Innovative Design of Laminated Bamboo Furniture Using Finite Element Method

V. Laemlaksakul

***Abstract*—** Development of the numerical evaluation method of the strength and the durability for the furniture was attempted using for an example the chair in order to utilize it for a quality control, a new products design. The objective of this research is to assess strength of laminated bamboo chair under static and dynamic loading and perform drop test analysis described in ISO 7173 (Furniture – Chairs and stools – Determination of strength and durability). The developed models establish procedure to perform virtual testing on laminated bamboo chair to reduce product design and testing time. The simulations are set up using a non-linear dynamic finite element (FE) software which is equipped with both implicit and explicit solvers. This virtual testing result focused on the improve design and development of laminated bamboo chair through virtual testing.

***Keywords*—** Simulation, Finite element, Modeling, Laminated bamboo chair, Strength, Durability.

I. Introduction

PRODUCT innovation is a key factor of enterprise innovation, and creative design is the core of product innovation. The application of new materials is mainly dependent on the properties of the specific materials. In furniture, engineered wood products, bamboo can easily be production.

Bamboo is another natural constructional material and there are over 1500 different botanical species of bamboo in the world. In general, it is believed that the mechanical properties of bamboo are likely to be at least similar, if not superior, to those of structural timber. Furthermore, as bamboo grows very fast and usually takes 3–8 years to harvest [1, 2], depending on the species and the plantation, there is a growing global interest in developing bamboo as a substitute of structural timber in furniture production. However, a major constraint to the development of structural bamboo as a modern furniture material is the lack of design standards.

Manuscript received July 29, 2008: Revised version received October 31, 2008. This research was a part of research project titled "Design of laminated bamboo furniture by using ergonomics method" supported by King Mongkut's University of Technology North Bangkok, Thailand (the fiscal year 2008) under code: 2551A11903002.

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The advancement in computer technologies has created a tremendous impact on several of industries, from automotive, military and aerospace industries to electrical and electronic and household industries. CAE (Computer Aided Engineering) is one of the computer technologies utilized by many OEMs (Original Equipment Manufacturer) during the design and development of products [3]. Today, application of CAE is commonly used to perform virtual analyses including structure, impact, drop test, thermal and computational fluid dynamic. Strength design of furniture can be accomplished by utilizing solid modeling and structural analysis software. All parts of the product can be modeled parametrically and required changes can readily be optimized via advantages that are provided by the solid modeling. Likewise, strength calculations of the designed product could be made by means of the computer aided structural analysis software. A simplified analysis method is desirable for furniture engineers to perform daily quick design calculations to estimate structural sizes without the need of assistance from expensive structural simulation software. Strength and durability design of chair to satisfy furniture performance test standards such as design loads.

Finite element methods (FEM) have been commonly utilized in structural analysis of the furniture systems. A theoretical study using advanced finite element analysis of one element per member was reported by Chan to assess the load carrying capacities of bamboo scaffoldings [4, 5]. Gustafsson structurally analyzed a simple chair by utilizing the FEM [6] and determined stresses at various nodes with the finite element method by modeling the chair [7]. FEM gives reasonable estimates of the overall strength performances of the sofa frames [8].

The purpose of this research is to assess strength of chair from laminated bamboo namely *Dendrocalamus asper* Backer (or Pai Tong) in Thailand under static and dynamic loading and perform drop test analysis. In this study, FEM is performed to investigate the characteristics of laminated bamboo chairs by revolution in culture bamboo armchair. The strategy of designer was to create several innovative concepts [9]. The computer model is constructed from the drawing by used human factor illustrated in Figure 1 [10].

Design #1 Design #2 Design #3

Fig.1. Design models of laminated bamboo chair

II. Materials and Method

A. CAE Procedure

The simulation models are set up using finite element softwere. Firstly, triangular shell elements are used to mesh the surfaces of laminated bamboo chair. Then, 4-node tetrahedron elements are generated based on these shell elements. Due to symmetry, only half of the chair geometry is considered. Mesh model of bamboo chair design #1, #2 and #3 consists of 9664, 8371 and 11041 tetrahedron (tetra) elements, respectively. Upon finishing model setup, the simulations or all case studies listed in Table 1 are performed using a non-linear dynamic finite element analysis (FEA) software which is equipped with both implicit and explicit solvers. The simulations are performed using a computer with 3.0 GHz processor and 1.3 GHz memory.

