and Synthetic Fibres.

4. Silkworm silk and its enhancement during sericulture

Different species of silkworms exist in nature that can be reared for their silk. These include *Bombyx Mori*, *Antheraea Mylitta*, *Philosamia Synthia Ricini* and Antheraea Assamensis. The domesticated *Bombyx Mori* silkworm, which feeds only on mulberry leaves, is easier to rear as compared to the other wild species. Being a natural biodegradable material, *Bombyx Mori* silkworm silk fibers generate no toxic waste in production and are cheaper to produce than synthetic fibres. This makes them a very attractive alternative to synthetic fibres. Although it may not be comparable in strength, *Bombyx Mori* silkworm silk has the advantage of being more ductile than synthetic fibres. As such, it may still be used in applications which is less stringent on tensile strength but require higher elongation.

4.1 Characteristics of silkworm

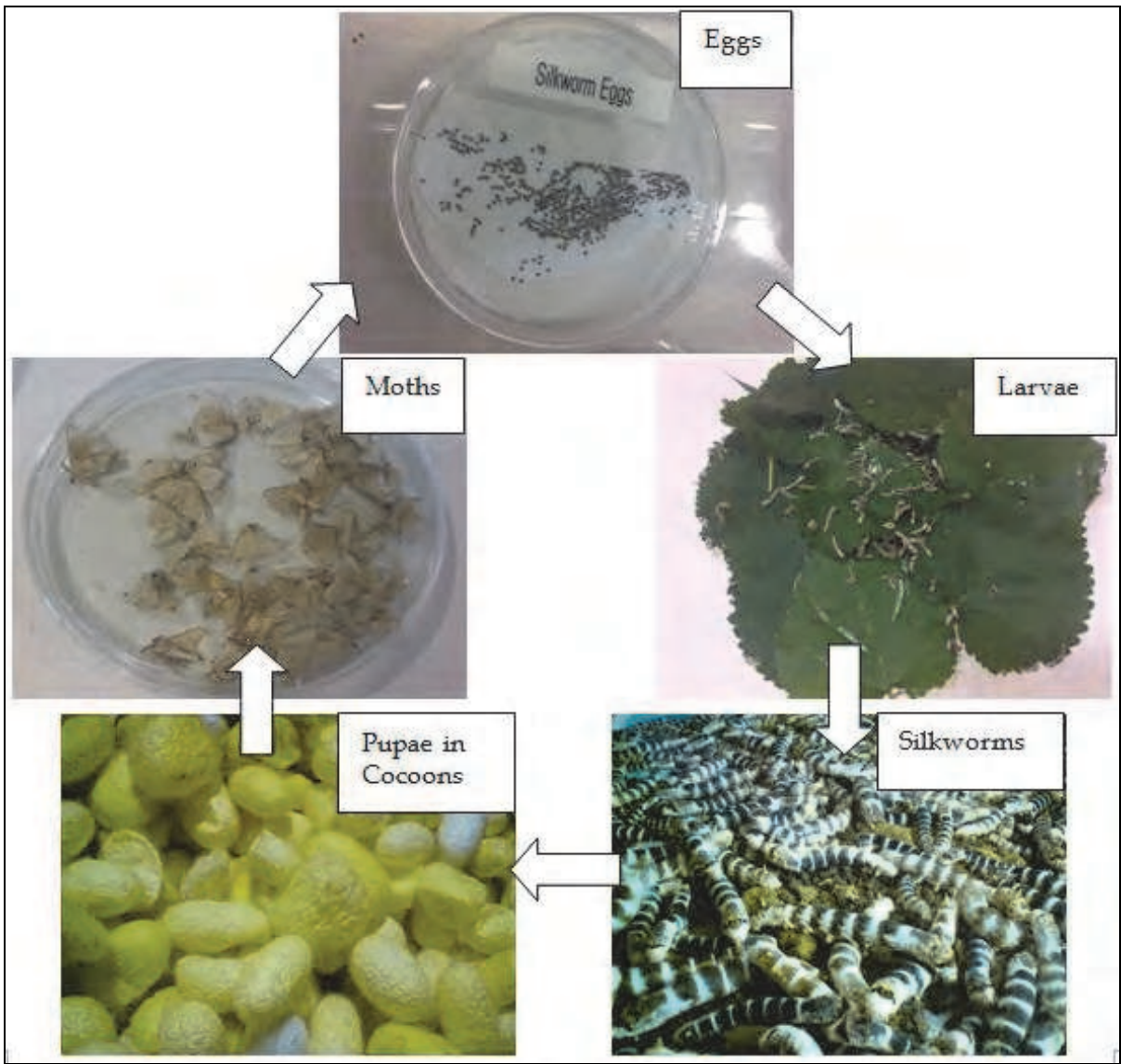The life cycle of *Bombyx Mori* silkworm is as below. (Fig. 1).

Fig. 1. Life Cycle of *Bombyx Mori* Silkworm

After hatching from the eggs, *Bombyx Mori* silkworm larvae will undergo a total of four rounds of moulting before they start to spin silk to form cocoons. On cocooning for a couple of days, the pupae are then stifled by heat to prevent them from emerging out of their cocoons, so that the silk can be reeled into yarns, and woven into fabric.

