FINITE ELEMENT ANALYSIS OF MECHANICAL PROPERTIES FOR 2D WOVEN KENAF COMPOSITE

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ABSTRAK

Komposit tenunan berdasarkan serat semulajadi semakin banyak digunakan untuk aplikasi dalam industri disebabkan oleh kos yang rendah, ringan, kurang menyebabkan kerosakan pada peralatan pemprosesan, kemasan permukaan yang baik, ciri-ciri mekanikal yang baik dan sumber yang boleh diperbaharui, terdapat beberapa masalah bagi membangunkan produk kerana kos dan tempoh masa untuk melaksanakan pengujian produk dalam skala sebenar. Teknik model ramalan digunakan untuk mengurangkan keperluan untuk ujian fizikal, memendekkan masa rekabentuk dan mengoptimumkan rekabentuk. Sifat-sifat mekanikal fabrik tenunan bagi teknikal tekstil bergantung kepada a) bahan mentah b) bilangan benang c) kepadatan benang dan d) struktur tenunan. Justeru itu, kajian ini dilaksanakan untuk mengenalpasti kesan rekabentuk fabrik terhadap sifat-sifat mekanikal. Kombinasi antara saiz benang dan corak tenunan bagi menghasilkan struktur fabrik yang optimum dikaji. Kajian ini dilaksanakan pada skala mikroskopik, mesoscopik dan makroskopik. Kelebihan menggunakan kaedah ini ialah: (1) mengurangkan kos pembangunan produk dengan kaedah cuba jaya (2) mengurangkan masa untuk memperkenalkan teknologi baru, (3) kaedah model pelbagai skala mengurangkan kemungkinan rekabentuk yang konservatif atau dikompromi yang menyebabkan kebergantungan kepada bahan yang kurang sempurna. Perisian digunakan bagi menghasilkan model komposit tenunan kenaf yang mempuyai ciri-ciri tersendiri. Seterusnya, model dianalisis menggunakan kaedah analisis unsur terhingga untuk meramalkan sifat-sifat mekanikal komposit tenunan kenaf. Di samping itu, kesan gabungan saiz benang dan corak tenunan bagi komposit kenaf tenunan dikenalpasti merujuk kepada sifat-sifat mekanikal untuk meramalkan struktur yang optimum bagi komposit kenaf tenunan.

ABSTRACT

Woven composite based on natural fiber increasingly used for many applications in industries because of their advantages such as low cost, low weight, less damage to processing equipment, improved surface finish, good relative mechanical properties and renewable resources, but there are some problems as cost and protracted development period to perform reliability evaluation by experimental with real scale. Predictive modeling technique is used to minimize the need for physical testing, shorten design timescales and provide optimized designs. Mechanical properties of woven fabrics for technical textile depend on a) type of raw materials b) type and count of warp and weft yarns c) yarn density and d) the type of weave structure. The effect of fabric architecture to the mechanical properties is investigated. The optimum fabric structure is crucial due to the combination of difference of yarn size and weave pattern are observed. The research is conducted in the microscopic, mesoscopic and the macroscopic scale. The benefit using the hierarchal method of multi scale modeling is: (1) it encourages a reduced reliance on costly trial and error. (2) Lead-time for the introduction of new technologies is reduced, (3) the multi-scale modeling system lowers the likelihood of conservative or compromised designs that might have resulted from reliance on less-than-perfect material. Woven kenaf composite is modeled using the modeling software to get the properties of the model. Further, the model is analyzed using finite element analysis to predict the mechanical properties of the woven kenaf composite. In addition, the effect of the combination of yarn size and weave pattern of the woven kenaf composite is stated based on the mechanical properties to predict the optimum structure of woven kenaf composite.

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CHAPTER 1

INTRODUCTION

1.0 Introduction to composite materials

Composite materials with woven fabric reinforcement have become increasingly popular for use in structural applications in recent years due to their advantages such as low fabrication costs, light weight, ease of handling and high adaptability, over tape laminates and several other engineering materials (Hallett, 2008).

As interest in the use of composite materials for structural applications continues to increase, alternative reinforcements to conventional pre-preg systems are being more widely considered. 3-D woven composites are gaining increased prominence due to their ability to produce near net shape preforms as well as integrated third direction reinforcement. The important characteristics of 3-D woven preforms that make them suitable for composites are high axial rigidity, flexibility, formability and stability. One of the barriers to their advancement and increased use is the difficulties associated with creating numerical models to predict their performance (Hallett, 2008).

Composite material performance is affected by the fiber architecture and fiber –matrix interface. Fiber architecture which consists of (i) fiber geometry (ii) fiber orientation (iii) packing arrangement and (iv) fiber volume friction, controls many composite mechanical properties. (Paul et al, 2006). The interface between fiber and the matrix is also crucial in terms of composite performance. The interface serves to transfer externally applied loads to the reinforcement via shear stresses over the interface (Paul et al, 2006). Therefore, many researches are conducted to determine early prediction mechanical properties of composite material.

Finite element analysis and analytical methods are powerful tools for studying the mechanical properties of woven composite. However, the complexity of the micro-structure is proportional to the number of parameters controlling the mechanical properties. So, various finite element techniques and assumptions have been proposed for simplifying the analysis. (Tan et al, 1997; Crookston et al, 2005). A Domain Superposition Technique (DST) has been previously proposed, which is able to overcome a number of traditional difficulties in creating finite element models of composites with complex internal architecture (Jiang et al, 2008). One of the fundamental difficulties faced in modeling the detailed unit cell is to build geometry free from interpenetration at tow crossovers. Another significant problem is that a very fine finite element mesh is required to deal with the degenerated volumes of the resin pockets between tows. This can lead to very large finite element models exceeding a million degrees of freedom to model a single unit cell, which is only a very small part of the structure. DST is successfully implemented for the development on 2D weave structures (Hallett, 2008). A mesh sensitivity study has been conducted showing that good results are still obtained even when a relatively coarse mesh is used.

Finite element analysis is based on the modeling of the composite material. Several methods were adopted for the mechanical modeling and analysis of the composite structures. A basic classification, according to the modeling method used, divides them into the analytical and numerical or computational approaches. The dominant engineering design culture played important role for the development and the succession of these approaches. Another essential classification of the modeling of the textile structures is made according to the scale of the model. There is micromechanical, meso-mechanical and the macro-mechanical modeling (Takano et al, 1999).

The micromechanical modeling stage focuses on the study of the yarns, tows even fabrics taking into account the structure, orientation and mechanical properties of the constituent fibers. The meso-mechanical modeling, on the other side, studies the mechanical characteristics of the fabric unit cell considering the yarns as homogenous structures. Finally the macro-mechanical modeling stage is referred to the prediction of mechanical performance of the composite in complex deformations, as drape, studying the composite as a continuum material (Bogdanovich, A.E, 2006;

Lomov et al, 2001). Thus the textile society implemented a modeling hierarchy based on three modeling scales: the micromechanical modeling of yarns, the meso-mechanical modeling of the fabric unit cell and the macro-mechanical modeling of the fabric sheet.

The first numerical studies is conducted to studies for the evaluation of the elastic properties of the plain woven composite structures based on a strain energy method applied to a one-direction undulation model using the FEM (Zhang, Y.C. and Harding, J. A, 1990). The studies consider of the tow undulation in one-direction that is a non-realistic assumption for woven fabrics. Research by Naik and Ganesh (1992), expanded the above approach taking into account the strand cross section geometry, possible gap between two adjacent strands and the two-direction undulation geometry with a detailed model of a large number of geometrical parameters to describe the undulation and varying thickness of the tow structure .