B. Bamboo Mechanical Properties

An elasto-plastic material with an aribitrary stress versus strain curve is chosen to model behavior of bamboo in each simulation [11]. The mechanical properties of bamboo are listed in Table 3. The Krupskowsky law listed in Equation 1 is adopted to model the hardening behavior of bamboo during tensile test. The stress-strain relationship illustrated in Figure 2 is used in all simulation. The bonding between laminated layers is assumed to be perfect.

$$\sigma_{eff} = K\,(e_0 + e_p)^n \qquad (1)$$

Table 1. Mechanical properties of bamboo

Properties	Value
Density	800 kg/m^3
Young's Modulus	13.68 GPa
Yield Strength	100 MPa
Poisson Ratio	0.35
Strength Coefficient	438 MPa

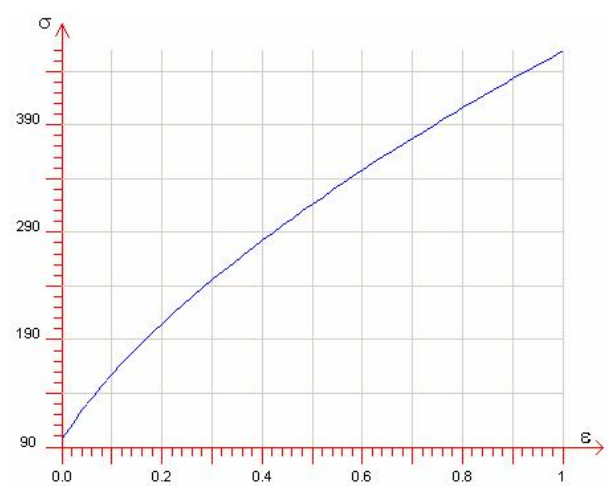

Fig.2. True stress-strain curve

C. Static Loading Simulation

The static loading simulation is conducted using the implicit solver. The model setup for static loading simulation is illustrated in Figures 3-5. The pad is placed at the center of each laminated bamboo chair. The clearance between pad and laminated bamboo chair is set as 0.5 mm. The applied pad force for static test is 2000 N as described in ISO 7173 for Test Level #5. Due to symmetry, applied pad force is set to1000 N in the static loading simulation. The trajectory of applied pad force is illustrated in Figure 6. The static loading event takes 0.25 seconds.

D. Dynamic Loading Simulation

The dynamic loading simulation is conducted using the explicit solver. The model setup for dynamic loading simulation is similar to setup described in static loading simulation. The applied pad force for dynamic test is 950 N as described in ISO 7173. Due to symmetry, applied pad force is set at 475 N for one cycle of loading condition. The trajectory of applied pad force in dynamic loading simulation is illustrated in Figure 7. The dynamic event takes 0.5 seconds