The structure of Bombyx Mori silk consists of two main chains of fibroins protein made up of parallel bundles of nanofibrils. Fibroin is coated with the gummy sericin protein. The chemical composition of fibroin consists of the amino acids glycine, alanine and serine present in the form of beta sheets. High tensile strength of silkworm silk is attributed to two main reasons. Firstly, the large amount of small sized glycine molecule produces a tightly and efficiently packed structure. Secondly, the extensive network of strong hydrogen bonds within the fibroins chains renders the silk fibres high strength and elongation. The gummy sericin is responsible for conferring the properties of anti-oxidation, antibacterial, UV resistance and hydrophilicity (Zhang *et al.*, 2002, as cited in Hakimi, 2006).

4.2 Enhancement of silkworm silk

Silkworm silk is inferior in mechanical properties as compared to spider silk. Numerous methods have been attempted to enhance the mechanical properties of silkworm silk including force silking and most recently, genetic modification. Artificial spider silk produced by transgenic silkworms was claimed to achieve similar mechanical properties to that of the original spider silk. As for force silking of *Bombyx Mori* silkworm, an enhanced tensile strength of 650 MPa was reportedly obtained at an optimum silking speed of 240 cm min^{-1}. The enhanced tensile strength was attributed to a greater conformation of the beta sheet molecular structure and a smaller silk diameter obtained by the accelerated silking speed (Morikawa et al., 2008). However, these two methods have yet to achieve large-scale commercial feasibility due to high cost of genetic modification and difficulty in obtaining large length of silk from force silking.

Another method of potential commercial viability is to enhance the mechanical properties of silkworm silk with a low cost and easily implemented technique. This method subjects the *Bombyx Mori* silkworm to electric field stimulation when the adult silkworm starts to spin silk to form a cocoon. The resultant silk fibre reportedly gained a 40% in tensile strength (682 MPa), 100% in breaking strain (34.4%) and 200% in breaking energy (124kJ/kg) as compared to the ordinary silkworm silk. In addition, optical light stimulation was also reported to have a slight improvement on the mechanical properties of the silk fibre. Analysis of the enhanced silkworm silk fibre found that it possessed greater crystallite alignment than an untreated silkworm (Liu & Du, 2008).

As this method is an environmentally friendly solution to enhancing the mechanical properties of silkworm silk without the need of expensive and sophisticated machines, it presents a viable alternative material to replace synthetic fibers in composites where high breaking strain and breaking energy are more important. This will be especially appropriate for ballistic applications where the high breaking energy of fabrics is needed to absorb the high projectile energy.

5. Optimization of yarn and weaving parameters for enhanced silk

Likewise for synthetic fibres, silkworm silk can be processed into yarns and weaved into fabrics. The mechanical properties of *Bombyx Mori* silkworm silk, as a potential replacement for synthetic fibres in composite, can be possibly further enhanced by optimization of the

yarn and weaving parameters for its specific application. Research on the optimization of silk for incorporation into composites may not be as extensive as that conducted for synthetic fibres like Kevlar and carbon, however the results can potentially be adapted and used on silk material too.

5.1 Optimization of yarn parameters

Tensile strength, one of the most important mechanical properties of yarn for high performance applications, is influenced by many parameters including yarn diameter, degree of twisting and yarn irregularities. Tensile properties of silk yarn can be determined by ASTM D2256 (Standard Test Method for Tensile Properties of Yarns by the Single-Strand Method).

Commercial reeled silk yarn is normally available in the sizes 20/22 Denier or 40/44 Denier which consist of 10 and 20 silk filaments respectively. Doubling to increase the number of filaments of silk is used to increase the yarn diameter and minimise irregularities inherent in the length of a single ply of silk yarn. Furthermore, a thin silk yarn is too weak to withstand the stress present in the fabric weaving process. An increase in yarn diameter usually results in higher average strength of the yarn, as irregularities along the length are averaged out.

Twisting of two or more single silk yarns, by introducing spiral turns to hold them together to form plied yarns by interfacial contact, is an important step in a yarn configuration Thinner yarns require more twist than thicker yarns. In general, the maximum tensile strength and strain of yarns tends to increase with the increase in twist factor. However in some cases, an optimum value will be reached after which there will be a drop in mechanical properties.

In a woven fabric, the warp yarns that make up the length of a fabric require more twist than the weft yarns that make up the width of a fabric. The higher degree of twist in the warp yarns allow them to withstand the tension imposed on them by the weaving machine. Some high twist yarns might tend to unravel when left free. In order to minimise untwisting of these high twist yarns, the yarns may be conditioned at high temperature and moisture to heat set the twist incorporated into the yarns. Excessive twisting of yarns might not be desirable for woven fabric, as shrinkage in yarn and fabric after weaving produces an unbalanced fabric with localised stress concentration.

The direction of twist is also important in producing a balanced fabric. Twist direction present in a yarn may be either of a S or Z spiral. This does not influence the strength of the yarn, but is crucial in providing a balanced yarn structure to prevent kinking of the yarn and fabric.