Whitcomb introduced the first 3D finite element model of plain woven composites to studied the effect of quadrature order, mesh density and material degradation on the predicted failure resulting from the in-plain loading (Whitcomb, J. and Srirengan, K, 1996). Figure 1.1 shows the 3D solid modeling of the composite structure consists in the generation of the volumes representing the woven unit cell and composite unit cell as an external volume. Finally the volume of the matrix material is the subtracting volumes of the woven structure from the external volume.

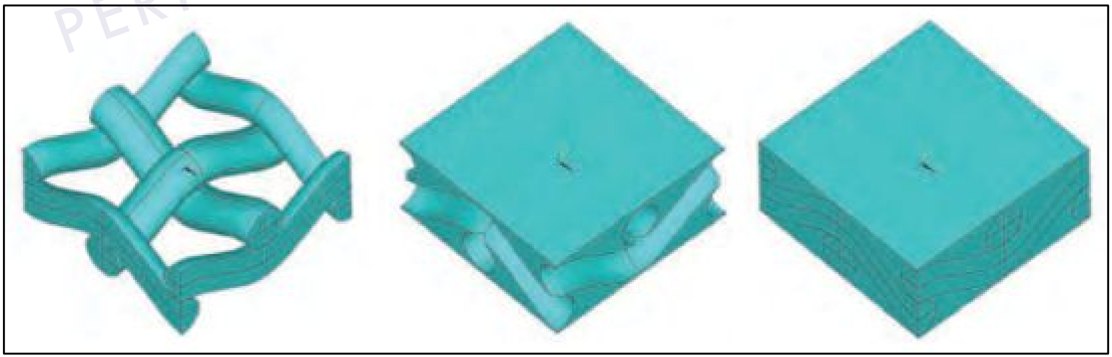

Figure 1.1: Geometrical model of composite woven structure
(woven reinforcement, matrix, composite) (Whitcomb, J. and Srirengan, K, 1996)

The prediction of the in plane elastic properties for the tow cross section (consideration of compressed hexagonal shape) of single layer 2/2 twill weave fabric composite was conducted by Ng et al (1998). The model approximately 52000 finite elements and 12000 nodes was generated using the finite element analysis software for modeling and mechanical analysis based on the 8-node solid elements with 3 degrees of freedom (translational) per node. The contact areas generated during the subtracting operation (for the generation of matrix material) were assigned to be shared entities for both the yarn and the matrix volumes, to ensure the transmission of loading.

1.1 Problem statement

In recent years, natural fiber is considerable attention as a substitute candidate for synthetic fibers. The application of natural fiber growing in many sectors such as automotive and construction due to their advantage compared to synthetics fiber. The advantages of natural fiber are low cost, low weight, less damage to processing equipment, improved surface finish, good relative mechanical properties and renewable resources (Chin CW, Yousif BF, 2012; Yousif BF, Ku H, 2012). Fiber construction in form of fabric can be construct in many ways such as woven, braided, stitched, and so forth can be used to form the fabric reinforcement. Woven composite offer a number of attractive properties compared to non woven. Woven composite is consists of microscopic scale (bundle of fiber in yarn), mesoscopic scale (sets of yarns in fabric) and macroscopic scale (fabric itself). The considerations of the mechanical properties of woven composite are tensile strength, impact properties, torsional stiffness, fatigue, vibration and flexural strength (Joshi SV et al, 2004; Velmurugan R and Manikandan V, 2007). Woven composites have many design parameters such as volume fraction of fiber, architecture of reinforced fibers, the mechanical properties etc. There are some problems as cost and protracted development period to perform reliability evaluation by experimental with real scale. Recently, many researchers have studied the finite element analysis to predict mechanical properties of textile composite and mechanical properties and failure behaviors of plain weave composites have been estimated (Tang and Whitcomb, 2003).

Textile composite structures are still designed largely on the basis of experience, intuition and trial-and-error. Therefore, tracing any final product error is very complicated. Predictive modeling technique is use to minimize the need for physical testing, shorten design timescales and provide optimized designs. Approach of multi-scale modeling system is use to developed an energy-based argument combined with elastica methods to incorporate non-linear frictional behavior for yarn modeling. Yarn constitutive mechanical properties are computed at fiber-yarn scale. These material properties form an input to yarn–fabric scale simulations. The finite element method is employed at yarn–fabric scale, with the yarn modeled as a continuum (Tan et al, 1997).

Combined model is use if the mechanical properties of fabric effect by surface treatment. Suitable model should include a description of both the effect of meso-friction (i.e., between the yarns) and the effect of micro-friction (i.e. between the fibers in a yarn), together taking into account of fiber distribution within yarns and yarn topologies within a fabric. The benefit using hierarchal method of multi scale modeling is: (1) it encourages a reduced reliance on costly trial and error. (2) increases the confidence that new materials will possess the desired properties when scaled up from the laboratory level, so that lead-time for the introduction of new technologies is reduced, (3) the multi-scale modeling system lowers the likelihood of conservative or compromised designs that might have resulted from reliance on less-than-perfect materials. There are many challenges for development of multi-scale modeling approach without loss of intrinsic structural information for such a complicated structure material as shown in Figure 1.2.

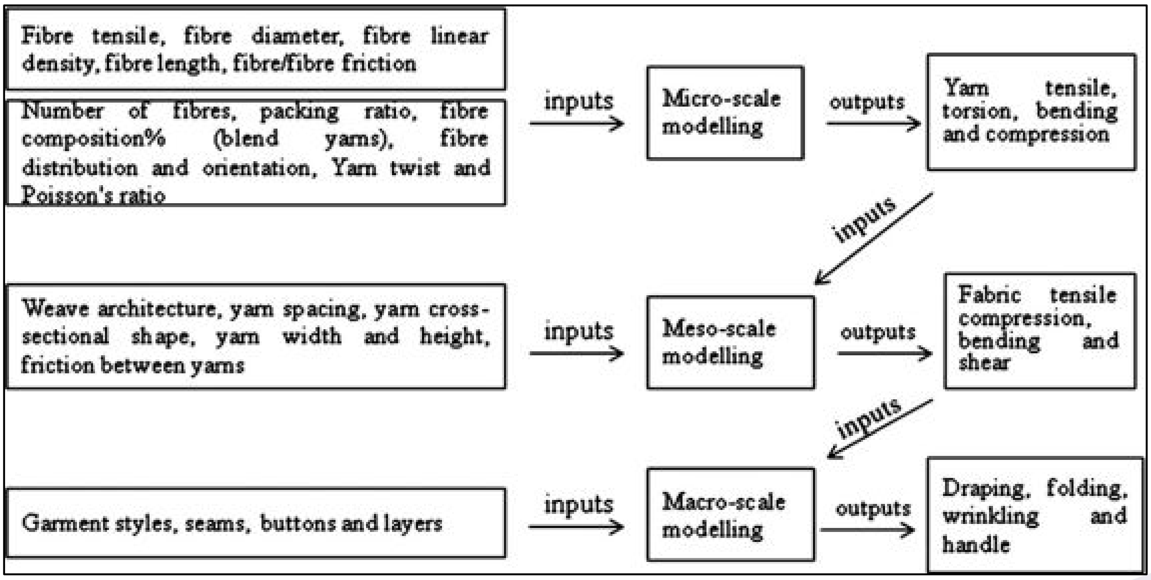

Figure 1.2: Structure–property relationships for textiles and associated multi-scale modeling hierarchy (H.Lin et.al, 2012).