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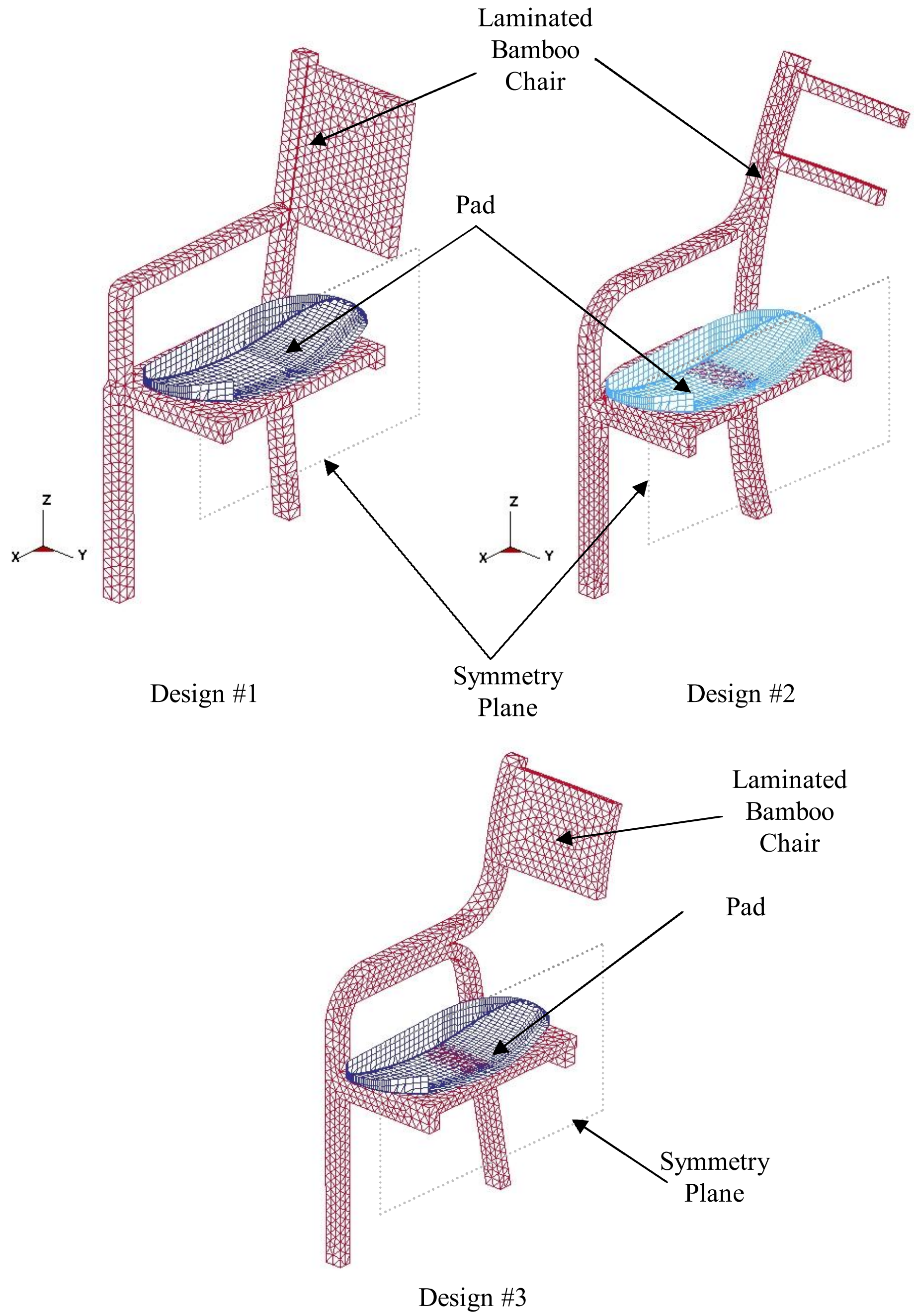
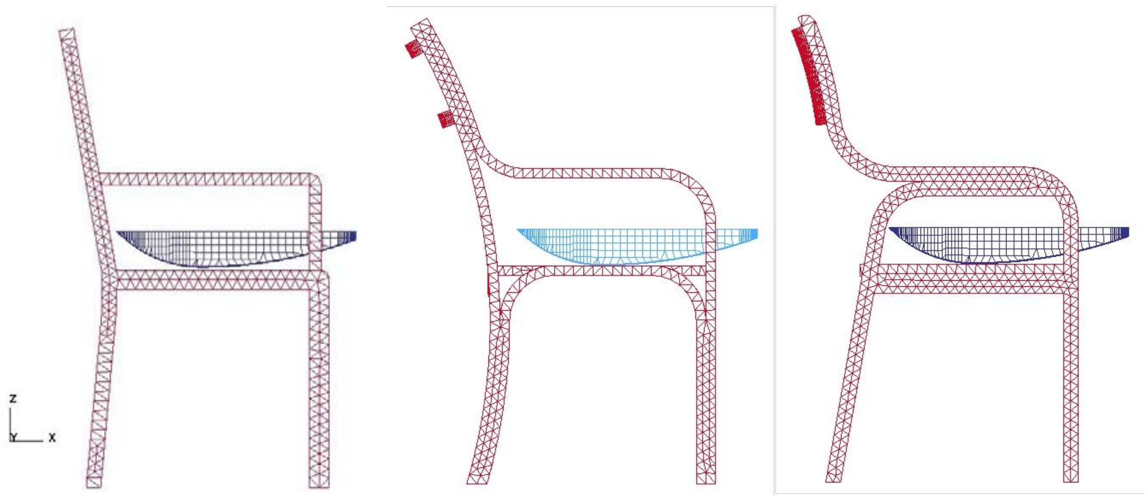
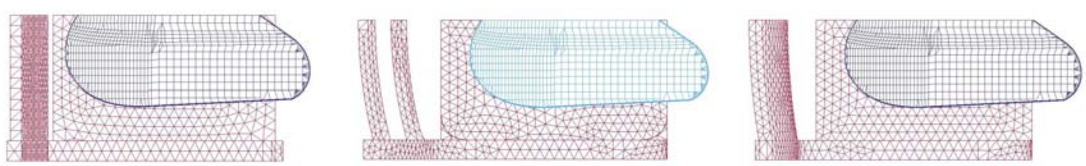