In particular for protective woven fabrics used in ballistic applications, ballistic resistance is dependent on friction, modulus and tensile strength of yarns. Yarns with high modulus and tensile strength are the main influences for better ballistic performance. Friction between yarns served to maintain the integrity of weaved fabrics (Keefe, 2009). Typically, ballistic fabrics are constructed from low-twist, low crimp yarns, often with equal thread densities in the warp and weft (Cork, 2005).

5.2 Optimization of weaving parameters

In addition to yarn parameters playing an important role to the overall composite mechanical properties, fabric weave structure is also as important. Weaving patterns represents the interlocking arrangement of warp yarns and weft yarns. In the optimization of fabric stability, crimp, drapeability and mechanical performance of the fabrics, weaving

patterns must be looked into. Tensile properties of differently woven silk fabric can be determined by ASTM D5035 (Standard Test Method for Breaking Force and Elongation of Textile Fabrics (Strip Method).

Plain weaving pattern is typically used for weaving reinforcement fabrics due to its balanced structure. However, the low drapeability of plain weave will require basket, twill, satin weave when conformance to special geometry is required.

Stitching is another commonly used method to improve mechanical properties of weaved fabrics. When multiple layers of weaved fabrics are incorporated into composites, the through thickness properties are weak. Stitching of multiple layers of woven fabrics together can improve the interlaminar fracture toughness. Plain woven Kevlar fabrics-rubber composite were demonstrated to have higher ballistic performance than that of unstitched fabrics, due to diamond stitching of the Kevlar fabrics, (Ahmad, 2007).

6. Fabrication of natural silkworm silk fabric-epoxy resin composite

The feasibility to fabricate natural silkworm silk fabric-epoxy composite will be explored in this section. Wet layup method will be used to create silk-epoxy composite. Compaction of the composite will be done via the hot press method with vacuum bagging to increase the volume percentage of reinforcement in the composite and lower the void content. Mechanical testing of the composite will thereafter be performed to analyze and evaluate the experimental results.

In theory, 61% reinforcement by weight is considered to be the optimum ratio for standard composites. There are several predicted issues with the fabrication of silk-epoxy composites for actual commercial purposes, such as delamination, adhesion problems of epoxy with silk, selection of epoxy to used, fracture analysis, design of the composite, and design of the silk. In this section of our study, we will aim to explore some of these issues and improve them in future works.

6.1 Analysis of silk fabric

A typical un-dyed silkworm silk woven fabric was obtained from China. No alteration to the silkworm sericulture or silking process was done. A small sample of the silk fabric was analyzed under the scanning electron microscope (SEM). Analysis of the fabric at 100X magnification revealed that it was of a satin weave with 10 untwisted warp yarns interlocked with 10 twisted weft yarns. (Fig.2).
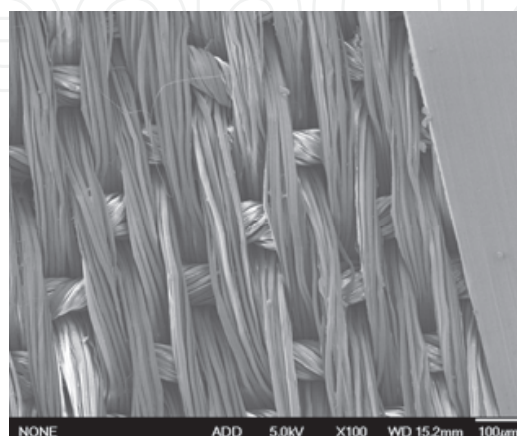

Fig. 2. SEM Analysis of Woven Silk Fabric.

Satin weave possesses the advantages of good drape, low porosity, low crimp, but brings along the negativity of poor stability, balance and symmetry.

6.2 Wet-layup of composite

Composite fabrication involved wet-layup of the silk fabrics with epoxy. The silk fabric serves as the continuous reinforcement phase while the epoxy is the matrix that binds with the reinforcement to form the composite together. Epoxy is chosen as the matrix due to its high structural strength.

The two component epoxy system consists of a resin and a hardener. The resin contains epoxide functional group, formed from the reaction between epichlorohydrin and bisphenol-A. The hardener contains polyamine monomers with amine functional groups. After mixing the resin and hardener according to the ratio of 10:6, the amine groups will react with the epoxide groups to form covalent bonds, resulting in a strongly cross linked polymer. Curing can be fine-tuned through temperature adjustments, mixing ratios and selection of resin and hardener. The selected viscosity of this epoxy system is one that allows adequate time for the operator to perform wet-layup of multiple pieces of silk fabric.

A square metal mould was first treated with a suitable mould-release agent for easy release of the silk epoxy composite panel from the metal mould after curing. Multiple layers of silk fabric were cut to suit the size of the mould. The hardener component was added to the resin component before use. (Fig.3).

