WOOD-BASED TRI-AXIAL SANDWICH COMPOSITE MATERIALS: DESIGN, FABRICATION, TESTING, MODELING AND APPLICATION

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ABSTRACT

As the demand for sustainable materials increases, there are unique challenges and opportunities to develop light-weight green composites materials for a wide range of applications. Thus wood-based composite materials from renewable forests may provide options for some niche applications while helping to protect our environment. In this paper, the wood-based tri-axial sandwich composite materials either made from hardboard or laminated paper are being studied for various applications having different performance requirements. The wood-based tri-axial sandwich composite is composed of a tri-axial interlocking structural ribbed core bonded to stiff and strong faces with or without reinforced synthetic fiber fabric. Foam can also be selectively filled in the core to achieve specific performance requirements. The geometrical dimension of each component of the tri-axial sandwich composite can be optimized to achieve in the full use of material. Both static and dynamic performance is studied to help determine failure criterion of the wood-based sandwich composite panel. The panel is also being analyzed using compression test, bending test, buckling test, and fatigue test, the results shows these tri-axial composites have excellent mechanical performance. Furthermore, the equivalent analytical and finite analysis models were developed to simulate the mechanical behavior of the wood-based tri-axial sandwich composites for optimal design. The possible options and applications for the wood-based sandwich composite materials were also discussed.

1. INTRODUCTION

Sandwich panels with high strength to weight ratios are used for a variety of packaging, building, transportation, aerospace and marine applications [1-5]. Sandwich panel efficiencies are achieved by optimizing geometry and selective placement of materials for the faces and core to optimize performance characteristics. Marine and aerospace applications have the most demanding design requirements of strength-to-weight ratio and use the highest strength materials [6, 7]. These sandwich composites are generally produced utilizing metal or fiber reinforced polymer (FRP) materials. Recently, developments and future trends for sandwich composite materials were compared by Karlsson [8]. The typical structural forms can be produced using various cores (i.e.: foam, honeycomb, corrugated, trusses, and grid core), each of them having unique characteristics for specific applications. A literature review on cellular core material was presented by Gibson and Ashby [9]. Typically, sandwich structural composites are fabricated

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using honeycomb construction for the core structure. Honeycomb cores can be made from natural or artificial materials. Those made principally from wood-based fiber provides a composite with minimal density and high mechanical properties [10]. The paper honeycomb cores are made from linear ribs that are selectively bonded along the length and then pulled open to form a roughly shaped hexagon having a rib angle of near 0 and 60 degrees from the linear-direction. Thus, the effective hexagon rib alignments are generally 120 degrees apart and the ribs are segmented and not continuous. The hexagonal rib alignment improves stiffness in all planer directions, but the effective stiffness in the primary rib direction is slightly higher due to the double bonded area of the original linear ribs.

Another core concept called an isogrid structure was made from aluminum first proposed in the field of aerospace by Robert R. Meyer in 1964. He showed that this structural pattern of triangular trusses was very efficient [11]. Since that time, many other researchers have studied this structure's mechanical behavior, manufacturing methods, and applications [12-13]. Its enhanced mechanical performance has been extensively researched for axial compression, bending, and torsion for aircraft [14-18]. With the development of advanced FRP technology, isogrid structures have been widely applied in structures that exhibited advanced performance. Fan, L.H. et al, have investigated the improved mechanical performance of structural panels made from $[0/\pm45/90]_2$ carbon fiber laminates using compression and bending tests [19]. Chen and Tsai have proposed an integrated equivalent stiffness model for these composite isogrid structures with or without faces through multiple loads and multiple failure mechanisms [20]. Several manufacturing methods have been proposed for constructing these of isogrid structures [19, 20]. Cremens, W.S. proposed a manufacturing method for thermal expansion molding to produce isogrid [21], and Kim, T.D presented a isogrid fabrication process using unidirectional carbon fiber prepreg tow and epoxy [22]. Han, D.Y et al, have introduced another manufacturing method of interlocked composite grid arrangement that could simplify assembly by using prefabricated materials [23]. According to Fan et al, this core configuration has been shown to be stiffer and stronger than foams and honeycombs [19]. In addition, Vasiliev, V.V. et al have summarized the development and application of isogrid structures in the field of aerospace [24], and Olsson, K.A also concluded the design and utilization of the structural has advantages for marine applications [25]. Most studies on these structures were made using either metal or FRPs for specific high-strength to weight applications rather than common applications. The mechanical properties and failure modes of the structures all varied depending on different materials and geometry used, as expected. The isogrid structure, as has been shown, can be easily modified including the size of the equilateral triangle, the thickness and height of the linear rib, and its material properties. The triangular structure has also shown it is possible to modify the linear ribs spacing adjusting the distance between slots for one of the ribs and thus produce an isosceles triangle by adjusting the distances between slots for the double-slotted rib, thus creating a core with performance options that can be engineered to meet various loading conditions[26].

As mentioned above, all the work on isogrid found in the literature were made from either metal or FRP rather than renewables such as wood-based materials. Our forests are a naturally renewable resource that has been used as a primary source of building materials. Substantial increases in demand and consumption for all raw materials have occurred due to growth of world's population and affluence. Continuing to use wood fiber or natural products provides a unique challenge and opportunity for developing new generation of renewal, sustainable, and

efficient natural-fiber-based composite materials. The key to effectively developing marketable higher strength-to-weight wood-based composites is to understand the performance capability of these types of panel structures. Treated wood-fiber-based composite materials from renewable forests may use for numerous applications while helping to protect our environment.