Finite element analysis is use to predict the mechanical properties of the woven composite by using the finite element analysis and modeling software to do the modeling of the woven fabric in difference fabric weave structure. Finite element modeling solution process consists of the following steps (H.Lin et.al, 2012):

i. Divide structure into piece elements with nodes (discretization / meshing)
ii. Connect (assemble) the elements at the nodes to form an approximate system of equations for the whole structure (forming element matrices)
iii. Solve the system of equations involving unknown quantities at the nodes
iv. Calculate desired quantities (e.g., strains and stresses) at selected elements.

1.2 Objective of study

i. To analyze the mechanical properties of woven kenaf composite with difference yarn size (759 tex, 413.4 tex, 276 tex)
ii. To analyze the mechanical properties of woven kenaf composite with difference 2D weave pattern (Plain 1/1, Twill ½, Satin 5/2)
iii. To optimize the fabric structure of plain 1/1, Twill ½, Satin 5/2

1.3 Scope of study

In order to achieve the objective, the scope of research was to analyze the mechanical properties of woven kenaf composite with different yarn size, different 2D weave pattern and to optimize the fabric structure. The yarn size use in this research is 759 tex, 413.4 tex and 276 tex for difference 2D weave pattern; Plain 1/1, Twill ½ and Satin 5/2. Furthermore, effect of using the combination for optimum mechanical properties of woven kenaf composite was investigated.

1.4 Research outcome

i. The effect of different yarn size to the mechanical properties of the woven kenaf composite.
ii. The effect of different 2D weave pattern to the optimum value of mechanical properties.
iii. The optimum value for the mechanical properties depends on the combination of yarn size and weave pattern.

CHAPTER 2

LITERATURE REVIEW

2.0 Textile structure composite

Composites can be defined as a combination of dissimilar material with a specific internal structure and internal shape. This combination lead to singular mechanical properties and increase the performance characteristic compared to the material alone. Additionally, composite materials give superior strength to weight basis compare to other materials (e.g. metal). Based on the advantages of composite, the range of application for composite material appears to be limitless (Paul et al, 2006).

Textile structure composites represent of advanced material which are reinforced with the textile for structural or load bearing applications. Textile structure composites are part of larger category of textile composite. Textile composite is the combination of a resin with a textile fiber, yarn or fabric in form of flexible or rigid body. Flexible textile composite includes the heavy duty conveyer or the inflatable life rafts. Besides that, textile structural composite are also use as the structural materials to resist heavy loads in the basic framework for buildings, vehicles, etc. The majority of textile composites are fiber reinforced plastic (FRP). FRP made of a textile composite perform embedded with a resin, metal or ceramic matrix. The matrix provides rigidity and holds the textile reinforcement material in prescribed orientation and position in the composite (fibers, yarns or fabrics) (Poe, C. C., and Harris, C.E, 1995).

Aircraft and automotive manufacturers have been focus in the application of textile composites structure for more than two decades. Woven carbon fiber is use as the textile structure composite in the component part is shown in Figure 2.1. The composites structure offer competitive cost reduction and improve structural performance compare to current metallic materials. Numerous micromechanical models have been developed to predict the effective strengths and stiffness. Finite element analysis is use to predicted the textile mechanical properties even though they are based on simplifying assumptions but it’s provide good approximation to extensive testing. (Poe, C. C., and Harris, C.E, 1995)

Figure 2.1: Preform/RTM parts in NH90 (Dumont et al, 2008)

2.1 Natural fibers

Natural fiber can be divided into vegetables, animal and mineral fibers. Vegetables fiber can be classified either wood or non-wood. Bast and leaf fibers are example of non-wood fibers. Due to environmental awareness, the fiber use to build the textile structure composite previously focuses for natural fiber like cotton, flax, hemp and kenaf (Paul et al, 2006). The selection of suitable fibers is determined by the values of the stiffness and tensile strength of the composite. Other criteria for the choice of reinforcing fibers are elongation of failure, thermal stability, adhesion of fiber and matrix, dynamics and long term behaviors, price and processing costs (Paul et al, 2006). Hemp and flax fiber can compete with E-glass fiber due to the tensile strength, elasticity and elongation at failure. Table 2.1 shows the classification of vegetable and cellulose fiber.

Table 2.1: Classification of vegetable and cellulose fiber (Paul et al, 2006)

Bast	Leaf	Seed	Fruit	Stalk	Wood Fibers
Flax	Sisal	Cotton	Coconut	Bamboo	Hardwood
Hemp	Manila	Kapok		Wheat	Softwood
Jute	Curaua			Rice	
Kenaf	Banana			Grass	
Ramie	Palm			Barley	
Banana				Corn	
Rattan					

Kenaf fibers can be use because of the properties which are low cost, lightweight, renewability, biodegradability and high specific mechanical properties as shown in Table 2.2. It has superior flexural strength and excellent tensile strength which make kenaf a good candidate for many applications. Kenaf fibers also have high absorption in moisture (hydrophilic) which can affect the mechanical properties whereas most common polymer matrix is hydrophobic but with certain treatment the adhesion can be overcome. The strength of kenaf is quite low compare to carbon and glass fiber but due to its low density it can compete with those synthetic fibers (I.S Aji et al, 2009).

Table 2.2: Properties of principal fibers (I.S Aji et al, 2009)

	Diameter µm	Ultimate Stress Mpa	Strain %	Modulus Gpa	Density Kg/m³	Specific Stress (Mpa*m³/Kg)	Cellulose/ lignin	Microf. Angle 0°
Ramic	16-120	800-1000	1.7-3	50-80	1560	0.51-0.64	70-80/0.5-1	6.0-10.0
Pincapple	20-80	400-1000	0.8-1.6	34-82	1440	0.28-0.69	84-5/12-7	14-80
Banana	80-250	500-700	2-3.5	7.7-20.8	1350	0.37-0.52	63-64/5	11
Palmyra	70-1300	95-220	3.2-11	3.3-7.0	1090	0.09-0.20		30
Sisal	50-300	500-600	3.0-7.0	9.4-16	1450	0.34-0.41	66-72/14-10	18-22
Coir	12.0-24.0	100-200	15-20	4.0-6.0	1150	0.09-0.17	32-43/40-45	30-49
Jute	25-120	400-700	1.5-2	2.5-15	1450	0.28-0,48	63-70/12	7.0-9.0
Hemp	16-50	400-700	1,6-2,5	35	1480	0,27-0,47	70-88/3-4	6,0-10,0
Kenaf	15-30	350-600	2.5-3.5	40	1500	0.22-0.40	75-90	9.0-1.0
Cotton	15-25	300-600	5.0-8.0	4.0-12.0	1520	0.20-0.39	90-95/0	20-30
Flax	12.0-30.0	900-1200	2.0-3.0	100	1540	0.58-0.80	71/2.2	6.0-10.0
Carbon	6-10.5	1700-2400	1.4-1.8	180-415	1880	0.90-1.28		
Glass	2.5-15	1400-2500	2.5-5	68-96	2540	0.57-0.98		

2.2 Textile structure composite manufacturing process

Textile structural composites can be studied in their hierarchical manufacturing process. There are usually four important levels in the manufacturing process for textile composite as shown in Figure 2.2.