Fig. 3. Mixing of epoxy resin and hardener

Silk fabric and epoxy were alternatively applied onto the metal mould. A metal roller was used to remove air bubbles that were trapped in between the fabric layers and remove excess epoxy from the composite. (Fig. 4).
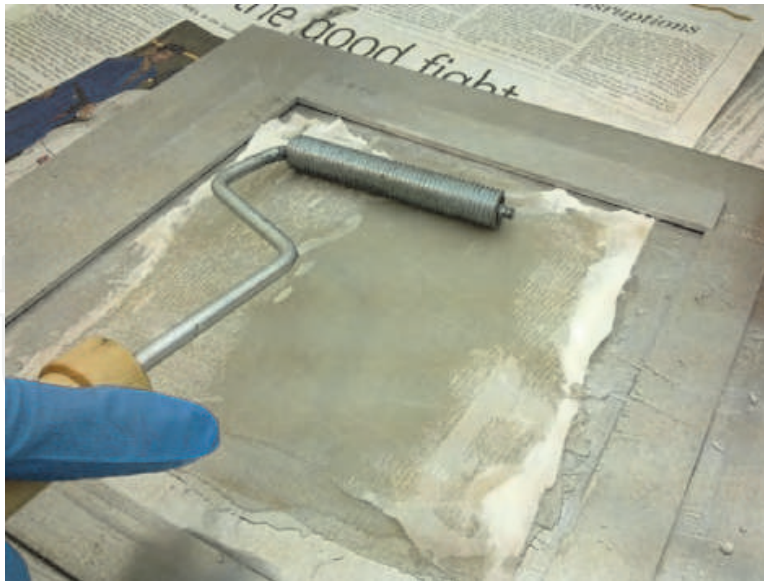
Fig. 4. Wet layup of silk fabric

After the stipulated numbers of layers of silk fabric were laid on the metal mould, another piece of square metal mould treated with mould-release agent was place on top of the composite, before vacuum bagging.

6.3 Vacuum bagging setup

The whole setup was transferred into a vacuum bag consisting of a high temperature vacuum bagging film, breather/bleeder fabric and sealant. The breather/bleeder fabric (glass fiber cloth) is placed at the vacuum port to better allow the air to be sucked out, by providing a small gap between the vacuum bag and composite. It also acts as a filter to prevent the leakage of epoxy to the vacuum pump by absorbing any excess resin that overflows during hot pressing. The sealant serves to seal off the edges of the vacuum bagging film, by maintaining a continuous airtight seal. (Fig. 5).
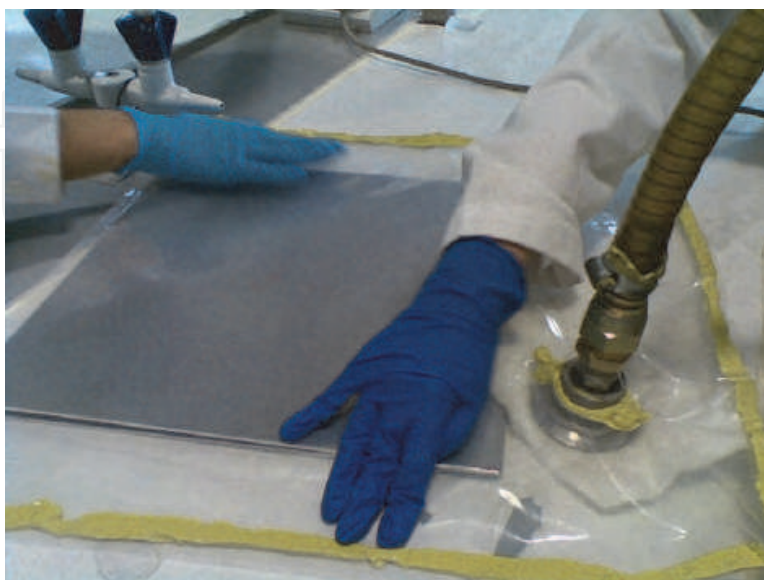

Fig. 5. Vacuum Bagging Setup

Next, the vacuum bag was connected to a vacuum pump via a plastic hose and vacuum port to remove air from within and decrease the occurrences of void and air bubbles inside the silk-epoxy composite. A vacuum pressure of at least 600-800MPa, as indicated by the vacuum gauge was obtained, before the vacuum bag was transferred to the hot press.

6.4 Hot press setup

In the absence of external applied stress on the silk-epoxy composite panel during its curing stage, the compactness of the final cured composite will only be dependent on the atmospheric pressure exerted on its surfaces and the rolling that was used to squeeze out excess epoxy during the wet-layup. In order to increase the volume percentage of silk fibre in the composite, an external applied stress need to be applied onto the composite panel at the curing stage to remove excess epoxy from the composite, while sufficient epoxy remains to bond the silk reinforcement in the composite. The use of hot press allows the application of external pressure and heat to enhance densification, compressing a laminate into a compact shape and squeezing out any excess material. The higher temperature also expedite the curing time of the epoxy system, which will otherwise take at least 24 hours to cure at room temperature.