In this research, we are working to develop engineered sandwich composites made from wood-fiber-based composites with enhanced performance capabilities. For some applications, high-performance and water resistance are critical design requirements, but do not have the same high performance or weight requirements as marine or aerospace panels. It may be possible that a phenolic impregnated laminated paper might be sufficient to fill some niche applications at reduced costs. Therefore, for this research laminated paper composite material is being used to fabricate the tri-axial rib core components and also for the initial layer of the top and bottom faces. To achieve even higher stiffness, reinforced materials may be selectively used to reinforce the outer layer of faces. This paper introduces our work using the tri-axial ribbed core structure in the design, fabrication, testing, modeling, and application of wood-based engineered sandwich composites.

2. EXPERIMENTATION

2.1 Design

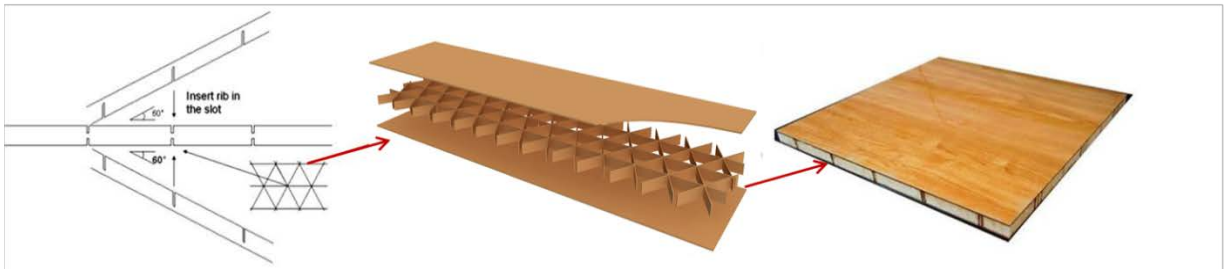
2.1.1 Tri-axial Core Basics

The basic tri-axial core design is made using tri-axial linear ribs of composite material aligned along specific axes. The multiple design of the core provides the potential for improved panel stiffness and shear load capacity. Intersecting linear ribs use an alternating slot design that is specifically shaped to allow two or more ribs to intersect for minimal reduction in strength and optimized assembly. The assembled tri-axial ribs are bonded to two faces thus creating a structural panel. The number of ribs, the rib axial orientation, the material properties, rib thickness, and face properties are all design variables to coincide with loading conditions along specific axes for specific panel applications and loading conditions. The basic design has increased stiffness and strength properties over honeycomb cores that are partially achieved due to the linear ribs not being bent as part of the honeycomb fabrication process. The honeycomb material must allow for some amount of reshaping to achieve the honeycomb geometry. This tri-axial design also allows for improved flat-crush performance based on increased rib thickness as well as orienting the rib material maximum property direction parallel with the compressive load. The ability to have thicker ribs significantly reduces buckling of the ribs under z-direction compressive loads. It’s also possible to mix rib materials for optimum performance. Other known core manufacturing processes do not discuss non-uniform material composition or the thickness of the ribs.

2.1.2 Structural Design

Our goal is to develop high performance wood-based engineered sandwich composite panels using a significant portion of wood-based materials. The interlocking tri-axial core structure was assembled using linear ribs that were either double–slotted at 1/3 the width or single-slotted at 2/3 the width of the rib, in Figure 1(a), the double-notched ribs were used for the main rib direction and the 2/3 notched ribs were inserted from either the top or bottom side to create a tri-axial ribbed structural core. The assembled core was then bonded on top and bottom to

laminated paper sheets using epoxy resin Figure 1(b) to create the structural panel shown in Figure 1(c).



(a) (b) (c)

Figure 1. The construction of engineered structural composite panel with fastening configuration (a) Tri-axial structure; (b) sandwich composite configuration; (c) sandwich products.

The quality of the adhesive interface between the core and faces significantly affected the panel strength, as was evident from our initial static mechanical tests [2]. Premature adhesive failure at the core-to-face interface was an unacceptable failure mode for engineering applications. Therefore, it is essential to estimate the shear transfer capacity of the face-core interface of the panel and then adjust core design considerations to possibly increase the interface bond area for predominantly bending or shear applications.

The design of wood-based engineered structural composite panels is very flexible. Variables such as face and rib orientation, rib dimensions, rib spacing, rib material properties are all used to meet the design requirements for various applications.

2.2 Material Selections

2.2.1 Wood-Fiber-Based Laminate Paper

Phenolic impregnated laminate paper has been the primary material used for our research. The laminated paper is made from resin impregnated laminated paper pressed under heat and pressure. The paper to resin ratio is about 75:25. Compared with metal or FRP, wood-fiber-based phenolic impregnated laminate paper has acceptable mechanical strength with low cost. It also exhibits good moisture resistance with little change of mechanical properties after being subjected to previous boiling tests. Furthermore, the paper within laminate paper is wood fiber, which is a renewable material that could be obtained from sustainable forestry.

2.2.2 Wood-Fiber-Based Hardboard

Hardboard, also called high-density fiberboard (HDF), is made from wood fiber as an engineered wood product for many structural applications. It is similar to particle board and medium-density fiberboard but thinner and slightly higher in density producing a stronger and stiffer panel. In this study, hardboard was used as an alternate raw material to fabricate the tri-axial cores and panels, as similarly done with the laminated composite paper, to produce wood-based engineered structural panels. Compared with the laminated composite paper, the wood-fiber based hardboard had a lower stiffness and strength, but it demonstrated that it was possible to make strong wood-based engineered sandwich composites for less demanding applications.