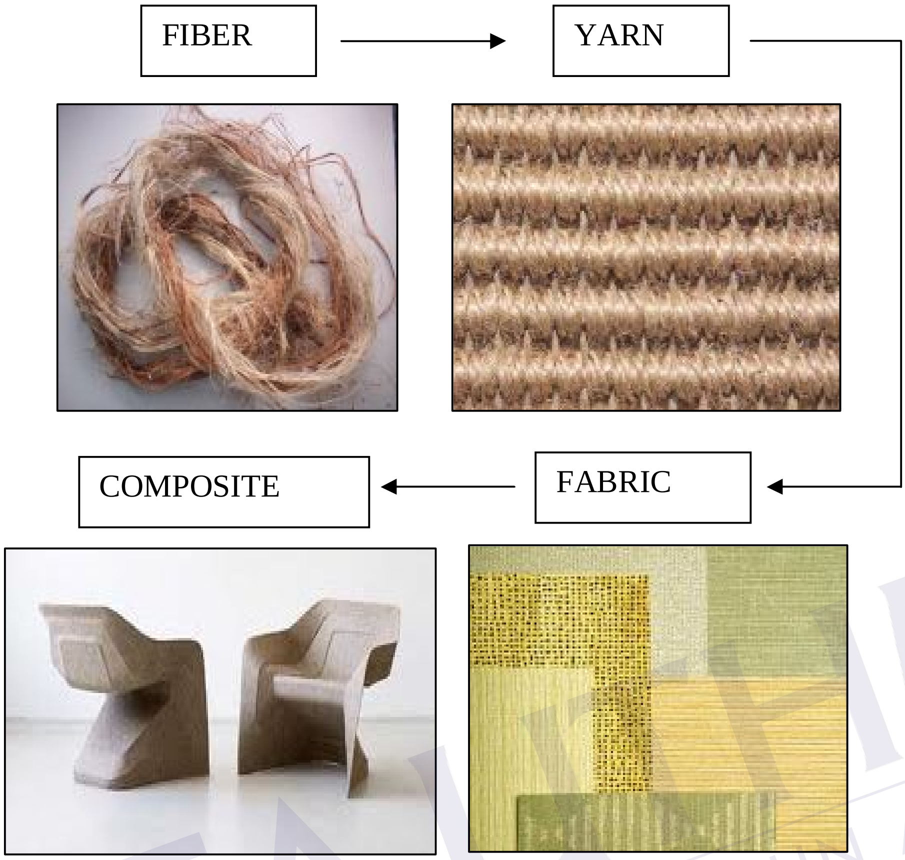

Figure 2.2: Hierarchical of textile structure composite (Scardino, F, 1989)

First step is the choice of the high modulus fibers to resist high loads in structural applications. Second step of the manufacturing process is grouping together the fibers (or filaments) in a linear assemblage to form a continuous strand having textile-like characteristics. After that, a group of filaments is then impregnated with resin (for non-hybrid fabrics, the resin is the same for all the strands and usually the same for the preform) and the resulting a tubular form called yarn (Scardino, F, 1989). As shown in Figure 2.3, yarns may be composed of one (a) or more (b) continuous filaments, or even discontinuous chopped fibers (c). Finally, two or more single yarns can be twisted together to form ply or plied yarns (d and e). The manufacturing process of yarns itself can involve rather complicated shapes.

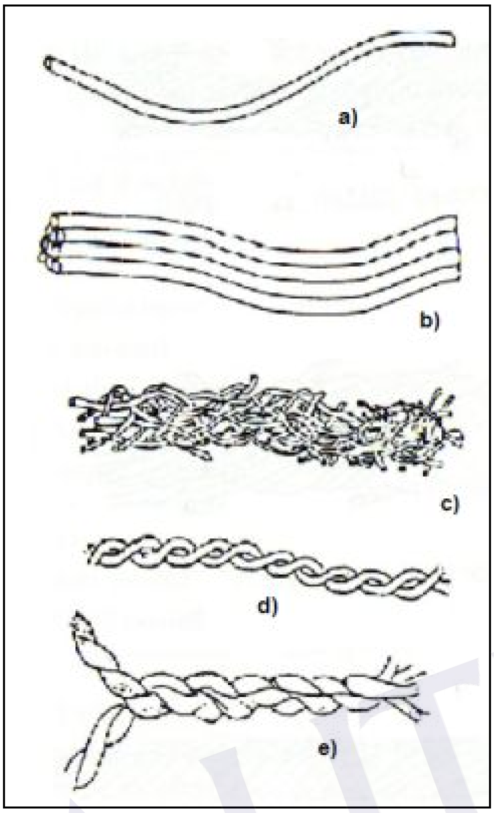

Figure 2.3: Different examples of idealized models of various yarn structures (Scardino, F, 1989)

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Yarn structural features can be characterized by several geometrical parameters such as number of filaments, the diameter of the filaments (assuming the fibers have a cylindrical shape), and the yarn packing density, defined as the ratio of the fiber volume to the yarn overall volume. Yarn structure plays a dominant role in the translation of fiber properties into yarn properties. Table 2.3 listed the typical fiber-to-yarn strength translation efficiencies in various yarn structures for ordinary textile composites.

Table 2.3: Typical fiber-to-yarn strength translation efficiencies in various yarn structures (Scardino, F, 1989)

Yarn Structure	Strength translation efficiency (%)[a]
Monofilament	100
Multifilament	
Untwisted	98
Slightly Twisted	95
Air jet texturized	85
Stretch texturized	85

The mechanical properties of the yarns are mainly affected by the fiber orientation relative to the yarn axis and the fiber entanglement in the various structural forms. Multifilament untwisted yarn structures, the strength translation efficiency ratio is 98% close to 100%, therefore the behavior of these yarns are very close to that of the fibers themselves. The loss of strength in the fiber direction is due mostly to degradation during yarn processing and lack of toughness. The fibers are also assumed to be transversely isotropic and the resin isotropic, such that untwisted yarns can be considered as transversely isotropic.

The third step consists of bonding and interlocking the yarns together to produce a flat sheet with a specific pattern. Fabric types are categorized by the orientation of the yarns used, and by the various construction methods used to hold the yarns together. The periodicity of the repeating pattern in a textile fabric can be taken as a small repeating unit cell (RUC) which is sufficient to describe the fabric architecture. Figure 2.4 shows the four basic fabric structure categories are wovens, knits, braids, and nonwovens.

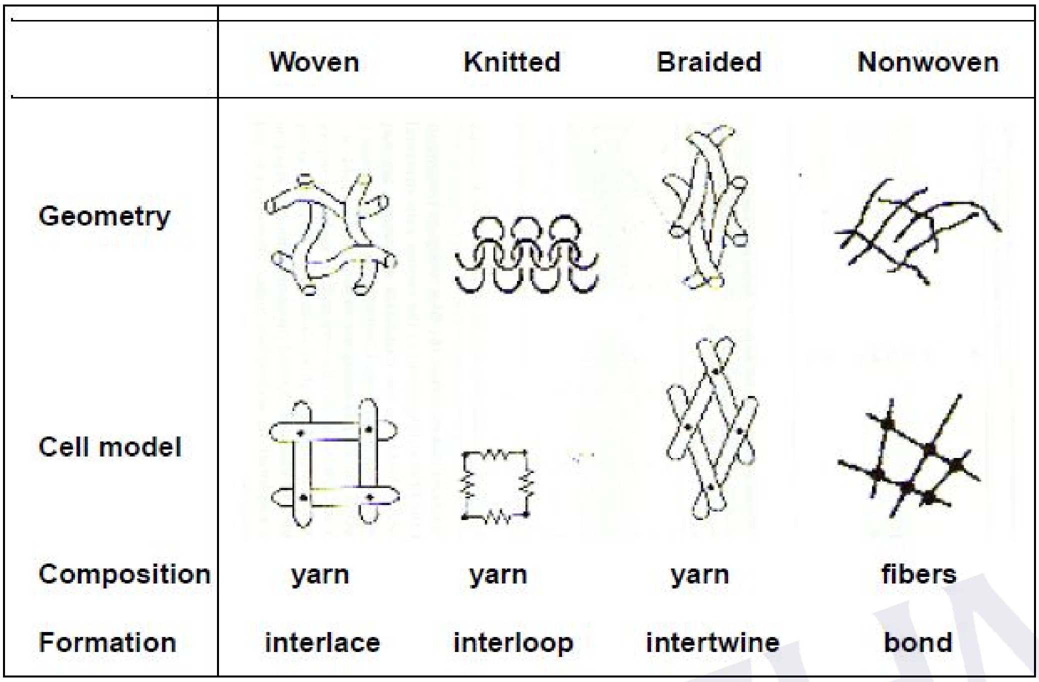

Figure 2.4: Comparison of basic fabric structures (Scardino, F, 1989)

