AN EXPERIMENTAL AND FINITE ELEMENT ANALYSIS OF THE STATIC DEFORMATION OF WOOD SAWDUST- POLYPORPYLENE COMPOSITE PALLET

by

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LIST OF ABBREVIATIONS

ABS	- Acrylonitrile Butadiene Styrene
ANSI	- Amreican National Standards Institute
ASME	- American Society of Mechanical Engineers
ASTM	- American Standards Test Methods
CCD	- Coupled Charge Device
DT	- Destructive Test
ESPI	- Electronic Speckle Pattern Interferometry
FEA	- Finite Element Analysis
FOS	- Factor of Safety
FRP	- Fiber Reinforced Polymer
ISO	- International Standard Organization
ISS	- Interfacial Shear Strength
M	- Metric Coarse
MA	- Maleic Anhydride
MAPP	- Maleated Polypropylene
MOE	- Modulus of Elasticity
NDT	- Non-Destructive Test
OPFRC	- Oil Palm Fiber Reinforced Composite
PP	- Polypropylene
SEM	- Scanning Electron Microscopy
UNC	- Unified Coarse
UNF	- Unified Fine
UTS	- Ultimate Tensile Strength
WFRC	- Wood Flour Reinforced Composite
WSD	- Wood Sawdust
3-D	- Three-Dimensional

AN EXPERIMENT AND FINITE ELEMENT ANALYSIS OF THE STATIC DEFORMATION OF WOOD SAWDUST-POLYPROPYLENE COMPOSITE PALLET

ABSTRACT

In this research work, a conventional stringer-class natural fiber-composite pallet model was generated using *SolidWorks* modeler and its load bearing capabilities and structural strength were investigated using finite element analysis software (FEA), *Cosmos/works*. Among several natural fibers, namely wood fiber and wood sawdust (WSD)-polypropylene (PP) composite materials, wood sawdust (particle size 100µm) with 30% filler content and 70% PP matrix composite was selected with mechanical properties, tensile modulus of 2.7564 GPa and ultimate tensile strength of 14.95 MPa respectively. Besides, fastening study was carried out to determine a suitable fastening method and avoid premature damage caused by excessive drilling / fastening torque and unsuitable nominal size of fastener. The findings from fastening study show that smaller nominal size screws can be driven closer to the edge compared to larger one and minimum spacing between two screws is increased if the nominal size of screw increased. Besides, an appropriate nominal screw size and length for both full size and one-fifth scaled pallet model was determined in this fastening investigation. Lastly, the shadow moiré technique was applied to measure the deformation profile of one-fifth scale model of WSD-PP composite pallet under static load and the experimental results are compared with data obtained from FE analysis. Shadow moiré technique was initially verified using known cylinder profile and this verification showed a measurement error of less than 5%. In another verification study, the deflection of a 6061-aluminum plate was measured under static load. The experimental result of deflection at the centre of 6061-aluminum plate was 2.16 mm while 1.64 mm deflection obtained from FEA results. The comparative study of deflection profile of wood based composite pallet between experimental and modeling showed close agreement at the centre of the pallet model. The deformation difference was found to be large except at the center deck board of the pallet model. The difference between experimental and FEA results are mainly due to the assumptions made in FEA where all the joints of the pallet is considered as bonded and it may due to not totally well mixed between the fillers and polypropylene. This research shows that the structural strength of such complex natural fiber-composite structure such as a pallet can be analyzed using FEA and verified using the shadow moiré method.

‘EKSPERIMEN DAN ANALISIS UNSUR TERHINGGA UNTUK UBAH-BENTUK STATIK DALAM PALET KOMPOSIT GENTIAN KAYU’

ABSTRAK

Dalam penyelidikan ini, satu jenis bentuk traditional palet komposit gentian kayu telah direkabentuk dengan menggunakan perisisan ‘*SolidWorks*’ dan sifat ketahan-bebanan bagi palet ini dianalisis dengan menggunakan perisian unsur terhingga iaitu ‘*Cosmos/work*’. Antara beberapa jenis gentian semulajadi yang dibandingkan, komposit gentian kayu dengan komposisi kandungan 30% gentian kayu (saiz 100μm) dengan 70% plastik (polypropylene) dipilih disebabkan komposit ini mempunyai sifat mekanikal yang diingini seperti modulus kekenyalan yang bernilai 2.7564 GPa dan kekuatan tegangan muktamat yang bernilai 14.95 MPa. Sifat mekanikal adalah penting disebabkan eksperimen akan dijalankan untuk mengukur nilai statik ubah-bentuk palet komposit ini. Di samping itu, kajian ke atas kaedah pemasangan komponen-komponen palet yang sesuai untuk mengelakkan sebarang kerosakkan ke atas palet yang disebabkan oleh penggunaan kalis yang terlampau dan pemilihan skrew yang tidak sesuai. Rumusan dari kajian ke atas pemasangan skrew adalah skrew yang berdiameter kecil dapat dipasang dengan lebih dekat ke tepi atau hujung bahan yang dipasang berbanding dengan skrew berdiameter besar. Di samping itu, ruangan di antara dua skrew akan meningkat bergantung kepada saiz skrew yang dipilih. Selain itu, panjang dan diameter skrew yang sesuai juga ditentukan masing-masing untuk palet saiz sebenar atau palet di mana saiz menjadi 1/5 daripada model asal. Akhir sekali, teknik bayangan moiré telah digunakan untuk mengukur profil ubah-bentuk palet komposit gentian kayu yang bersaiz satu perlima daripada model asal di bawah keadaan beban statik. Hasil daripada eksperimen akan dibandingkan dengan keputusan dari analisa unsur terhingga. Teknik bayangan ‘moiré’ perlu disahkan dengan menggunakan paip silinder di mana jejari diketahui dan keputusan dari kajian ini menunjukkan sisihan pengukuran adalah kurang daripada 5%. Satu lagi kes