Both the top and bottom platens of the hot press were set at 60 degrees Celsius. The vacuum bag holding the uncured silk-epoxy composite was placed between the two platens. The two platens were closed and a pressure of 1.38 MPa was applied in between the two platens onto the silk-epoxy composite. (Fig.6).
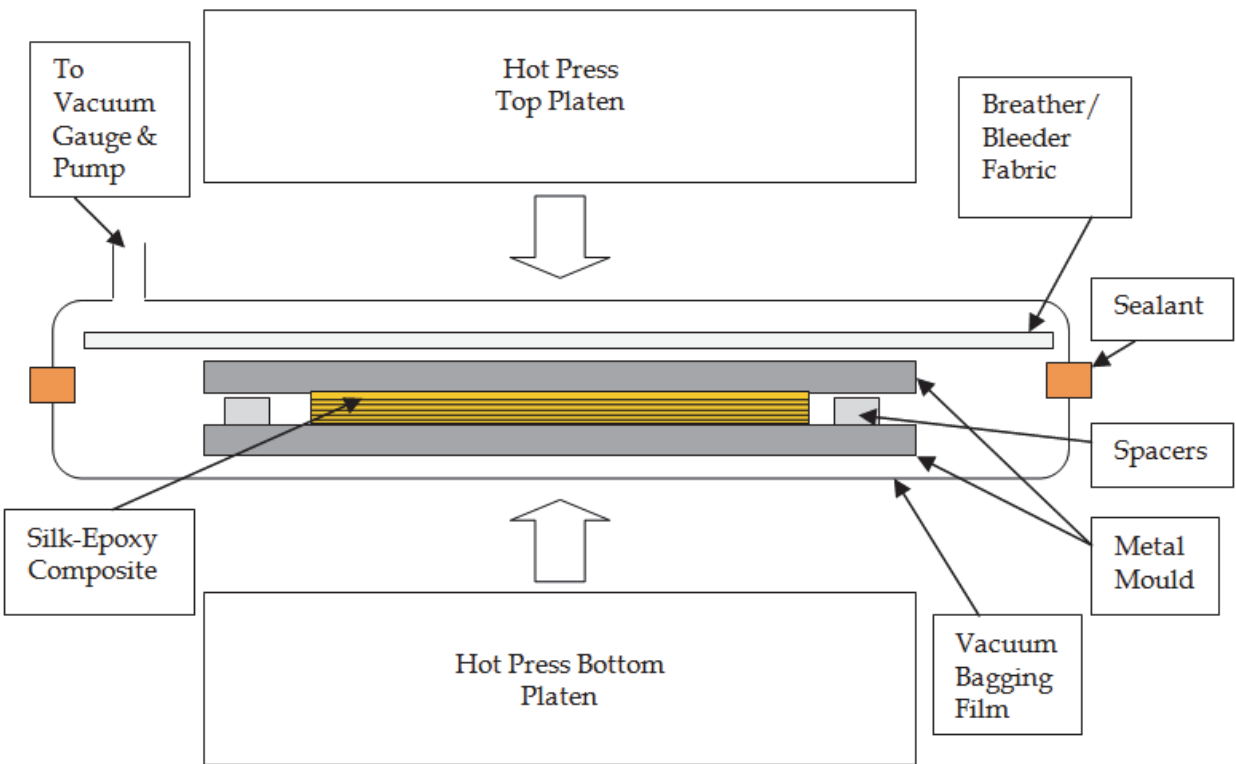
a) Detailed schematics of hot press setup

b) Actual hot press setup

Fig. 6. Hot Press Setup

The setup was left in this condition for 3 hours in accordance with the recommended elevated curing time of the epoxy system. At the end of the 3 hours, the cured composite panel was removed from the mould by gently forcing the pieces apart. The composite panel was left to cool at room temperature for at least 24 hours before any tests were performed on it. (Fig. 7).
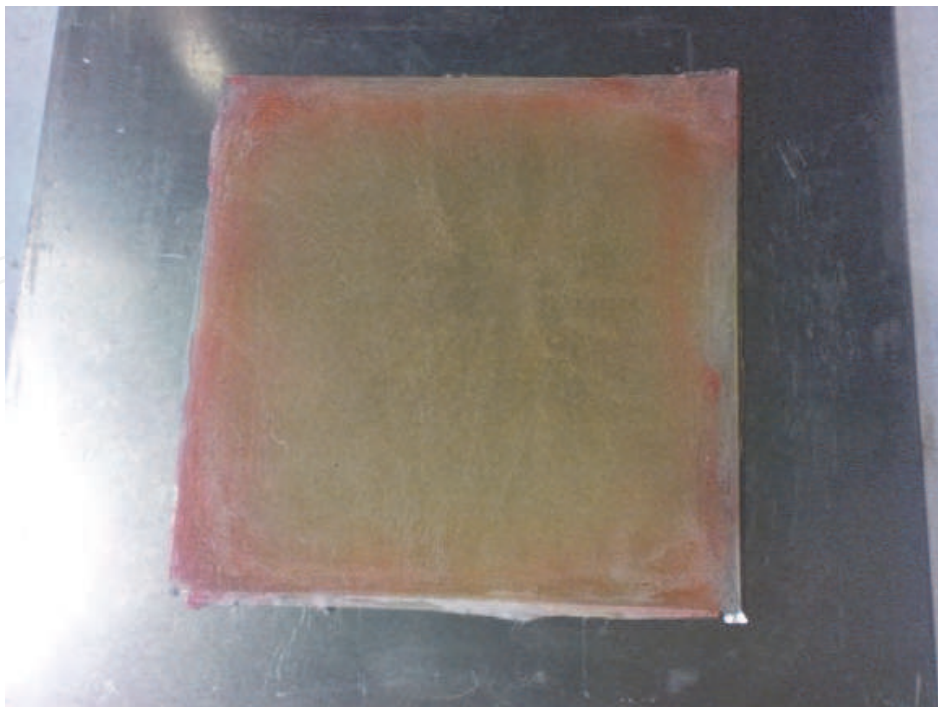