The interlacing of the yarns in a fabric leads to yarn crimp and give a critical influence on the composite stiffness and strength properties. Other factors such as the ability of a fabric to conform to a complex surface, stability, or porosity are also very important for the manufacturer.

2.3 Woven fabrics

Conventional woven fabrics consist of two sets of yarns mutually interlaced into a textile fabric structure. The threads that run along the length of the fabric are called warp or ends. The threads that run along the width of the fabric from edge to edge of fabric are referred as weft or picks. Warp and weft yarns are positioned under the angle of 90°. Warp and weft density is the number of warp and weft yarns per unit length. The warp and weft yarns in a woven fabric could be interlaced in various ways that is called a weave structure. The ratio of the yarn actual length to the length of the fabric it traverses is called crimp. The fiber volume fraction, fabric thickness and fabric mechanical properties influence by the crimp (J. W. S. Hearle et al, 1969). A cover factor is the fraction of the total fabric area that is covered by the component yarn. The strength, thickness, stiffness, stability, porosity, filtering quality and abrasion resistance of fabrics will be influence by fabric area density and cover factor (J. E. Booth, 1997).

Plain weave is the structure where warp yarns alternatively lift and go over across one weft yarn and vice versa is the simplest woven structure (Figure 2.5a). Twill is a weave that produces diagonal lines on the face of a fabric (Figure 2.5b). The direction of the diagonal lines viewed along the warp direction can be from upwards to the right or to the left making Z or S twill. Twills have longer floats, fewer intersections and a more open construction compared to plain weave of the same cloth parameters. There are many variations of twill construction (the smallest repeat is three in warp and weft direction) but the technical application of twills is restricted to simple twills.

A weave where binding places arranged to produce a smooth fabric surface free from twill lines is called satin (Figure 2.5c) whereas the distribution of interlacing points must be as random as possible to avoid twill lines. The most popular are satins of 5 and 8 repeats and the smallest repeat of satin weave is 5. These 5 ends satin is most frequently used for technical applications for providing firm fabric although having moderate cover factor (A. Bogdanovic & K. Pastore, 1998). Mechanical properties of woven fabrics for technical textile depend on a) type of raw materials b) type and count of warp and weft yarns c) yarn density and d) the type of weave structure.

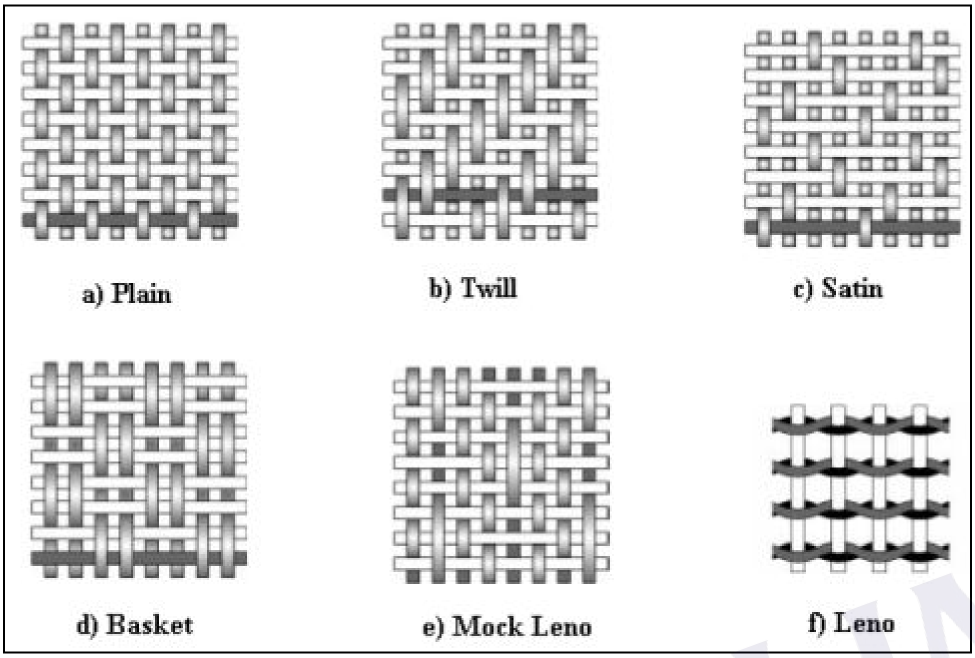

Figure 2.5: Comparison of most common woven fabric structures (David Cripps , 2002)

2.4 Effect of weave pattern in woven composite

Identification of woven fabric composites is based on their microstructure called unit cell (UC) (Alif N, et al. 1998). The interlacing of weave pattern and unit cell for orthogonal plain weave, twill weave and satin weave is shown in Figure 2.6. The interlacing counts between the fill and weft yarn determine by the index, n_g. The index for plain weave is two ($n_g = 2$) , twill weave is three ($n_g = 3$) and satin weave is four or greater ($n_g = 4$) . The research by Nidal Alif et al. using the two woven fabric composite system (glass/epoxy and carbon/epoxy), three weave pattern of glass/epoxy composite (plain weave, twill weave) and carbon/epoxy composite (5-harness satin weave, 8-harness satin weave). Figure 2.7 shows representative load-displacement (P-δ) curves for the Double Cantilever Beam (DCB) mode I fracture specimen (ASTM D5528) for glass/epoxy (Alif N, et al. 1998).

The load-displacement curves for the plain weave composite are similar in both directions (Figure 2.7(a) and (b)). For the twill and satin weaves, however, crack propagation in the 90^0 direction, i.e. along the weft yarns (Figure 2.8), requires significantly larger loads than propagation in the 0^0 direction. As the weave index, n_g increases the fracture toughness increase. The fracture resistance of the plain weave composite is almost independent of direction. The small difference in toughness between the two directions may be due to a fill-to-weft ratio other than 1 shown in Table 2.5. The resistance curves for the plain weave composite are almost horizontal indicating no change in the fracture mechanisms after precracking. The twill and satin weave composites it is observed that crack propagation in the 90^0 direction is associated with greater resistance than that in the 0^0 direction. No oscillations happen in the fracture resistance curves which might be influent by the small tow width (Table 2.6). The reason for the stable growth observed may be the matrix ductility as reflected by the large failure elongation of the LY1802 epoxy (Table 2.4). The resistance curves for all glass/epoxy composites in a steady state without much of an increase in toughness. Steady-state fracture toughnesses for the glass/epoxy woven fabric composites are about: 425 (0^0), 450 (90^0), (plain), 525 ($0\ ^0$), 620 ($90\ ^0$), (twill), and 775 ($0\ ^0$) and 925 (90^0) (8H-satin) in units of J/m^2 (Alif N, et al. 1998).