verifikasi di mana ubah-bentuk bagi kepingan aluminium berkod 6061 diukur di bawah keadaan statik telah dijalankan Keputusan menunjukkan bahawa ubah-bentuk di tengah-tengah kepingan aluminium adalah 2.16 mm dan 1.64 mm antara eksperimen dan analisa unsur terhingga. Eksperimen terakhir melibatkan kajian ubah-bentuk ke atas palet komposit gentian kayu dan perbezaan adalah kecil antara keputusan eksperimen dengan analisa unsur terhingga semasa ukuran dibuat ke atas tengah-tengah 'deck board' palet komposit Walaupun begitu, perbezaan menjadi besar dan sukar diramal selain dari tengah-tengah 'deck board' palet komposit. Perbezaan yang besar mungkin disebabkan oleh sifat tidak homogen bagi bahan yang digunakan ataupun disebabkan juga oleh anggapan yang tidak sama dibuat seperti kesemua pemasangan mekanikal antara palet dianggap lekat bersama ('bond') semasa dalam analisa unsur terhingga.

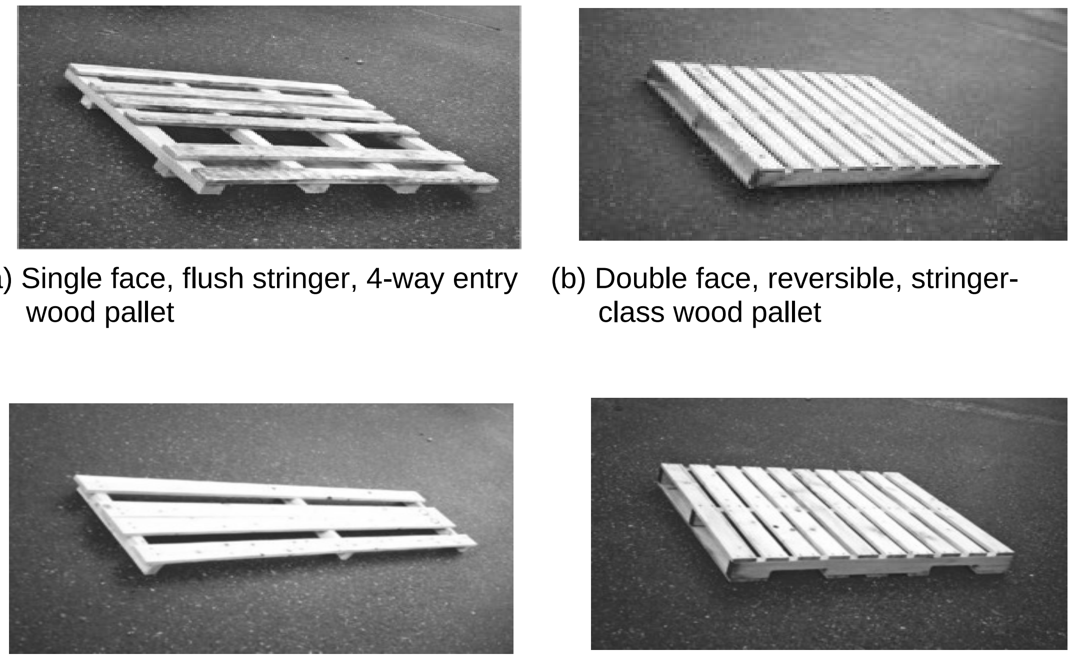
CHAPTER 1

INTRODUCTION

1.0 Introduction

Pallets are widely used in most industries for material handling. Various designs and types of pallet are fabricated mainly due to different load bearing requirements. For instance, there are stringer-class pallets, block-class pallets, panel deck pallets, grocery industry four-way pallets and so on. The pallets are designed so that products/goods can be easily retrieved and delivered using lift truck such as forklift or pallet jack. Most of the pallets are made of wood (see Figure 1.1) and nearly 400 million wood pallets are produced annually, accounting for 86 percent of all pallets sold (McCoy, 2003). However, wooden pallets have some disadvantages although they are cheap compared to non-wood pallets such as plastic pallets. Among these are: (i) wood can undergo degradation due to environment factors such as heat, moisture and fungal infection especially when used in the open space, (ii) the method of fastening various members of the wooden pallet usually by nailing or screwing, does not guarantee a reliable performance of the pallet over a period of time and (iii) excessive use of wood in production of pallets require a lot of trees, causing forest depletion and thus leading to environment problems such as landslide and flood (Moore *et al.*, 2002) .

In view of this, some pallet manufacturers worldwide used metals, such as steel, aluminum and plastics in place of wood (see Figure 1.2(a)-(b)).The plastic pallets which are lightweight, high strength and durability are increasingly used instead of conventional wooden pallets (Ohanesian, 2002). However, the non-wooden pallets are more expensive compared to the wooden pallets. Plastic pallets are more expensive than the wood pallets by three to five times but this cost can be offset by the number of trips and shipments that can be achieved with plastic pallets compared to wooden pallets (William, 2002). One main disadvantage of using plastic pallets is that non-biodegradable plastic is hazardous to human and environment when disposed by burning.