Fig.3. Isometric view of FEA models in static analysis



Design #1 Design #2 Design #3

Fig.4. Side view of FEA models in static analysis



Design #1 Design #2 Design #3

Fig.5. Top view of FEA models in static analysis

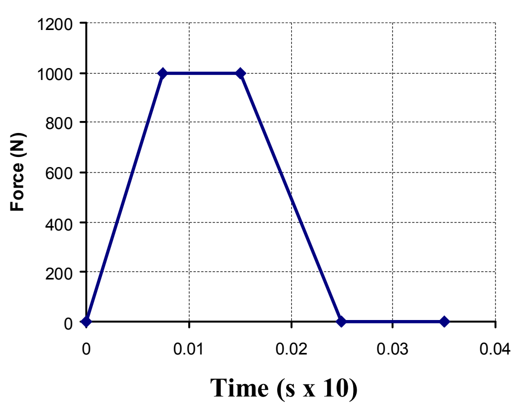


Fig.6. Applied pad force for static loading

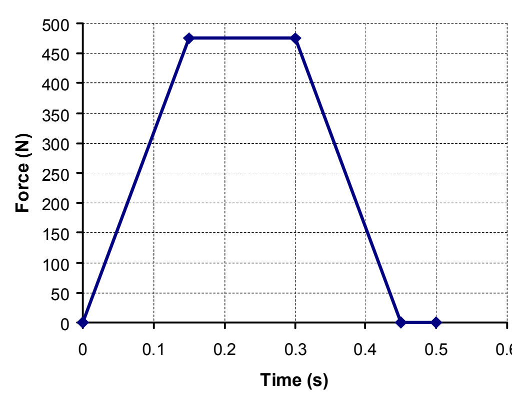


Fig.7. Applied pad force for dynamic loading

F. *Impact Simulation*

The impact simulation is conducted using the explicit solver. The model setup for impact simulation is illustrated in Figures 8-10. The impacter is placed at the center of each laminated bamboo chair and 300 mm above the chair. Element mass was added to adjust the total weight of impacter to 25 kg in simulation. The initial velocity of impacter prior to hitting the laminated bamboo chair is computed as below:

Initial velocity, $v = \sqrt{2gh} = \sqrt{2*9810*300} = 2426$ mm/s (2)