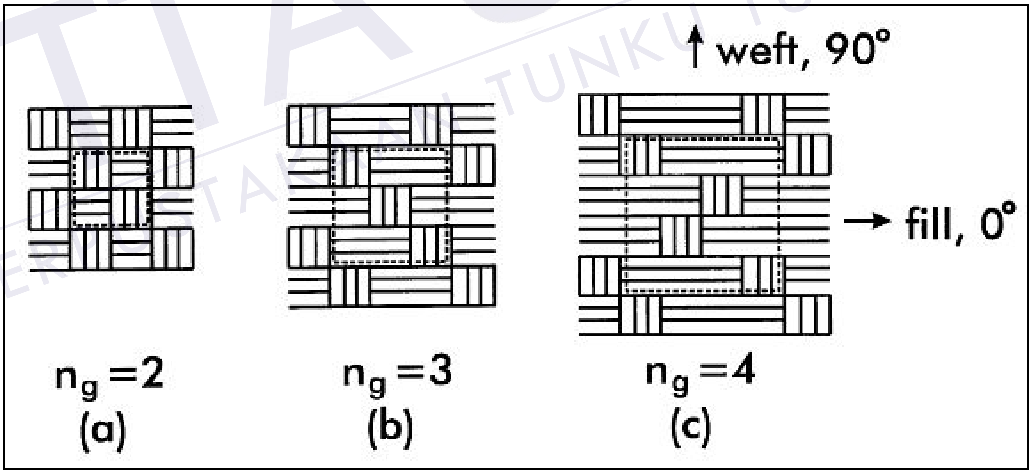

Figure 2.6: Interlacing patterns for woven fabric composites (a) Plain weave (b) Twill weave (c) Satin weave (Alif N, et al. 1998)

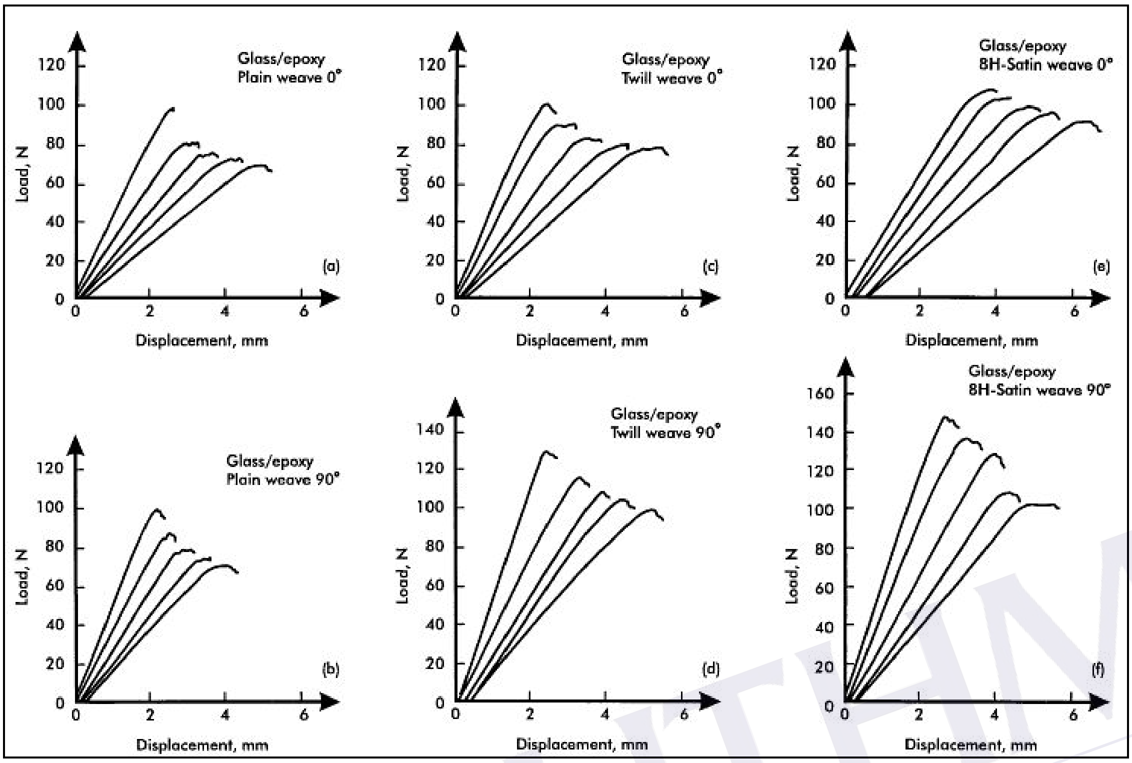

Figure 2.7: Load-displacement curves for the glass/epoxy composite DCB specimens (a) Plain weave 0^0; (b) Plain weave 90^0 (c) Twill weave 0^0 (d) Twill weave 90^0 (e) 8H-satin weave 0^0 (f) 8H satin weave 90^0 (Alif N, et al. 1998)

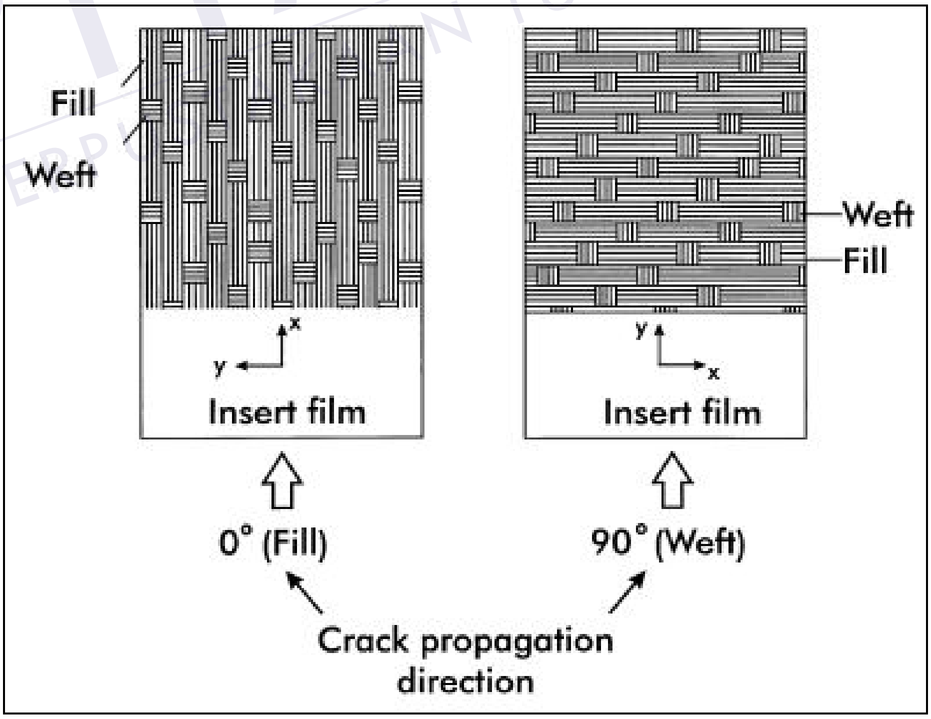

Figure 2.8: Positioning of the insert film in the interplay region for crack propagation along the fill and weft yarns (0^0 and 90^0 directions) (Alif N, et al. 1998)