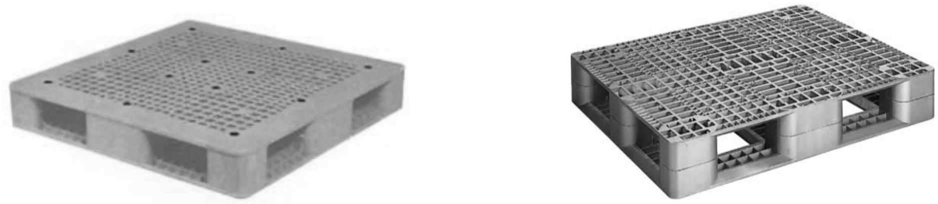
(a) Single face, flush stringer, 4-way entry wood pallet

(b) Double face, reversible, stringer-class wood pallet

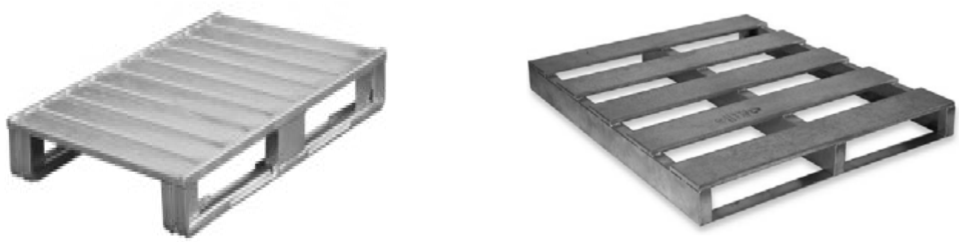
(c) Single face, flush stringer, 2-way entry wood pallet

(d) Double face, non-reversible, 4-way notched wood pallet

Figure 1.1: Various designs and types of wooden pallets. *Resource: Larson pallet company. http://www.larsonpallet.com (2002)*.



(a) Block-class plastic pallets



(b) Sheet steel and aluminum pallets

Figure 1.2: Various designs and types of non-wooden pallets. *Resources: Plastic pallet and container, Inc*. *http//www.pp-c.*com *and Metal Pallet Corporation*. *http://www.metalpallet.com*. (2000).

The interest in using natural fibers, such as sisal, oil-palm empty fruit bunch fibers, coconut husk fibers, jute fibers and wood fiber as reinforcement in plastics has increased dramatically for the past few years, and undoubtedly, environmental concern is one of the driving forces (Oksman *et al.*, 2002 ;Bledzki *et al.*, 1999; Bledzki *et al.*, 2001; McHenry, 2003). Natural fibers have some advantages compared to man-made fibers. For instance, natural fibers are easily available, have low density, and are bio-degradable. They are renewable raw materials and have relatively high strength-to-weight ratio (Oksman *et al.*, 2002 ;Bledzki *et al.*, 1999; Bledzki *et al.*, 2001; McHenry, 2003). Although the natural fiber-reinforced composite pallets could also undergo degradation due to attack by micro-organisms, the resistance to microbiological degradation can be improved by means of chemical modification (Hill and Khalil, 2001). With the current emphasis on recycling and environmentally friendly approaches to manufacturing, composite pallets made from waste fibers and recycled plastic (polypropylene) have significant potential for use as raw material in the fabrication of pallets for the material handling industry.

According to Stokes (1989), joining of plastic or plastic composites is becoming important because the composites are increasing used in structural assemblies. Besides, applications of polymeric materials and composites require structural joints that must withstand static and fatigue loads. Unlike joining of metal structures, only mechanical fastening and adhesive bonding can be used for polymer matrix composites (Vinson, 1989; Stokes, 1989). Mechanical fasteners such as wood screws and tapping screws are used in the fabrication of the composite pallet in this research. The advantage of mechanical fasteners is that, despite their design simplicity, they provide high clamping forces and the structure can be disassembled easily for maintenance (Mackerle, 2003). Fasteners are designed and selected for specific applications so that each connection can transmit forces adequately and provide satisfactory performance for the life of the structure (Committee of ASCE, 1997). With this reason, fastening study was carried out in order to ensure joining of various components of the composite pallet will not causing cracking and failure of the pallet while it is performing its intended function.

The load bearing capabilities of the natural fiber composite pallet need proper and careful design before turning into end-user products and this can be done using computer simulation (Lim *et al.*, 2003; Qiao *et al.*, 1998; Wang & Lam, 1997; Wu *et al.*, 2003). The pallet can be generated using 3-dimensional solid modeler such as *SolidWorks* and *ProEngineer* while structural analysis of the product can be done using finite element analysis such as *Cosmos/Works* in this case. This can reduce the fabrication of actual prototype in field testing, thus saving overall cost and time involved in product design. Besides, for materials such as wood fillers composite material, comparative study between the experimental and FEA should be carried out to ensure the agreement between these results.

In a closely related research carried out by Lim Jiunn Hsuh (MSc.Thesis, 2002) from School of Mechanical Engineering (USM), comparative study of the static deformation of oil palm fiber composite pallet between experimental and FE analysis was done. Lim designed and modeled one type of oil palm composite pallet and use phase shift shadow moiré method in optical measurement. Small rig was fabricated in order to applied point load at the centre of the pallet. The difference between Lim's work and the work carried out in this research are explained in the next section.

1.1 Research Problems

Wood fiber composites have potential of replacing man-made fiber composite such as glass fiber composites in load bearing applications mainly due to its low cost and availability (Hattotuwa *et al*., 2002; Hill & Abdul Khalil, 2000). The utilization of agro-waste material such as wood sawdust and oil palm empty fruit bunch fiber instead of glass and carbon fibers can reduce the cost of the composite material significantly. Besides, studies carried out in this field have shown that stiffness, hardness and dimensional stability of plastics could be improved by the incorporation of these types of fillers (Hattotuwa *et al*., 2002; Ismail & Jaffri, 1999).

Use of such composite material in load bearing applications usually requires a careful study and design of the component or product to be made. This can be achieved using numerical modeling software such as finite element analysis (FEA) software (Lim *et al.*, 2003; Wu *et al.*, 2003). However, the accuracy of the input parameters such as mechanical and physical properties of material, loading and constraint conditions plays an important role in the correct prediction of the structural behaviour of the composite from numerical analysis. Mechanical testing is usually carried out in order to determine the mechanical property of the composite but this may not be representative of the whole structure due to non-homogeneity of the material and sometimes due to the presence of internal flaws like moisture and delaminations within the material. Ambiguous mechanical property may affect the prediction of structural behaviour from FEA and this could result in failure of the structure under service.