2.2.3 Epoxy Resin

Epoxy resin from US Composites, no. 635, was used for all of our bonding needs for bonding the core to the faces and also bonding fiberglass and carbon fiber fabric to the outside faces. It was chosen because of its good mechanical properties and moisture resistance. The ratio of epoxy to hardener was 3:1, and the drying time was 8-10 hours.

2.2.4 S-Fiberglass Fabric Cloth

To achieve higher strength and stiffness for the wood-based engineered structural composites, it was necessary to use a high tensile strength fiberglass fabric cloth bonded with epoxy resin to the outside laminated faces. A S-fiberglass, square woven fabric with a weight of 0.285 Kg/m^2 at a nominal thickness of 0.25 mm was used in this study.

2.2.5 Carbon Fabric Cloth

Carbon fiber fabric, a tri-axial woven material, QISO, from A&P Tehnology was also used to increase stiffness in bending. It was bonded to the outside layer of the laminated paper faces of the wood-based engineered structural composite panels.

2.2.6 Urethane Self-Expanding Foam

To improve the thermal resistance performance and to improve support of the faces between the ribs urethane self-expanding foam was used to fill the core volume between the tri-axial ribs. The expanding foam had a cured density of approximately 48 kg/m^3 and used to help support both the ribs and faces to help improve the mechanical properties of composite panels.

2.3 Component Fabrication Dimensions

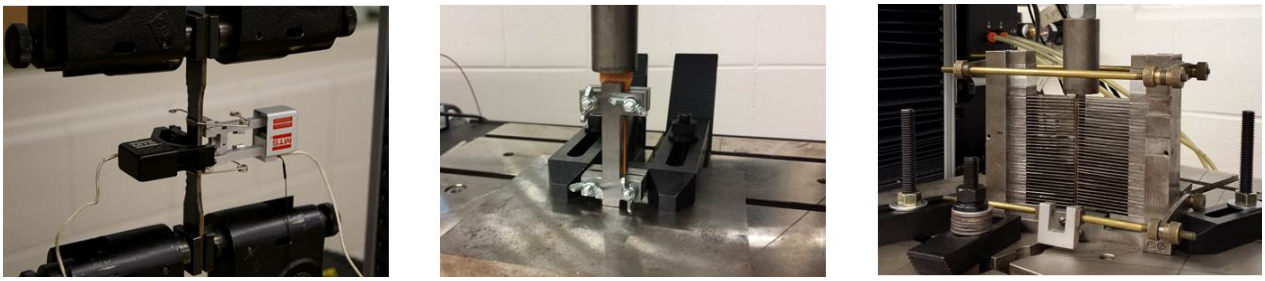
The wood-based sandwich composite panels were fabricated from tri-axially assembled core using laminate paper as linear ribs in each of three axes with an interlocking structure (Figure. 1). In these studies, the core or linear rib height was 33.0 mm and rib thickness was 2.36 mm. The slots in the linear ribs were cut slightly oversized to accommodate the 60° angular orientation between the ribs when assembled. The slot spacing for all pieces was 117.3 mm, thus creating an equilateral triangle. The laminated paper material was orthotropic that could be modified according to the application requirements. All these components were cut using digitally controlled machines. Before applying epoxy resin, all laminate paper face surfaces were first prepared by lightly sanding on the glue side, and then the epoxy resin was spread on the faces to bond the core to the faces. The configurations and dimensions of wood-based sandwich panels were varied; however, they used the same fabrication process.

2.4 Testing

2.4.1 Material/Component Test

The component materials were tested to obtain the mechanical properties for all materials used in our panel for use in our design model. Tensile, compressive, and shear tests were used to measure the basic strength properties. Laminated paper, carbon fiber composite, fiberglass composite, epoxy resin and urethane foam were all tested to determine their fundamental strength properties. For the tension test, two extensometers were attached to the samples, Figure 2(a), to measure the axial and transverse displacements to determine the Possion's ratio.

Properties for the carbon fabric/epoxy resin composite and the fiberglass fabric/ epoxy resin composite were difficult to obtain because of weave separation in the samples rather than tensile failure. Therefore, the carbon fabric and fiberglass composite were first bonded to the laminated paper sheet and then the composite panels were tested in machine direction (MD) and cross direction (CD). Machine direction is defined as the primary direction of the paper laminates were fabricated, and generally the MD mechanical properties are greater than the CD properties. Testing the combined laminated paper with the carbon fabric or fiberglass fabric provided better interaction test results among the combined materials. Tension, shear, and compression test set-ups are shown in Figure 2, respectively.



(a) Tensile test (b) Shear test (c) Compression test

Figure 2. Materials properties test.

The component material properties for the engineered structural composites have good mechanical properties. The laminated paper had tensile strengths of 174 MPa in the MD direction and 119 MPa in the CD direction. The modulus of elasticity in the MD direction was 11.6 GPa and 8.3 GPa in the CD direction. The carbon fiber/ laminate paper composite was stiffest part in same sandwich composite, which has 16.3 GPa modulus of elastic in MD with 241MPa compressive strength and 217 MPa tensile strength, respectively.

2.4.2 Compressive Panel Tests

Sandwich structures are sometimes used for compressive applications. In this research, the flat-wise compressive behavior was determined for the tri-axial core with and without foam reinforcement [26], Figure 3. We also investigated edgewise compression properties. For both tests, the sandwich panels with different component configurations were fabricated and tested to investigate initial compressive properties. The failure mechanisms were analyzed. Some typical samples and failure modes from flatwise and edgewise compression are shown in Figure 3 and Figure 4, respectively. Orthotropic plate buckling theory was used to simulate the mechanical properties and compared with the experimental results [26].