Table 2.4: Properties of fibers and matrix E_L and E_T are axial and transverse Young Modulus, V_{LT} Poisson ratio for longitudinal extensions, ε_t ultimate tension strength (Alif N, et al. 1998)

Material	**E-glass**	**IM7 Carbon**	**LY 1802 Epoxy**	**8551-7 epoxy**
E_L	72	276	2.8	4.1
E_T	72	56	2.8	4.1
V_{LT}	0.3	0.25	0.36	0.37
ε_t (%)	2.4	1.81	4.5	1.93
ρ (g/cm^3)	2.54	1.77	1.18	1.372

Table 2.5: Weave characteristics for the glass/epoxy woven fabric composites (Alif N, et al. 1998)

Weave-type	Fiber diameter (μm)	Fill-to-weft ratio	Sizing
Plain	9	1.3	Volan A03
Twill	7	1.1	OSI A-1100
8H-satin	6	1.0	Volan A03

Table 2.6: Weave geometry parameters for the composites (Alif N, et al. 1998)

Composite	**Repeat unit (n_g)**	**Tow width (mm)**	**Gap (mm)**	**Unit cell dimensions (mm)**
Glass/epoxy (plain)	2	0.56	0.02	1.21 x 1.35
Glass/epoxy (twill)	3	0.51	0.02	1.54 x 1.55
Glass/epoxy (8H)	8	0.46	0.06	3.8 x 3.7
Carbon/epoxy (5H)	5	2.4	0.22	11.8 x 12

2.5 Numerical simulation system for woven

Woven composites have many design parameters such as volume fraction of fiber, architecture of reinforced fibers, the mechanical properties, etc. Therefore, there are some problems involved cost and development period for air planes and vehicles that must perform reliability evaluation by experiments with the real scale (Tetsusei Kurashiki et. al, 2007). Sherburn.M et al (2005) and Tang. X et al (2003) has conducted a research using finite element analysis to predicted the mechanical properties of textile composite, mechanical properties and failure behaviors of plain weave composites. From the research, local delamination appears in resin region of crossing parts of yarns but there is no consideration for effect of resin region and damage development. Therefore, Lomov et al (2007) proposed numerical simulation system in multi-scale simulation to evaluate the damage development of woven composites shown in Figure 2.9. The step for the multi-scale simulation consists of macro, meso and micro model of woven composite is shown in Figure 2.10 (Verpoest, I. and S. V. Lomov , 2005).

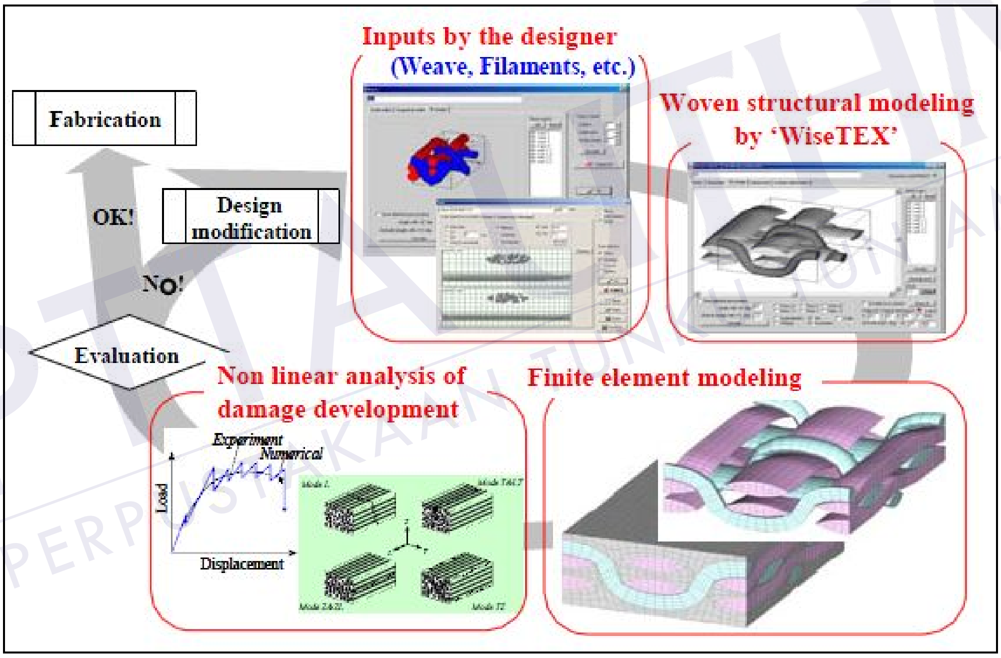

Figure 2.9: A practical numerical simulation system (Tetsusei Kurashiki et. al, 2007)

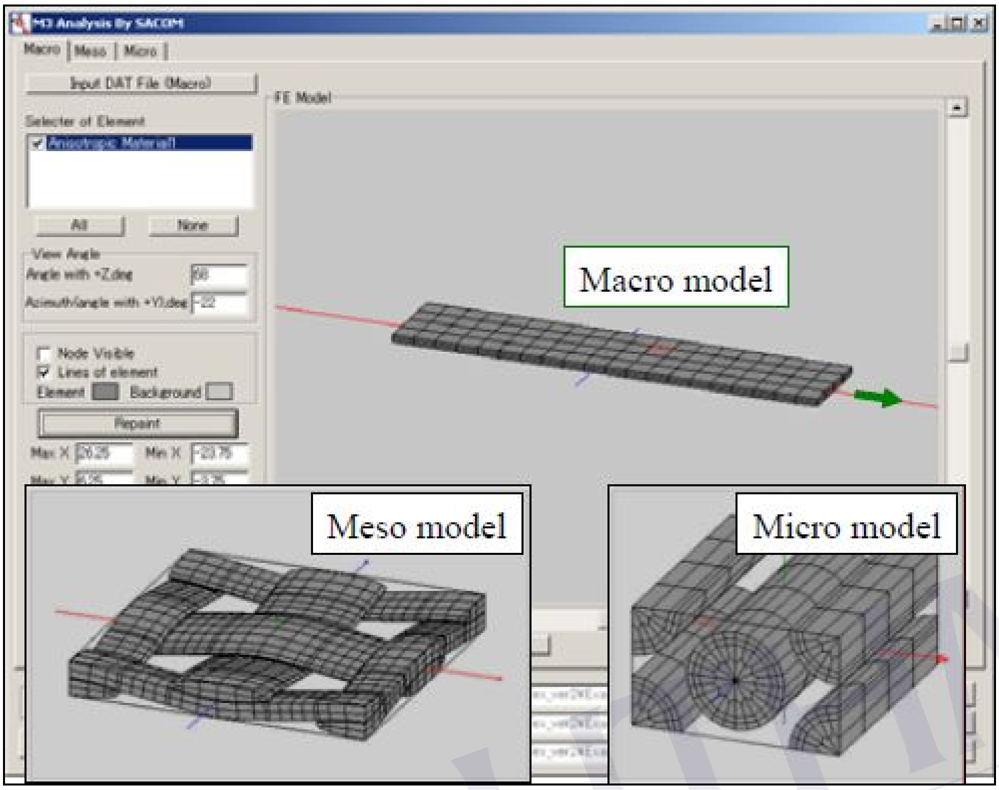

Figure 2.10: Multi-scale modeling of woven composites with 3 scales
(Tetsusei Kurashiki et. al, 2007)

The input data for a filament diameter, architecture of strand, etc will determine the topology of weave architecture and the structural model of internal geometry of the fabrics is generated. Numerical modeling program will generate hexahedron element for finite element model with yarns and matrix (Tetsusei Kurashiki et. al, 2007). The modeling simulation has a function to create 3D visual image of woven structure form weave diagram, etc. and also can determine the trajectory of the yarn in the stable state using the bending energy minimum theory within the software. The numerical modeling program not only generates the 2- dimensional textiles such as a plain weave and twill, but 3D woven or knitting can be corresponded and a structural image of a 3D fabric can be visualized by using the input information on the arrangement of weave yarns shown in Figure 2.11.