The predictions of FEA can be verified by experimental means, that is, by direct measurement of deformation. In the conventional point-wise surface measurement using instruments like digital calipers and strain gages, where the measurement was carried out point-by-point or line-by-line basis, the collection of many data points sometimes may cause errors like missed data points, including the highly stressed or deformed areas of the structure. Besides, direct contact with measuring equipment may influence the deformation resulting in erroneous data. With these reasons, a non-contact measurement technique is needed for surface measurement. There are several techniques available for measuring deformation such as the moiré method, electronic speckle pattern interferometry (ESPI), holography and shearography interferometry (Chen *et al.*, 2000). This subsequently raises the issue of how to analyze the data in a highly accurate manner and perform local and global coordinate transformation.

Moiré method was selected in this research due to its simplicity in implementation and is most cost effective compared to the other techniques. Besides, this method is suitable for measuring large deformation that is outside the range of the interferometric methods, for instance in the order of millimeter. However, the main drawback of the shadow moiré technique is that it is not sensitive enough for practical applications and requires a reference grating larger than the size of the object.

This research project aims at a comparative study of the experimental and FEA deformation result of a wood filler composite structure under static loading. The shadow moiré technique was applied to measure the static deformation of the wood filler composite pallet. The composite pallet was modeled and analyzed using FEA. A one-fifth scale pallet model was fabricated and assembled using mechanical fasteners. The pallet model was used in the measurement. The difference between the optical measurement and FEA results was investigated.

1.2 Research Objectives

The main objective of this project is to compare the deformation profile from the optical measurement and FEA for static loaded wood fillers composite pallet with the aim of understanding the capability and limitation of using FEA in designing products made from the composite material.

In order to achieve the main objective, the following sub-objectives were identified:

1. To design natural fiber reinforced composite pallet using computer modeling and investigate the load capability and study the strength characteristic of various composite pallet using finite element analysis (FEA). The materials used are such as:
   - (i) Oil palm empty fruit bunch + Acrylonitrile-Butadiene-Styrene (ABS);
   - (ii) Oil palm empty fruit bunch + Polypropylene (PP);
   - (iii) Oil palm pulp fiber + Polypropylene (PP);
   - (iv) Coarse wood sawdust + polypropylene (PP);
   - (v) Wood flour + polypropylene (PP);
   - (vi) Polypropylene plastic

2. To optimize several dimensions of the parts such as thickness of stringer and width of the deck board of the pallet for raw material saving purpose.
3. To study the effect of screws size and types, pilot hole size, spacing distance between two screw, edge and end distance of screw to the fastening members during pallet assembly.

There are a few important points that differentiate between this research work and previous work done by Lim Jiunn Hsuh. First of all, thermoplastic to be used in this research is a recycled polypropylene from industrial waste plastics whereas Lim used thermoset resin as the matrix. Besides, wood fillers were used in this research while oil palm empty fruit bunch fiber was used in previous work. Secondly, several designs are be made under the same load conditions and analyzed under two support conditions, namely 'stacked one unit load high' and 'racked across width', so that the condition of the pallets under racking system in a warehouse is taken into consideration. Besides, study of the strength characteristic of various composite pallets, as well as optimization study for cost saving purpose was done unlike previous where only one type of natural fiber-reinforced composites pallet was designed and no attempt to optimize the design was made. The new experimental rig for deformation measurement on the composite pallet was designed and built. The deflection profile of an aluminum plate was studied as verification between optical measurement data and FEA results. An additional piece of study carried out in this research that was not attempted in the previous work was the study on the fastening of the composite material.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

This literature study focuses on the review of using composite materials in complex product design such as a composite pallet. Comparative studies on finite element analysis (FEA) and experimental work on the behaviour of the product, as well as products composed of composite materials carried out worldwide by other researchers are reviewed. Besides, literature studies on the application of non-destructive and non-contact whole field optical measurements methods are reviewed as well. The optical techniques such as shadow moiré, projection moiré, holographic interferometry and shearography techniques used to measure deformation in composite materials are reviewed and a suitable technique for the experiment was selected for this research is proposed. Literature study on fastening method on composite materials is done in order to aid in assembly of pallet model.

2.1 Agricultural Waste Composites

Strict enforcement of government regulations and a growing environmental awareness throughout the world have lead to increase of interest in using biomass / agricultural waste incorporate with thermoplastic matrices to make composite product instead of using wood alone. Utilization of these agro-wastes as reinforcing fillers with thermoplastic is believed to replace the use of traditional reinforcing materials such as glass fiber and carbon fiber to reduce the cost of composite product while maintaining their desired properties (Hanafi *et al*., 1996; Hattotuwa *et al*., 2002; Karnani *et al*., 1997; Bledzki *et al*, 1999; Tomoyuki & Qin, 2002). Furthermore, one of the main disadvantages of using glass fiber is the occurrence of health problem when handling glass fiber. Examples of agricultural waste fibers are sisal fibers, kenaf fibers, jute fibers, wood fibers, oil palm empty fruit bunch fibers and coir which offer several advantages like biodegradability, recycle-ability, low density, high toughness and acceptable specific strength properties (Bledzki *et al*, 1999; Karnani *et al*., 1997; Wollerdorfer & Bader, 1998; Hill & Abdul Khalil, 2000).