Hardboard composites | Laminate paper composites | Laminate paper / foam composites

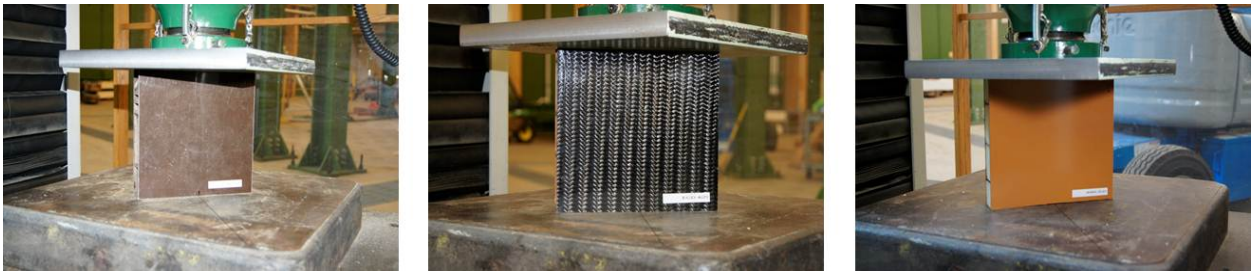
(a) Flatwise compressive test set-up

Hardboard composites | Laminate paper composites | Laminate paper / foam composites

(b) Rib buckling failure modes

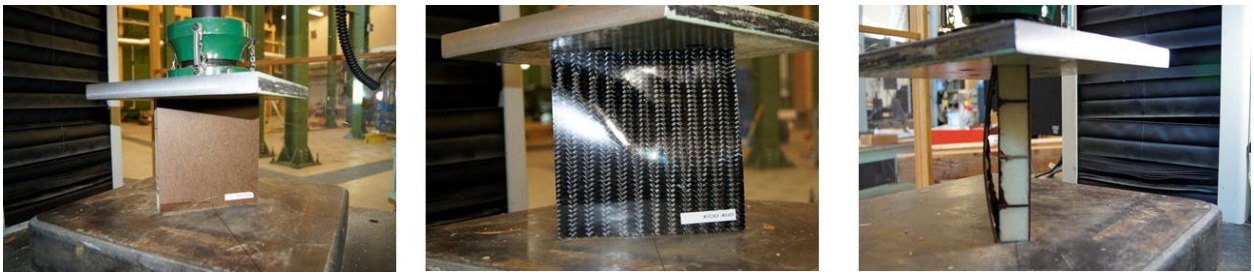
Figure 3. Flatwise compression testing.

Results from the flatwise compressive tests showed the maximum ultimate panel stress of 7 MPa occurred when using laminated paper rib with foam; laminated paper composites without foam were lower at 6 MPa. The hardboard composites had even less compressive strength compared to laminated paper composites with a capacity of 2 MPa in the flatwise compressive test. Improved flatwise panel compression properties would be possible if thicker ribs had been used that would fail in compression rather than buckling or with a smaller tri-axial equilateral triangle size that effectively decreases the equivalent stress in the ribs, σ_r, but effectively increases the panel stress, σ_p. Also, if stiffer foam had been used it would have improved the resistance force to rib buckling in the flatwise compression test. There may be applications where buckling would be the preferred method of failure, such as for cushioning and impacting applications. For these situations, buckling stress and load values would be necessary and could be estimated and engineered to fail at the appropriate load.



Hardboard composites | Laminate/Carbon composites | Laminate paper / foam composites

(a) Edgewise compressive testing set-ups



Hardboard composites Laminate paper composites Laminate / foam composites

(b) Face buckling failure modes

Figure 4. Edgewise compression testing.

2.4.3 Bending Test

Bending evaluation for sandwich composites applications is one of the primary properties that should be well studied and understood. Initial bending tests showed that the quality of adhesive between the core and faces significantly affected panel performance [2]. Premature failure at the face and core interface of the panels is an unacceptable failure mode for engineering applications and needs careful attention. Core to face ratio dominates the failure mode, insufficient core design caused core-shear failure while excessive core design caused face compression or bucking. A balanced approach to determine what is needed for each application is required.

Figure 5. Interface shear failure [2].

The goal was to increase shear transfer to the core. Testing of the tri-axial core helped to better understand the strain distribution of the composite panels with different configurations. A four point bending test was used to determine the failure mechanism, the set-up is shown in Figure 6.