Fig. 7. Completed silk fabric epoxy composite

6.5 Surface treatment of silk

Delamination is most often the crippling cause of failure for fibre-reinforced composites. Good surface interaction of fibres with the matrix in a composite is dependent on the physical and chemical characteristics on the fibres' surface. Silk fabric can possibly be treated with suitable surface coupling agents to minimize interlaminar delamination and make it adhere better to the epoxy before being used to make the composites. The use of silane coupling agents to treat silk fibre was found to increase the interlaminar fracture toughness for woven silk-epoxy composites. (Zulkifli, et. al., 2009). In this section, surface treatment of silk fabric with silane coupling agent will be performed. Mechanical tests on silanated silk-epoxy composites will be conducted thereafter to gauge its effectiveness.

Silane coupling agent was originally developed for glass fibres. Silane coupling agents are usually used to bind organic and inorganic materials together. Resistance to moisture uptake by fibres in wet or dry conditions can also be enhanced by silane treatment. Silane molecule contains a central silicone atom, with organic functional group (R) like amino or epoxy vinyl, and a second functional group (X) like methoxy or ethoxy groups. A coupling effect occurs when the R functional group attaches to an organic substrate while the X functional group attaches to an inorganic substrate. Hydrolysis of the X functional group forms silanol which will react with the inorganic substrate to form a siloxane bond. The R functional group will react with the organic substrate to form a covalent bond. (Fig. 8).

Silquest A-1100 (Gamma-Aminopropyltriethoxysilane) with the chemical formula of $H_2NCH_2CH_2CH_2Si(OCH_2CH_3)_3$ was used in our study. A 95% ethanol / 5% water solution was adjusted to pH 4.5–5.5 with acetic acid. Silane was added with stirring to yield a 2% final concentration. Layers of silk fabric were then dipped into the solution, agitated gently, and removed after 5 minutes to allow for hydrolysis and silanol formation.. They are rinsed free of excess materials by dipping briefly in ethanol. Curing of the silane layer was performed for 20 minutes at 60°C or 24 hours at room temperature (60% relative humidity). The silanated silk fabrics were subsequently used to fabricate composite.
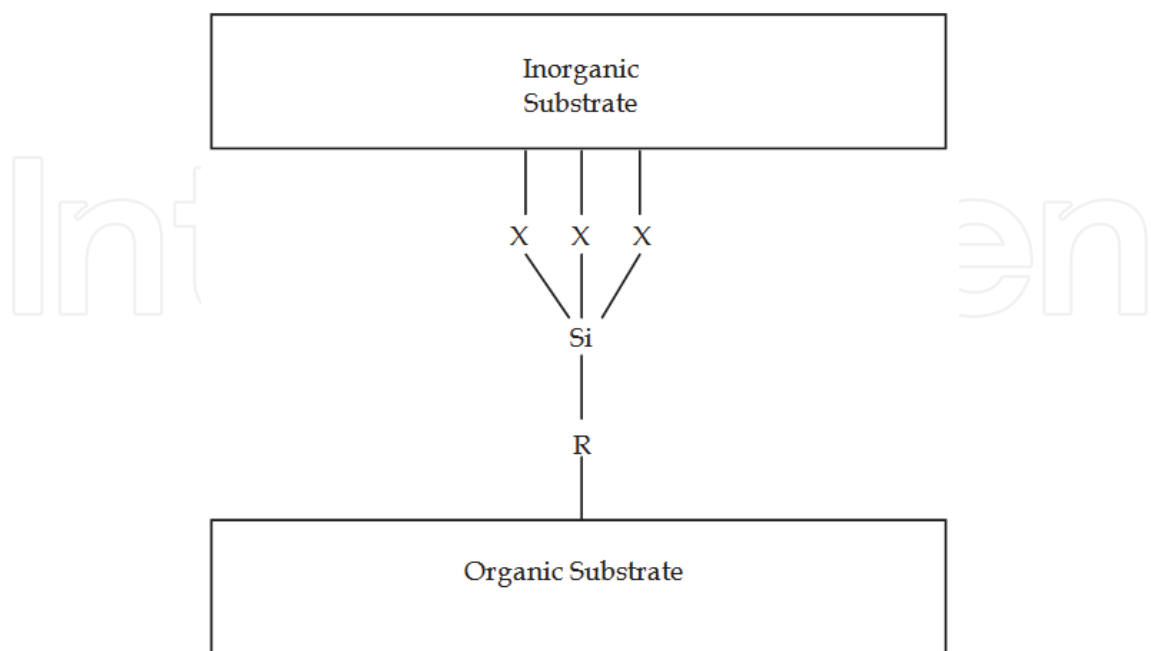
Fig. 8. Silane Bonding