Many studies carried out in this field have shown that stiffness, hardness, dimensional stability of plastic could be improved by using of the natural fibers or fillers. For instance, Hattotuwa *et al*. (2002) on compared the mechanical properties of rice husk powder filled polypropylene composite with talc filled polypropylene composite and Hanafi *et al*.' s work (1999) concerns on determining the mechanical properties of oil palm wood flour filled with natural rubbers. Research works on determining mechanical properties of sisal-epoxy composites (Oksman *et al*., 2001), natural fiber reinforced polyurethane microfoams (Bledzki *et al*., 2001), treatments and mechanical properties of wood flour-polypropylene composites (Ichazo *et al*., 2001) are reviewed. All of these works revealed that polymer matrices can be reinforced using natural fibers or fillers as reinforcing agent. In other words, enhancement in mechanical properties of the composite occurs if the compatibility / interaction between natural fillers and thermoplastic and dispersions of the fillers in the polymeric matrices were achieved. Incompatibility between natural fillers and polymeric matrices usually result in weak interfacial adhesion, and thus leads to inferior mechanical properties.

The researchers believe that if the interaction can be improved, the composite could be given better mechanical properties and better particle dispersion. They pointed out that the efficiency of a fiber reinforced composite depends on the fiber-matrix interface and the ability to transfer stress from the matrix to the fiber. This stress transfer efficiency plays a dominant role in determining the mechanical properties of the composite. Based on this hypothesis, many approaches have been carried out, such as the use of several kinds of compatibilizers and modifications with maleic anhydride (MA) (Coutinho & Costa, 1999; Karnani *et al*., 1997; Kazayawoko & Balatinecz, 1997; Oksman, 1996), chemical modification by acetylation (Hill & Abdul Khalil, 2000) and silane or titanate as coupling agents (Hill & Abdul Khalil, 2000; Kokta *et al*., 1990).

In Karnani *et al*.'s research work (1997), mechanical testing was carried out on kenarf fibers with polypropylene (PP) composite. Kenaf fibers were surface-grafted with siloxane chains using silane solution in water while maleic anhydride modification of polypropylene powder was used as matrix. A fixed percentage of maleated polypropylene (MAPP) as compatibilizer was mixed with polypropylene in the composite. Results showed that addition of kenaf fibers to the polymer matrix caused a significant increase in the tensile modulus or stiffness of the composite. The compatibilized PP-kenaf composites exhibit greater tensile strength than the uncompatibilized composites or just PP. This may be due to the enhanced of interfacial adhesion resulting from the presence of a matrix with increased of polarity that may react or interact with the hydroxyl group on the fiber surface. Evidence provided from Scanning Electron Microscopy (SEM) micrograph of the fracture surface of notched Izod specimens showed a significant improvement bonding with addition of the MAPP, where the fiber has pulled out from the matrix but a fair amount of polymer residue remains on the fiber explained by Karnani *et al*. (1997). Similar results were obtained from Kazayawoko & Balatinecz (1997) who investigate the effect of ester linkages on the mechanical properties of wood fiber-polypropylene composites. They prove that compounding of wood fiber under surface modification with maleated polypropylene and polypropylene matrix has improved the mechanical properties with explanation that the treatment of wood fibers with maleated polypropylene reduces the formation of agglomerates and wood fibers are dispersed more uniformly. The dispersion of fiber was analyzed using the Confocal Imaging System.

Hill & Abdul Khalil (2000) has investigated the effect of chemical fiber treatments on mechanical properties of coir or oil palm fiber reinforced polyester composites. The coir fibers and oil palm fibers with chemical modifcation by acetylation were used in the experiment. Comparison was done between fibers without treatment, acetylated fibers and fibers treated with silane and titanate coupling agents. The results showed that acetylation of fibers increases the interfacial shear strength (ISS) in all cases compared to the unmodified fibers. They used ANOVA test to show that there was no significant differences in ISS between coir and oil palm fiber, but there was a different between modified and unmodified fibers. These results indicate that acetylation of the fibers has improved the compatibility between the fibers and matrix in both cases as mentioned above. In addition, slight increase in the tensile strength, tensile modulus and impact strength of composites reinforced with modified fibers are noted. However, treatment of fibers with silane or titanate coupling agents does not result in significant changes of the composite formed.

A lot of work was done in the past on determining the mechanical properties of various composite material using natural fibers/fillers as reinforcing agent. Improvement of the mechanical properties of the composite was achieved with proper use of compatibilizers and chemical treatments. From the reviewed work, most existing products made of natural fiber reinforced composites were restricted to low-load or even load free applications such as automotive interior substrates, partition boards, fencing and window frame. With the abundant of agro-wastes and recycled polypropylene in Malaysia, it has great potential to use the composite material in high load bearing applications like material handling pallets.

2.2 Finite Element Analysis

The finite element concept is derived from the stiffness matrix for the triangular element based on the displacement and this triangular element is named as mesh (Martin & Carey, 1973). The development of FEA was greatly aided by developments in the computer industry, provides larger storage capacities for larger problem to run and modeling more accurate physical situation. It is not reasonable to expect designers to calculate those complex interactions and solutions using manual methods.

There are many journal papers worldwide using of FE analysis to predict the behavior of the products they are going to design, such as Qiao *et al.* (1998) using of finite element model to predict the response of the composite reinforced wood crosstie; Mahdi *et al.* (2002) using of FEA modeling to predict the mechanical performance of repaired stiffened panels. However, in this paper, the failure displacement from modeling was calculated to be 28% lower than experiment, they explained that the current finite element (FE) model which do not take into account the interaction of the repair plugs and the wall of the cut-out, and lead to the poor prediction when compared to experimental results. Besides, finite element analysis of impact damage response of composite motorcycle safety helmets was done (Kostopoulos *et al*., 2002). In this paper, they presented a basic shell structure comprising of a woven fabric and a glass mat ply with three different woven fabric reinforcement materials and the shell structure were analyzed using FE simulation of drop tests. This is one of the advantages from finite element analysis where various composites can be used in computer modeling without involving fabrication of many different prototypes, hence reducing the total cost and time saving in testing and manufacturing of new products.