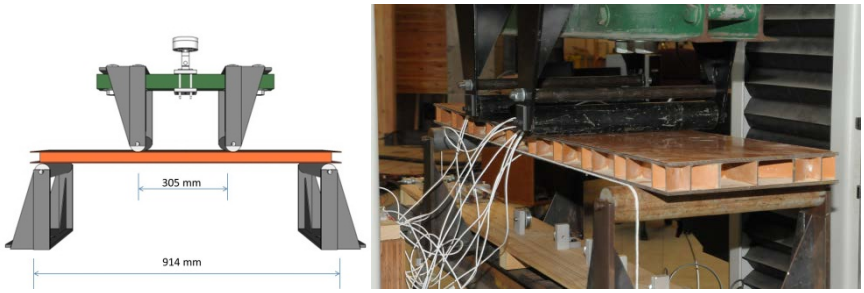


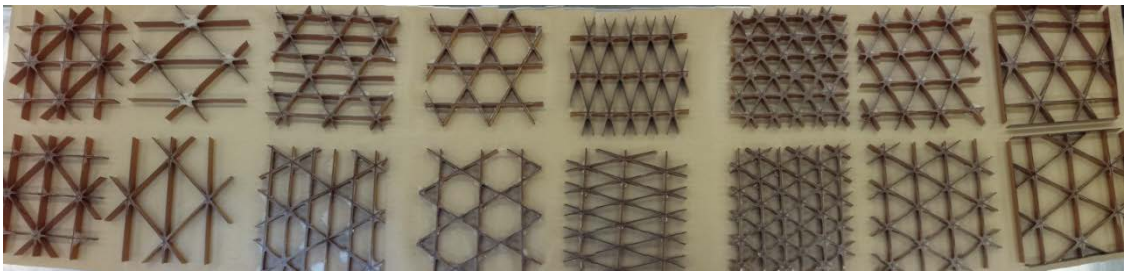
Figure 6. Bending testing set-up.

(a) Face failure (b) Core failure

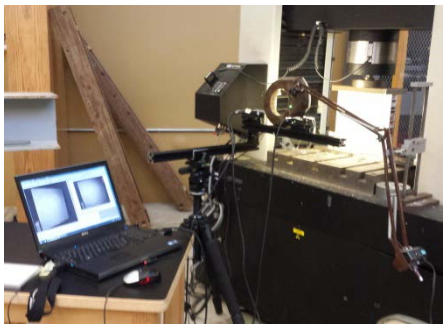
Figure 7. Typical failure modes: (a) one-layer-faces sandwich composites; (b) two-layer-face sandwich composites.

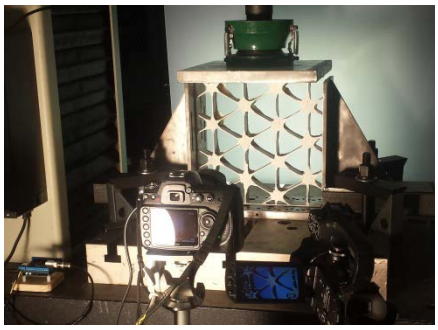
2.4.4 Buckling Test

Buckling of stiffened structural composites is one of the significant and common failure modes in engineering applications. It has a complex phenomenon that involves multiple interactions between the structural core and faces. In previous experiments, the pattern and dimension of sandwich composites observably affected the failure modes and failure loads either in the compression tests or bending test. In order to fully understand the mechanical performances of these wood-based structural composites and avoid unexpected failure in use, buckling of structural cores with and without faces was exclusively analyzed. In this test, buckling of variable wood-based composite structures involved in the cores of different geometries and dimensions with or without faces is shown in Figure 8(a). Load and displacement was measured by using experimental and analytical approaches, Figure 8(b) and 8(c).



(a)





(b) (c)

Figure 8. Grid structural patterns and Compressive buckling tests: (a) Structural patterns. (b) Digital image correction system for composite with faces; (c) Tracking technical system for the structural core.

The commercial Digital Image Correction (DIC) (Figure 8(b)) was used in structural buckling measurement with faces for determining buckling shapes and failure modes. The uniaxial compression test was applied in this study. For the structural core without faces, the buckling observed in the area of rib thickness included the entire structural area. The dot pattern captured using the DIC system was invalid due to limitations of the effective area for reasonable strain resolution. Therefore, Tracking Technical System (TTS) in Figure 8(c), which is a self-programming code based on J-Image and Matlab software, was used to measure shape deformation using a regular dot pattern on the rib cross sections. Responses of regular dots for the buckling were manually captured by camera every 5 seconds during as load increased. The camera was connected to control signals from the Instron testing equipment and triggered to automatically capture the image.

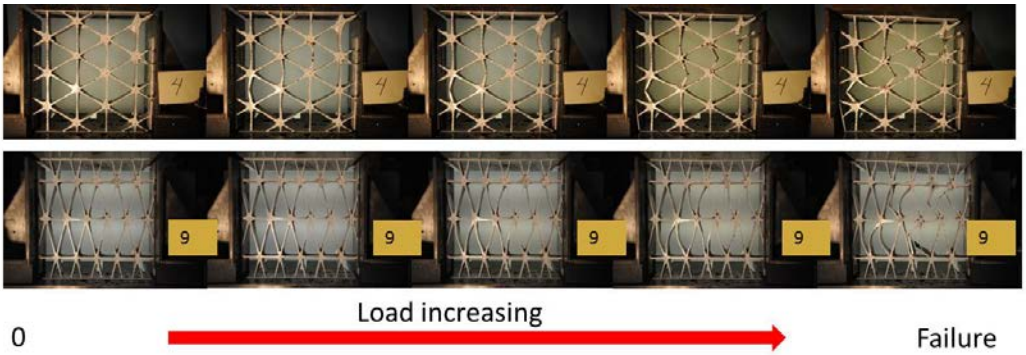


Figure 9. Typical compressive buckling deformation with load increasing.

2.4.5 Fatigue Test

Sandwich structural composites offer many advantages compared to solid construction. Due to the significant factor of strength-to-weight ratio, sandwich composites have grown rapidly in a wide range of applications in recent years. Long-term mechanical behavior for sandwich composites is a major concern and requires both dynamic behaviors for long term loading in structural applications. Previous research has shown that the junction between the faces and cores for aluminum honeycomb sandwich beams has a significant effect on fatigue performance [27], and it has also reported that fatigue strength increased with increased adhesive amount at the interface. However, this approach raises the weight and cost of the sandwich beams. Some imperfect sandwich composite beam was tested to analyze the failure process shown in Figure 10. The result shows that the initial crack propagated with the loading cycle increasing and dramatically decreased the fatigue life.