7. Mechanical testing & evaluation of fabricated composite

The completed silk-epoxy composite panels were subjected to three point flexural bend test based on ASTM D790 to determine the mechanical properties like flexural strength and flexural modulus. Flexural tests tell us the behaviour of materials subjected to simple beam loading tests and indicates the composite ability to resist deformation under load.

7.1 Procedure for flexural test

The test specimens were first cut according to the required dimensions in ASTM D790 by a diamond cutter. For blank epoxy, the test specimens were prepared in a Teflon mold of dimensions 88mm x 22mm x 5.5mm. The hot pressed silk-epoxy composite were of differing thickness, depending on the number of layers of silk incorporated. Thus, each batch of silk composite have to be cut into similar rectangular dimensions with a minimum span to depth ratio of 16:1 or 32:1. The length of each test specimen was cut long enough such that 10% of test specimen was left hanging over at each support. All uneven surfaces of the cut specimens were ground flat with a sanding machine. (Fig. 9).

Five test specimens per composite were tested. Each batch of test specimens was from a single panel of its respective number of silk fabric layers incorporated in the composite. The dimensions of the test specimens are shown below. (Table 2).

The test specimens were conditioned at 23°C ± 2°C and 50% ± 5% relative humidity for not less than 40 hours prior to test. Test specimens were supported on two points with load applied from the top at mid-length. Constant strain rate of 0.01mm/mm/min is applied until maximum flexural stress was obtained or test specimen had fractured. (Fig.10).

Fig. 9. Machining test specimen to size according to ASTM D790

No. of Silk Fabric Layers in Composite	Length (mm)	Span (mm)	Width (mm)	Depth (mm)	Span : Depth ratio
0 (blank)	105.60	88	22	5.5	16
15	92.16	64	16	2	32
20	96.00	80	20	2.5	32
20 (Silanated)	96.00	80	20	2.5	32
25	99.84	83.2	20.8	2.6	32
30	115.20	96	24	3	32

Table 2. Dimensions of flexural test specimens

In this study, calculation of volume fibre percentage was as below. Voids were assumed to be insignificant as hot pressing to achieve high compactness was used in the composite fabrication.

$$\text{Volume \%silk fibre} = (\text{volume of silk} / \text{volume of composite}) \times 100\%$$

$$= (\text{mass}/\text{density})_{silk} / (L \times B \times W)_{composite} \times 100\% \qquad (1)$$

In accordance with ASTM D790, the flexural strength and and modulus were calculated as below:

$$\text{Flexural Strength: } \sigma_f = 3PL/2bd^2 \qquad (2)$$

$$\text{Tangent Modulus of Elasticity: } E_B = L^3m/4bd^3 \qquad (3)$$

where:
D: maximum deflection of the center of the beam (mm),
d: depth (mm),
L: support span (mm),
P: load at a given point on the load-deflection curve (N),
b: width of beam tested (mm),
m: slope of the tangent to the initial straight-line portion of the load-deflection.

Fig. 10. Three point bending test setup

7.2 Results

The three point flexural bend test results for the composites of different volume percentage of silk fibre were calculated and compared against the flexural strength and modulus. (Table 3). (Fig. 11).

No. of Silk Fabric Layers in Composite	Volume % of Silk Fibre (%)	Average Flexural Modulus (MPa)	Average Flexural Strength (MPa)
0	0.00	1387.99	53.31
20	33.09	4083.71	123.75
20 (Silanated)	33.09	3162.11	106.08
25	40.41	3795.79	118.57
30	41.62	3459.63	91.53