According to Wu *et al.* (2002), use of finite element method to predict the performance of the fiber reinforced polymer (FRP) sandwich composite could lower cost and have accurate prediction of structural behavior of FRP. However, several assumptions were made in the model in order to achieve an agreement with finite element, such as that the material is homogeneous and linearly elastic in each layer and displacement in z-direction is small and interfacial layer is under anti-plane shear and shear stress throughout the plate thickness is uniform. Experimental work done by Lim *et al.* (2003) in experimental and finite element analysis of the static deformation of natural fiber-reinforced composite beam had revealed the assumptions like plastic and reinforcing agent are acted together and the matrices and fiber are equally mixed and the composite is obeying Hooke’s law. He also revealed that many heterogeneous composite materials are having non-linear and anisotropic material properties and these materials sometime have to be treated as homogeneous as well in order to simplify the analysis.

In another work carried out by Van Paepegem *et al*. (2001) to investigate the fatigue behaviour of reinforced composite materials, FEA simulation was used to compare against the results of fatigue experiments on plain-woven glass / epoxy specimens with a

[#45°] stacking sequence. They established a FE model that is incorporated in commercial FEA code which is able to deal with two conflicting demands: The first one is that the continuous stress redistribution requires the simulation to follow the complete path of damage states and simulation should be fast and efficient in order to save time in the stage of composite components designing.

2.3 Joining Methods for Plastics and Plastic Composites

According to Vinson, J.R. (1989), for structures composed of polymer and polymer-matrix composite materials, the components must be joined so that the overall structure will retain its structural integrity while it performs its intended function including both mechanical loads (static or dynamic) and environmental loads (temperature and humidity). Joining of plastics and plastic composites is become more and more important because of increasingly used of these materials in complex structural assemblies while the emerging structural applications of polymeric materials require structural joints that must withstand static and fatigue loads (Stokes, 1989).

There are various joining methods such as riveting, bolting, glueing, brazing, soldering as well as the welding method. Among these, adhesive bonding is preferred in use compared to mechanical fastening. This may due to a continuous connection that can be formed by using adhesive bonding. Besides, drilling holes for bolts or rivets induce to remove fiber or other reinforcements and thus leads to large stress concentrations at discrete fastener hole (Vinson, 1989).

Two journal papers by Vinson (1989) and Stokes (1989) are just a review paper of the joining methods that being used for the past decades. However, there are no standard being developed to specify a suitable joining method for particular polymeric or polymer-matrix composite. With this reason, fastening study is necessary to carry out to investigate the effect of the process parameters that are involved and affect the joint performance of the composite materials used in this research. Optimal joint designs for wood based composite hopefully can be developed from the fastening study.

2.4 Optical Metrology

Experimental studies are normally used to validate the results from numerical analysis and there are many experimental tools which can be divided into two categories: one with conventional destructive test and point wise contact measurements while the others are non-contact, non-destructive and whole field measurements (Cichocki & Thomason, 2002). Optical metrology is categorized as a non-destructive and non-contact measurement. Optical measurement is suitable in this research since optical techniques are non-contacting and they can detect surface displacement or deformation that result from the application of small load.

Various optical techniques are available including holographic and shearography methods which are based on interferometric principles. According to Hung *et al.* (2000), full field optical methods for 3-dimensional shape measurement are basically divided into two categories: coherent light methods and incoherent light methods. The coherent light methods are as mentioned above while the incoherent light methods can be further classified to shadow moiré and projection moiré methods.

In general, holographic interferometry is suitable for both in-plane and out-of-plane stress and displacement measurements (Lim's MSc. thesis, 2002). In contrast of this, shadow moiré and shearography techniques are more suitable for out-of-plane displacement and deformation, including surface profiling (Shang *et al.*, 2000). Shadow moiré technique was selected in the research is due to its simplicity in experimental set-up and does not require expensive equipments in the experiment compared to shearography method. In addition, one of the attractive features of moiré is that the resolution of the fringe pattern can be controlled by varying the pitch value of the grating. Besides, laser scanning techniques are also available for non-contact measurement. However, they are not in the option because this method requires point-by-point or line-by-line basis.

There are many journal papers in which moiré method for out-of-plane displacement or deformation are applied. For instance, Jin *et al*. (2000) used shadow moiré technique with integrated phase-shifting method in measuring the computer mouse. Quan *et al*. (1999) used the fringe projection technique for three-dimensional shape measurement of a hydroformed shell. A review paper of three-dimensional shape measurement using optical method was written by Chen *et al*. (2000). In this review paper, various three-dimensional optical measurements are reviewed. Besides these, there are other techniques, such as the time/ light in flight and photogrammetry. The time/ light in flight method for measuring shape is based on direct measurement of the time of flight of a laser or other light source pulse while photogrammetry employs the stereo technique to measure three-dimensional shape. Global and local coordinates translation and selection of camera model and system calibration are discussed in the review paper. Error in measuring or calculating the global and local coordinates will cause in low accuracy in final results while calibration of optical system is required in order to avoid error due to misalignment of optical set-up.

Most of the past research in optical metrology focused on measurement and generation of three-dimensional model except Lim *et al*. (2004) who applied phase-shifting shadow moiré method in measuring static deformation of composite pallet and compared the measurement with the prediction of FEA.

2.5 Summary

From the reviewed work on natural fiber reinforced composite (NFRC), most existing products made of NFRC were restricted to load free applications. With the abundant of agricultural wastes and recycled PP in Malaysia, it has great potential to use the composite material in high load application like material handling pallets. The literatures about the application of FEA in natural fiber reinforced composite are reviewed. Good understanding on mechanical behaviour of the products is needed to aid in designing and analyzing such a complex product. For the experimental techniques, the discussions are focused on the non-contact and non-destructive optical measurements. There was no literature about the application of optical metrology in wood based composite materials. From the literature on the optical metrology, shadow moiré was used due to its simplicity in experimental set-up and does not require expensive equipments in the experiment.