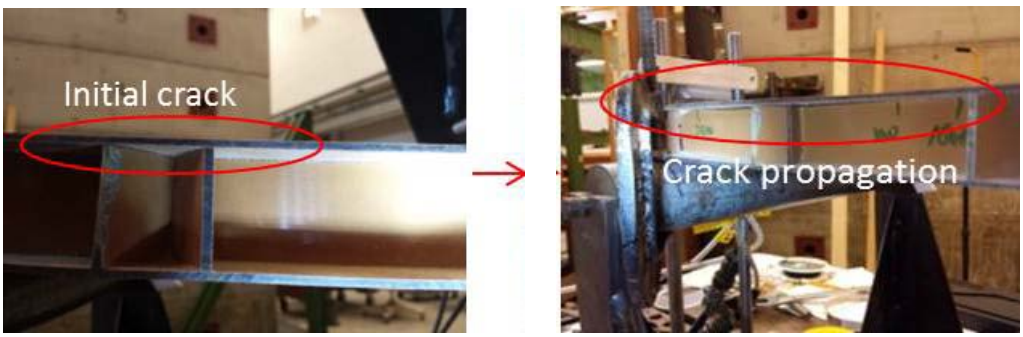


Figure 10. Damage propagation under cycle loading in imperfect sandwich beam.

Analytical models were used to simulate the fatigue characteristics for future design applications. Bending load in fatigue testing was controlled by ultimate flexural strength from static bending tests by a hydronic instron machine, and the stress levels of 80%, 70%, 60%, and 50% of the ultimate flexural strength were applied. The tri-axial engineered sandwich panels were analyzed to investigate the potential cyclic duration of load capacity. The fatigue testing set-up is shown in Figure 11.

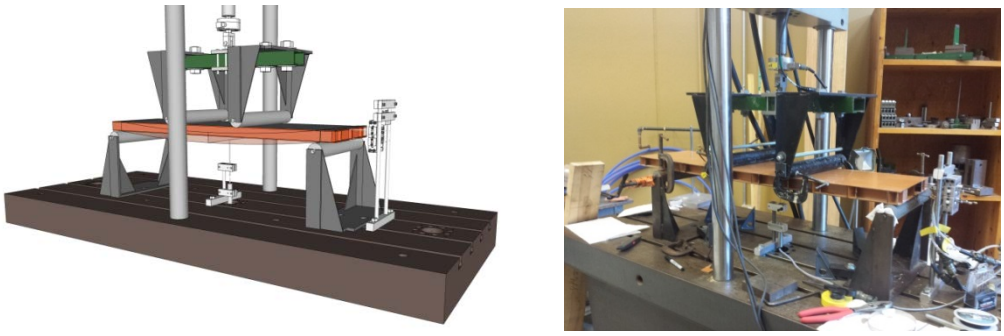


Figure 11. Bending fatigue testing set-up.

3. RESULTS

3.1 Mechanical Tests

3.1.1 Compression Test

Edgewise compression tests were used to determine the effects of face properties, orientation, face thickness, and core-face interface bonding mechanisms on edgewise compression strength. The face stiffness had a significant effect on compression capacities. While ribs bonded to the faces helped to restrain the global buckling of the faces, however, global buckling was affected by localized cell buckling based on the size of the triangular element. It was observed that the faces buckled into the cell area without the foam. Foam helped to resist the out-of-plane buckling deformation into the cells between the ribs. The panels with the foam had the highest edgewise compressive strength. If the size of the tri-axial cell were smaller and the ribs were slightly thinner to maintain the same weight of core, then there might be improved face buckling resistance due to improved support of the face rather than the larger cell size that we used. With the addition of the carbon fabric to the faces, the face stiffness increased and localized face buckling was reduced and failure occurred at the rib-to-face interface resulting in a global buckling of the face as shown in Figure 4(b).

3.1.2 Bending Test

Eight normal strain gages were used to measure the normal strains through the mid-span section on composite beam and 4 shear strain gages were used to measure the core shear strain at mid-span and shear sectional locations. The bending result showed that the face compression-tension failure and core shear failure were the two primary failure modes for the different designs for tri-axial core, Figure 7. Maximum normal strain occurred on the faces of the composite panel with thin faces and thick core, whereas, the maximum shear strain occurred on the linear rib of the core while using thinner thickness ribbed core. The core to face density ratio was one of significant factors that affected the bending strength and failure mode. Reinforced fiber coating on the faces improved the bending performance. Maximum bending load was up to approximate 25 kN for 350 kg/m^3 laminate paper composite beam with carbon fiber reinforcement using third point load bending test.

3.1.3 Buckling Test

Results of pre-buckling, post-buckling, failure load, buckling mode, modulus of elasticity and specific density were analyzed for future optimal design. Finite Element Method and analytical models were used to analyze the global buckling, local buckling and deformation tolerance of the different configurations. Different structural configurations significantly affect the buckling deformation modes. Figure 9 shows typical compressive buckling deformation with load increasing of some pattern. The detail results and analyses will be reported.

3.1.4 Fatigue Test

S-N curves were determined based on the results for future design consideration. The results show laminated paper structural panels showed good fatigue performance. It endured 1 million cycles for loading at 50% of the maximum bending stress level which is much higher than other wood or wood-based engineering materials [28, 29]. The detail analyses will be published.