Table 3. Flexural Modulus & Strength vs Vol % of Silk Fibre

It can be seen from the results that as the volume percentage of silk fibre increases, the average flexural strength and flexural modulus of the silk composite increase. However, both properties peaked at the point where about 33% of silk fibre was added into the composite. This indicated that the optimum percentage of reinforcement was almost reached. The reason that composite strength starts to decrease at high fiber volume fractions can be attributed to the shortage of resin to wet all fibers in the composite as more fibers are added.
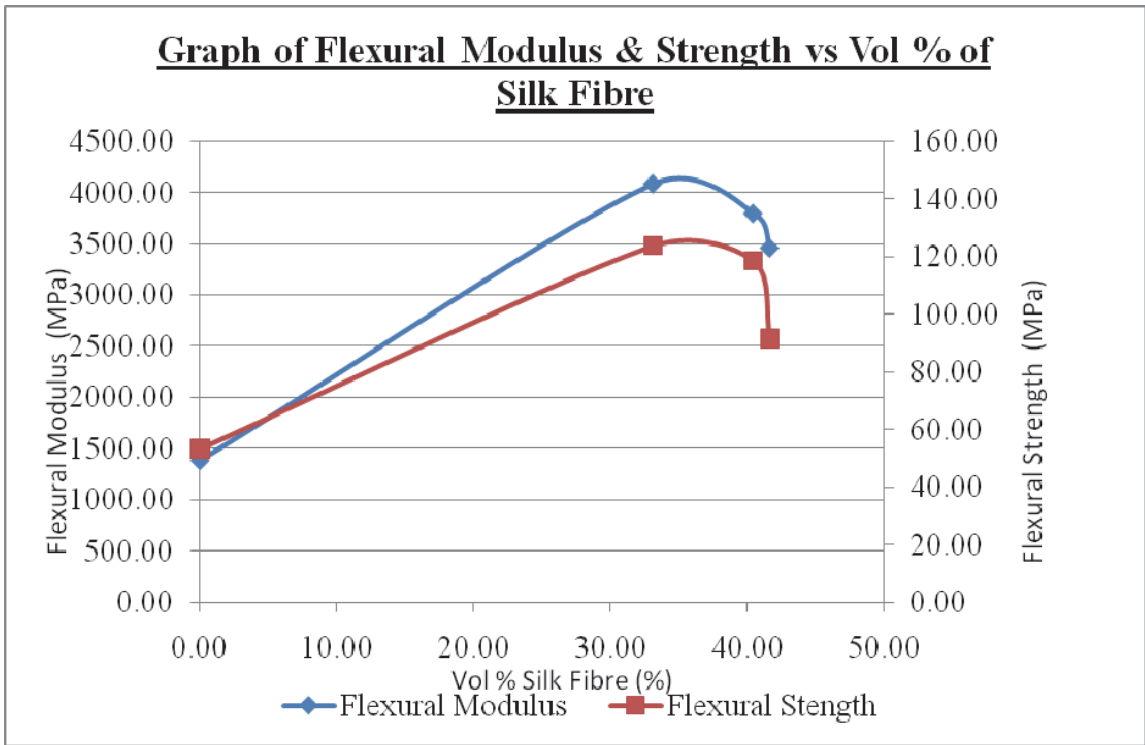

Fig. 11. Graph of Flexural Modulus & Strength vs Volume % of Silk Fibre

The silanated (20 layers) silk fabric composite exhibited lower flexural strength and modulus than the non-silanated (20 layers) silk fabric composite. This suggested that the silane treatment did not increase adhesion between silk and epoxy, but rather decrease it. Silk is organic and few sites to interact with the inorganic functional group of silane. As such, silane can only bond with epoxide functional groups in the epoxy resin, which reduces the available epoxide-bonding sites for silk amine groups to bond with epoxy groups. Thus, the flexural strength and modulus of silanated silk-epoxy composite were compromised, instead of improved.

8. Conclusion

Wet layup, vacuum bagging and hot press were successfully employed to fabricate the silk fabric-epoxy composite in this study. Based on the three point flexural bend test results, incorporating silk fabric into epoxy was found to increase the flexural strength of the composites up till a optimum volume percentage of 33% silk fibre reinforcement content. This favorable result indicated the potential to further explore and utilize natural silkworm silk-epoxy resin composite for actual high performance applications.

Future work to enhance the flexural strength of the silk–epoxy composite will include optimization of the yarn, weaving parameters and also utilize stitched multilayer fabrics to improve interlaminar strength. Enhancement of the silkworm silk fibre by electric field and optical light stimulation during the sericulture stage will also be tested. Additional mechanical tests like tensile, impact, fracture toughness will be performed on the silk composite in order to better compare with other synthetic fibres, such as carbon fibers and Kevlar. Due to the high elongation of silk fibres, the ductility of the silk-epoxy composite could not be covered in the flexural test conducted. This will subsequently be determined by tensile test. In addition, in order to further increase the volume percentage of silk fibres in the composite, higher pressing pressure will be explored.

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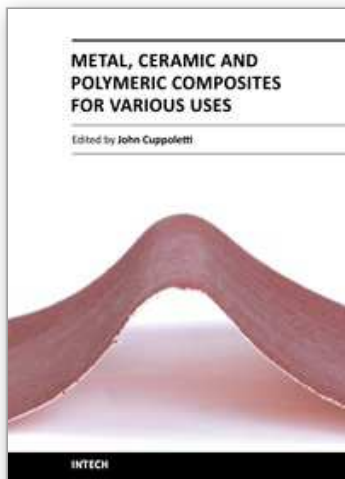
Metal, Ceramic and Polymeric Composites for Various Uses

Edited by Dr. John Cuppoletti

Composite materials, often shortened to composites, are engineered or naturally occurring materials made from two or more constituent materials with significantly different physical or chemical properties which remain separate and distinct at the macroscopic or microscopic scale within the finished structure. The aim of this book is to provide comprehensive reference and text on composite materials and structures. This book will cover aspects of design, production, manufacturing, exploitation and maintenance of composite materials. The scope of the book covers scientific, technological and practical concepts concerning research, development and realization of composites.

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