CHAPTER 3

SOLID MODELING AND FEA ANALYSIS OF COMPOSITE PALLETS

3.0 Introduction

Proper and careful designs of the structures made from these composite materials are required in order to ensure success in applications. The load bearing capabilities of the natural fiber composite pallets must be investigated before turning into end user products and this can be done using computer simulation (Lim *et al.*, 2003; Qiao *et al.*, 1998; Wu *et al.*, 2003). The pallet model can be generated using three-dimensional solid modeler such as *SolidWorks* and *Ideas* while structural strength analysis of the product can be done using finite element analysis (FEA) software like *Cosmos/works* and *Ansys*. Besides designing and analyzing the pallets, the product design can be optimized using computer modeling. These indirectly reduce overall cost and time spent in the fabrication and testing of the prototype.

This chapter presents the modeling of stringer-class and block-class pallet using *Solidworks* modeler using dimensions given by an example of *Pallet Design System* (PDS) software (http://www.nwpca.com/PDS/PalletDesignSystem.htm, 2003). Simulations of the load bearing capabilities of various natural fiber composite pallets were carried out under two support conditions using finite element analysis (FEA) software. Material properties of various natural fiber composite materials were obtained from Shanaz *et al*. (2003). Lastly, optimization of several parts of the pallet was carried out and dimensions of full size pallet that would be used for the later research work were finalized. The purpose of pallet optimization is to reduce the use of raw materials in pallet fabrication while maintaining its load bearing requirement.

3.1 Methodology

3.1.1 Introduction of Pallet Terminology

A pallet is a standard platform on which material is placed for storage and movement. These are platforms with an upper and lower flat surface with space in-between for easy lifting by the fork of an industrial lift truck such as forklift and pallet jack. Generally, the pallet is an assembly of deck boards, which are the boards that make up the faces of a pallet and either carry or rest upon the goods packed; stringers are the runners to which the deck boards are fastened and which serve as a spacer between the top and bottom decks to permit the entry of mechanical handling devices. For block-class pallet, blocks are square or rectangular parts employed on some four entry pallets in place of stringers and which serve the same purpose as runners (Kulweic, 1985).

United States began to use pallet standards in 1953 under the auspices of the organization now known as the American National Standards Institute (ANSI). The committee has responsibility for developing standards for pallets, slip sheets and other bases for unit loads. The first standard was published in 1959, revised in 1965 and subdivided into 3 standards:

MH1.1.2-1978 Pallet Definitions and Terminology;

MH1.4-1977 Procedures for Testing Pallets;

MH1.2.2-1975 Pallet sizes (12 standard sizes with dimensions stated in imperial inches and comparable hard and soft metric dimensions as shown in Table 3.1).

Table 3.1: Standard pallet dimensions. *Resource*: *Kulweic, 1985*.

Imperial (inches)	**Hard metric (inches)**	**Hard metric (millimeters)**	**Soft metric (millimeters)**
24×32	23.64×31.52	600×800	609×812
32×40	31.52×39.40	800×1000	812×1016
32×48	31.52×47.28	800×1200	812×1219
36×42	35.46×41.75	900×1060	914×1066
36×48	35.46×47.28	1060×1200	1066×1219
40×48	39.40×47.58	1000×1200	1016×1219
42×54	41.75×53.96	1060×1370	1066×1371
48×60	47.28×59.10	1200×1500	1219×1523
48×72	47.28×70.90	1200×1800	1219×1828
36×36	35.46×35.46	900×900	914×914
42×42	41.75×41.75	1060×1060	1066×1066
48×48	47.28×47.28	1200×1200	1219×1219

Besides, others standardized method for testing pallets are such as ASTM D1085-1973 provided by the American Society for Testing and Materials and ISO 8611-1991 by International Standard Organization.

According to Kulweic (1985), dimensions of pallets should be always stated in inches and parameter 'Length' should be designated before 'Width'. The 'Width' should always be the dimension parallel to the top of deck board. Besides, no deck boards shall be less than a nominal size of 4 inches (101.6 mm) board wide and not more than a nominal size of 8 inches (203.2 mm) board. Nevertheless, the thickness of the stringer must always be more than 3.25 inches (83.0 mm) because the thickness of the fork tine for the pallet jack is approximately 83.0mm. With this reason, deck board width, deck board spacing and thickness of stringer become important parameters that need to be considered properly during pallet design in order to produce a usable pallet. All pallets should not have less than the following number of blocks or stringers as shown in Table 3.2. For deck board lengths over 48 inches, it is recommended that additional stringers or blocks be used.

Table 3.2: Information of numbers of stringers or blocks required for different deck board length. *Resource: Kulweic, 1985*.

Deck board Length	Number of Stringers	Number of Blocks
Not exceeding 24 inches (609.6mm)	2	6
25- 48 inches	3	9
Over 48 inches	3	9

On the other hand, styles and types of the pallet also have to be noticed during pallet design so that pallet fabrication retain its structural integrity while saving material in fabrication, and hence, reducing cost for pallet production. There are two-way and four-way pallets which permit the entry of mechanical handling device from two sides and four sides respectively. Besides, there are many types of pallet with combination of style and construction such as: (1) single-face, non-reversible pallet; (2) double-face, flush stringer or block, non-reversible pallet; (3) double-face, flush stringer or block, reversible pallet; (4) double-face, single wing, non-reversible pallet and etc (Refer to Figures 1.1 and 1.2). Each type of the pallet will serve its own function in carrying goods or storage (Kulweic, 1985).