3.2 Modeling

Due to the relative complex nature of the core, specific modeling of the geometry using specific geometry-based finite element modeling might be difficult and costly to design and predict the mechanical behavior of engineered sandwich composites based on the numerous variable parameters in just in the core design. A simplified equivalent orthogonal constitutive properties model for the tri-axial ribbed core was developed based on equivalent element transformation. The theoretical process of equivalent element core for this sandwich structure is shown in Figure 12. This equivalent model can be directly incorporated into existing finite element methods (FEM) techniques resulting in a combined model that provides good initial guidance for mechanical performance behavior.

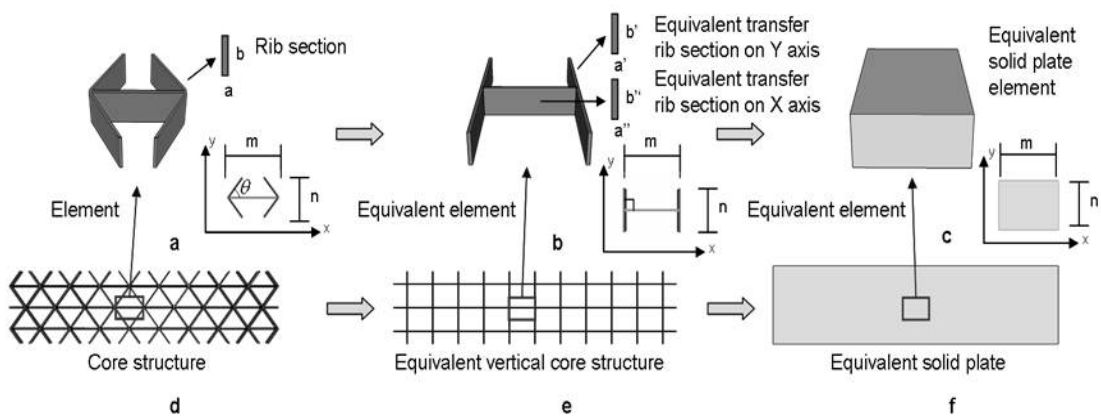


Figure 12. Core structural transformation process to an equivalent element structural core.

In this study, the simplified orthogonal model of an equivalent structural element for tri-axial ribbed core structures was developed based on classical laminate theory. In recent years, there were some advanced analytical theories that have been successfully used to describe the mechanical behavior of laminates such as first order shear deformation theory, high order shear deformation theory, and layerwise theory [30]. For the tri-axial core, the span to thickness ratio was generally larger than 20, thus classical laminate plate theory was the simplest method to use that predicted the mechanical performance with satisfactory accuracy. Then we used this model in a combined FEA model to predict the mechanical performance of the engineered structural composite panels. The basic formulas of classical laminate plate theory are given in Eq. (1).

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{pmatrix} A & B \\ B & D \end{pmatrix} \begin{Bmatrix} \varepsilon \\ \kappa \end{Bmatrix} \qquad [1]$$

Where N is the force, M is the moment, ε is the strain and κ is the curvature. [A] and [D] are the tension-compression rigidity and bending-twisting stiffness sub-matrix, respectively. For the symmetrical structures, the coupling stiffness sub-matrix [B] equals zero. And the calculations of [A], [B], [D] matrixes are as below.

$$(A_{ij,}\ B_{ij,}\ C_{ij}) = \sum_{n=1}^{3} \int_{h_n}^{h_{n+1}} Q_{ij}^{n}(1\ , z, z^2)dz \qquad [2]$$

Where n is the number of layers, h is the distance from neutral axis to each layer surface, z is integration variable and Q is stiffness coefficient. The composite panel was assumed as three orthotropic layers structure having two laminated paper faces bonded to a structural core. The estimated core bending performance characteristics were determined using this new orthogonal model and verified by FEM model in comparison with actual bending tests. The detail result has been submitted to journal and will be published soon. The repeatable element model had acceptable accuracy, within 7%, such that it could be used to decrease the modeling time that might be taken to determine estimated equivalent stiffness evaluation for a tri-axial ribbed core structures for most any structural applications.

4. CONCLUSION

Wood-based composites are naturally good engineered materials that could be used for many non-critical structural applications. Our goal is to provide the tools that could be used to help design these high performance and environment-friendly panels. Building construction material is one of principle expected usage; it can be made as prefabricated components for roofs, wall partitions, floors, decks, and etc. The raw material we used, laminated paper, has good moisture resistance, corrosive resistance, and some fire resistance. The tri-axial core might also have a potential market in packaging systems. For example, in the furniture industry, the design requirements are not as high as those used for building construction, so a sheet material like hardboard might be able to be used to fabricate engineered sandwich composites for the furniture industry at a reduced cost. The tri-axial core sandwich panel has potentially many advantages; wood-based engineered sandwich composites could be valuable for a number of applications. The modeling of the tri-axial core sandwich panel and subsequent validation tests of the panels show that such a structure could be engineered for a variety of applications.