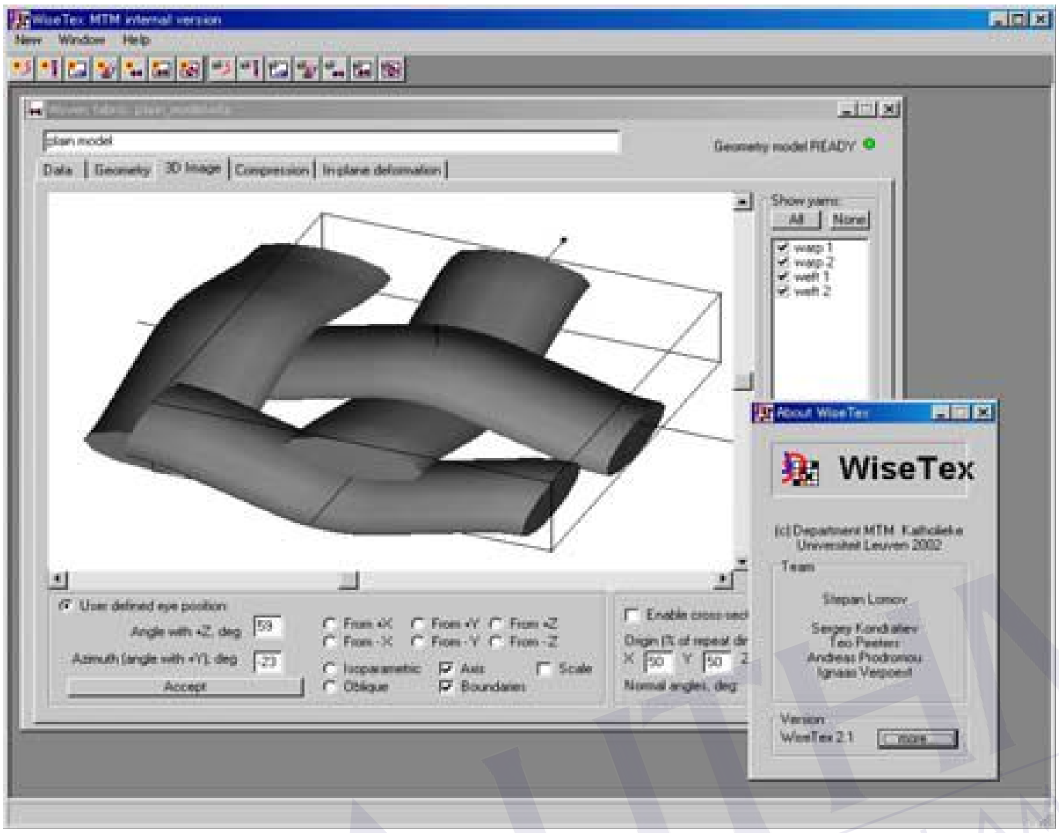

Figure 2.11: Geometrical modeling of 3D visual image by WISETEX program

(Tetsusei Kurashiki et. al, 2007)

2.6 Finite element modeling of yarns and resin

Hexahedron is used as a shape of a finite element of a yarn and the element is regularly generated so that an element coordinate system and the direction of a fiber may become equal. Figure 2.12 shows all the procedure for the finite element modeling. Figure 2.12(a) shows the position and direction of the cross sections form the WiseTex data. Delaunay method is used to generate the mesh of a cross section and the cross-sectional elements are combined to the neighbor element of another cross section. Figure 2.12(b) shows the repeated procedure in order to create the hexahedron elements of a yarn. Matrix cracks and delamination at the crossover parts of fiber bundle will influent the estimation of damage development of woven fabric composites and its may lead to complicated fracture modes in comparison with uni-directional fiber reinforced composites. Figure 2.12(b) show the yarn element was generated, the finite elements of matrix parts are generated on the circumference of a yarn shown in Figure 2.12(c).

Figure 2.12(d) shows the hexahedron elements are generated to connect the warp and weft yarns. Finally, finite elements in the upper and the lower parts of matrix are generated, and finite element model with yarns and matrix by the hexahedron element can be obtained as shown in Figure 2.12(e).

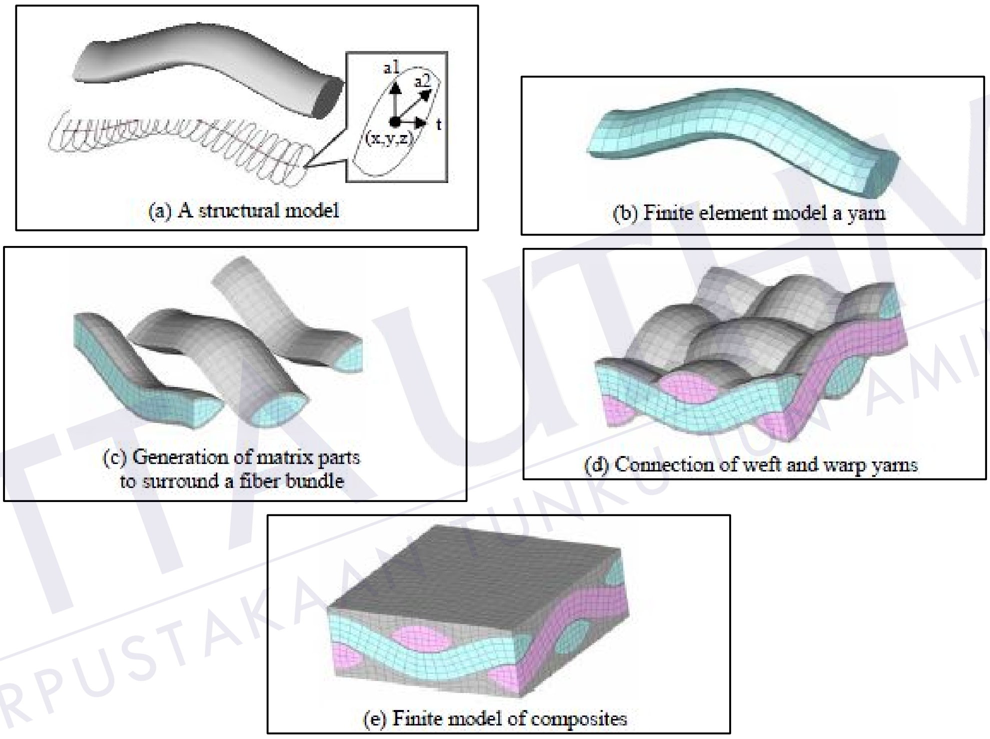

Figure 2.12: Procedure of finite element model of woven fabric composites

(Tetsusei Kurashiki et. al, 2007)

Figure 2.13 shows typical examples of finite element models with several fabric architectures based on the developed program MeshTex. Finite element models of a twill fabric and 3D fabric composites considering resin parts on the circumference of a yarn and 3 dimensional architecture of a yarn can be obtained easily using MeshTex.