3.1.2 Solid Modeling of Full Size Pallet

Solid modeler software, *SolidWorks* is mechanical design automation software that takes advantage of the familiar *Microsoft®* *Windows®* graphical user interface. This easy-to-learn tool makes it possible for mechanical designers to quickly sketch out ideas, experiment with features and dimensions and produce models and detailed drawings. Several advantages of this software are such as creating 3-dimensional parts and using these 3-dimensional parts to create 2-dimensional drawings and 3-dimensional assemblies and vice versa. *SolidWorks* is a dimension driven system which specifies dimensions and geometric relationships between elements and changing dimensions will change the size and shape of the part while preserving its design intent and so on (*SolidWorks* user guide, 2001). Due to the advantages aforementioned, *SolidWorks* was chosen in this project.

A 3-dimensional pallet model with 48" (L) × 40" (W) × 5" (H) was built using *Solidworks* modeler. This pallet model is a conventional stringer-class, double face and non-reversible pallet (Figure 3.1) and the detailed dimensions of its parts were referred to one of the examples provided in *Pallet Design System* (*PDS*) software (http://www.nwpca.com/PDS/PalletDesignSystem.htm, 2003). This software was used by many pallet manufacturers worldwide as an aid in pallet design and analysis. This pallet model is an assembly of two different dimensions of top deck and bottom deck boards and stringers that serve as runners. The detailed dimensions are given in Table 3.3. The important factor during pallet modeling is calculation of the spacing between deck boards and distance between the stringers. With known quantities and dimensions of the parts required in pallet modeling, the spacing or distance between them can be calculated without difficulty. For instance, with known information of total length of the pallet, 48", and width of the deck board, 4.5" with quantity 7, the spacing distance can be calculated by {48"- (4.5"×7)}/6, that is 2.75" between two deck boards. It is encouraged to draw a simplified side view and end view of the pallet (Figure 3.2(a)-(b)) during modeling while determining spacing and distance between deck boards or stringers because these drawings would be very helpful in later assembly of full size pallet.

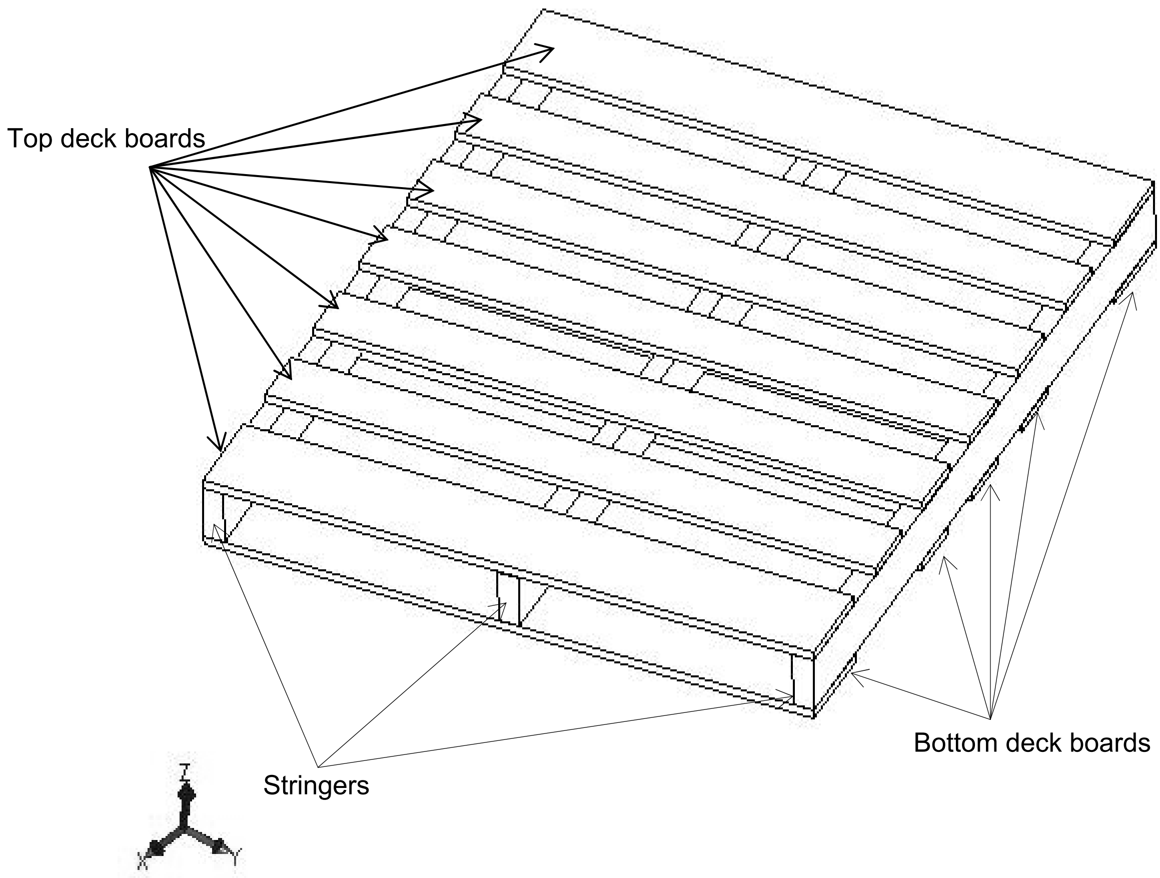


Figure 3.1: Solid modeling of conventional stringer-class pallet.

Table 3.3: The detailed information of quantities and dimensions of the parts that used in fabrication of stringer-class pallet. *Resources: http://www.nwpca.com/*.

Name of part	**Quantity**	**Dimensions, inches (.in)**
Top deck board 1	2	40.0” (L) × 5.75” (W) × 0.625” (H)
Top deck board 2	5	40.0” (L) × 3.75” (W) × 0.625” (H)
Bottom deck board 1	2	40.0” (L) × 5.75” (W) × 0.625” (H)
Bottom deck board 2	3	40.0” (L) × 3.75” (W) × 0.625” (H)
Stringer	3	48.0” (L) × 1.375” (W) × 3.75” (H)