5. REFERENCES

1. Davalos, J. F., Qiao, P. Z., Xu, X. F., Robinson, J. & Barth, K. E., “Modeling and Characterization of Fiber-Reinforced Plastic Honeycomb Sandwich Panels for Highway Bridge Applications.” Composite Structures 52 (2001): 441-452.
2. Li, J.H., Hunt, J. F., Cai, Z. Y. & Zhou, X. Y., “Bending Analyses for 3D Engineered Structural Panels made from Laminated Paper and Carbon Fabric.” Composites Part B 53 (2013): 17-24.
3. Sharaf, T. & Fam, A., “Experimental Investigation of Large Scale Cladding Sandwich Panels under Out-of-Plane Transverse Loading for Building Applications.” Journal of Composites for Construction 13(3) (2011): 422-430.
4. Vasiliev, V. V., Barynin, V. A. & Rasin, A. F., “Anisogrid Lattice Structures Survey of Development and Application.” Composite Structures 54 (2001): 361-70.
5. Wei, X., Tran, P. D., Vaucorbeil, A., Ramaswamy, R. B., Latourte, F. & Espinosa, H. D., “Three-Dimensional Numerical Modeling of Composite Panels Subjected to Underwater Blast.” Journal of the Mechanics and Physics of Solids 61(6) (2013): 1319-1336.
6. Vasilliev, V. V., Barynin, V. A., & Rasin, A. F., “Anisogrid Lattice Structures – Survey of Development and Application." Composite Structures 54(2-3) (2001): 361-370.

7. Bull, P. H., Edgren F., “Compressive Strength after Impact of CFRP-Foam Core Sandwich Panels in Marine Applications.” Composites Part B: Engineering 35(6-8) 2004: 535-541.

8. Karlsson, K.F. & Astrom, B. T., “Manufacturing and Applications of Structural Sandwich Components.” Composites Part A (28a) (1997): 97-111.

9. Gibson, L. J. & Ashby, M. F., Cellular Solids: Structural and Properties, Pergamon Press, Oxford, 1988.

10. Wahl, L., Maas, S., Waldmann, D., Zurbes, A. & Freres, P., “Shear Stresses in Honeycomb Sandwich Plates: Analytical Solution, Finite Element Method and Experimental Verification.” Journal of Sandwich Structures and Materials14 (4) (2012): 449–468.

11. Isogrid design handbook, NASA CR-124075, Isogrid design handbook, McDonnell Douglas Astronautics Company, Feb 1973.

12. Key, J. E., “Isogrid Strutural Tests and Stability Analyses.” Journal of Aircraft 13(10) (1976): 778-785.

13. Jenkins, W. C., “Determination of Critical Buckling Loads for Isogrid-Stiffened Cylinders.” McDonnell Douglas Report No. MDC-G2792, 1972.

14. Peterson, J. P., “Buckling of Stiffened Cylinders in Axial Compression and Bending - A Review of Test Data.” NASA TN D-5561, Dec 1969.

15. Meyer, R. R., & Anderson, H. A., “Space Shuttle Isogrid Tank Buckling Test.” design and analysis (1), McDonnel Douglas Report No. MDC-G24804, Feb 1972.

16. Meryer, R. R., “Buckling of Stiffened Cylindrical Shells Subjected to Combined Axial Compression, Normal Pressure, Bending, and Shear loading.” Ph.D. Dissertation, University of California at Los Angeles, Jun 1972.

17. Jenkins, W. C., “Determination of Critical Buckling Loads for Isogrid-Stiffened Cylinders.” McDonnell Douglas Report No. MDC-G2792, Feb 1972.

18. Heard, W. L., Anderson M. S., & Slys, P., “An Engineering Procedure for Calculating Compressive Strength of Isogrid Cylindrical Shells with Buckled Skins.” NASA Langley Research Center Report No. NASA TN D-8239, Jun 1976.

19. Fan, H. L., Meng, F. H. & Yang, W., “Sandwich Panels with Kagome Lattice Cores Reinforced by Carbon Fibers.” Composite Structures 81(4) (2007): 533–539.

20. Chen, H. J. & Tsai, S. W., “Analysis and Optimum Design of Composite Grid Structures,” Journal of Composite Materials 30(4) (1996): 503-534.

21. Cremens, W. S., “Manufacturing Methods for Thermal Expansion Molding of Advanced Composite Aircraft Structures.” AFML-TR-75-110, 1975.

22. Kim, T.D., “Fabrication and Testing of Composite Isogrid Stiffened Cylinder.” Composite Structures 45(1) (1999): 1-6.

23. Han, D.Y., & Tsai, S. W., “Interlocked Composite Grids Design and Manufacturing.” Journal of Composite Material 37(4) (2007): 287–316.

24. Vasilliev, V. V., Barynin, V.A. & Rasin, A.F., “Anisogrid Lattice Structures – Survey of Development and Application, Composite Structures 54(2-3) (2001): 361-370.

25. Olsson, K.A., “Sandwich Structures for Naval Ships: Design and Experience.” Mechanics of Sandwich Structures, ASME international mechanical engineering congress and exposition (62) (2000): 1-9.

26. Li, J.H., Hunt, J.F., Gong, S.Q. & Cai, Z.Y., “High Strength Wood-Based Sandwich Panels Reinforced with Fiberglass and Foam.” Bioresources 9(2) (2014): 1898-1913.

27. Jen, Y., Ko, C. & Lin, H., “Effect of the Amount of Adhesive on the Bending Fatigue Strength of Adhesively Bonded Aluminum Honeycomb Sandwich Beams.” International Journal of Fatigue, 31(3) (2009): 455–462.

28. Cai, Z. Y., Bradtmueller, J. P., Hunt, M.O., Fridley, K.J. & Rosowsky, D.V., “Fatigue Behavior of OSB in Shear.” Forest Products Journal 46(10) (1996): 81-86.

29. Bao, Z., Eckelam, C. & Gibson, H., “Fatigue Strength and Allowable Design Stresses for Some Wood Composites used in Furniture.” Holz als Roh und Werstoff (54) (1996):377-382.

30. Reddy, J. N., Mechanics of laminated composite plates and shells theory and analysis. 2nd edition, CRC press, Boca Raton, Florida, 2003.