where g and h is the gravity pulling force and height, respectively

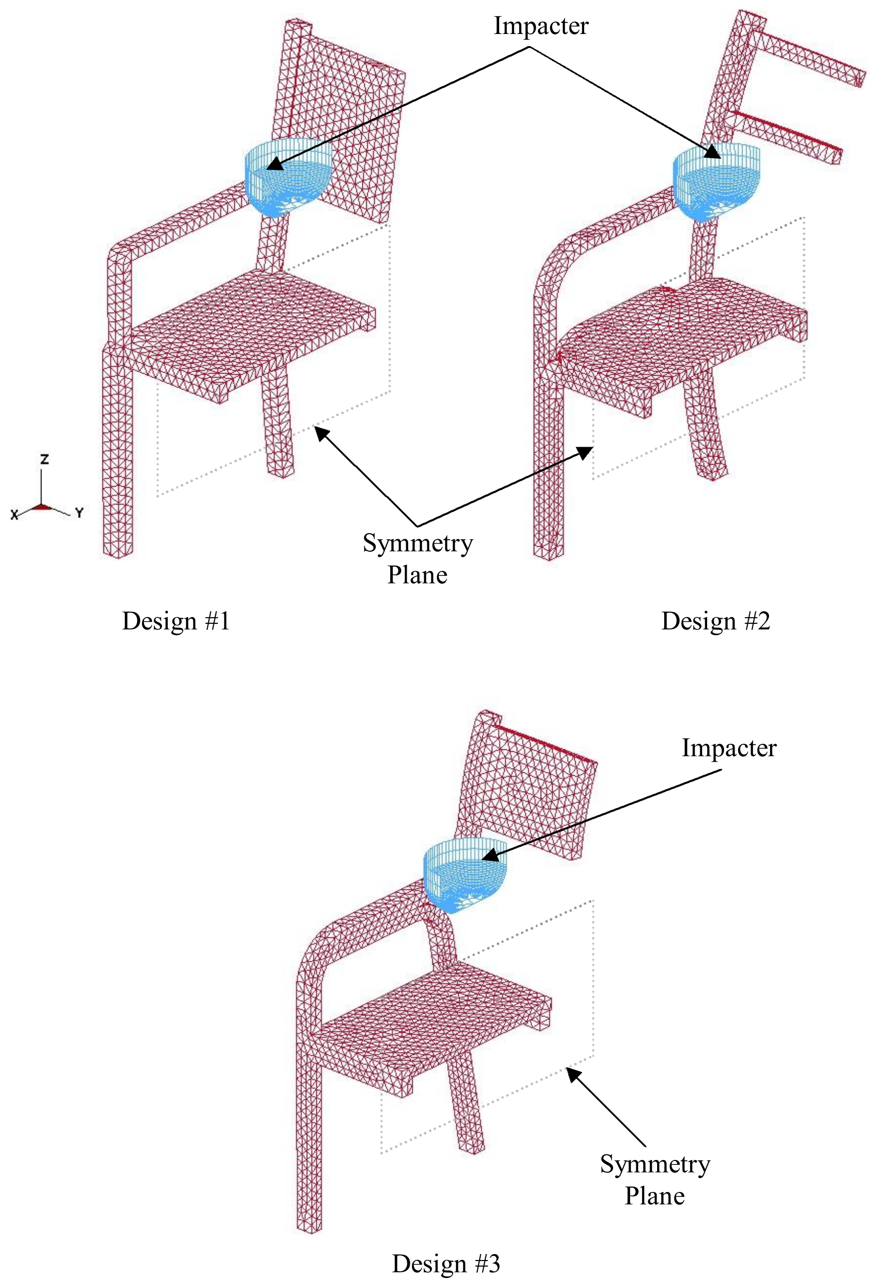
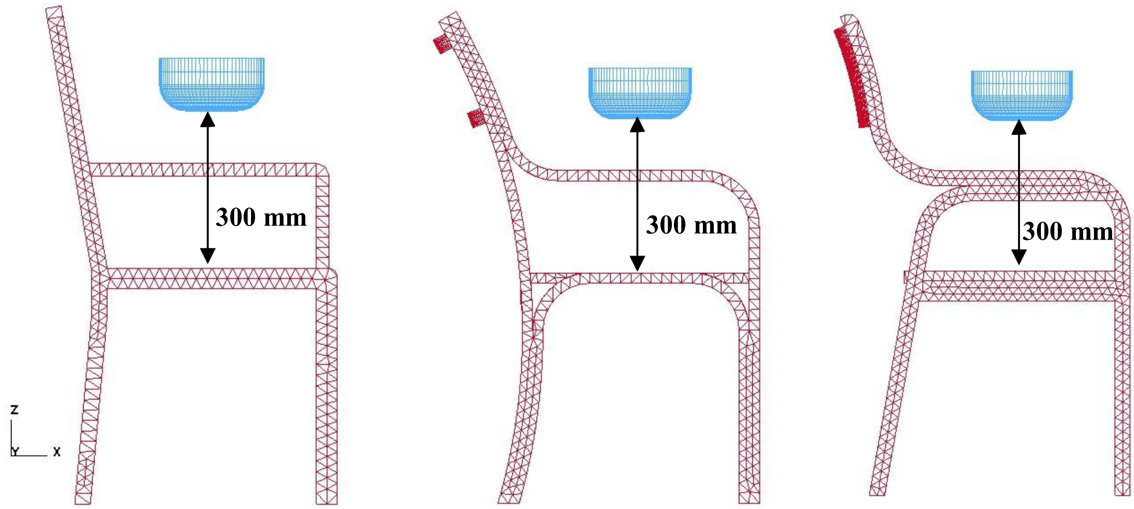
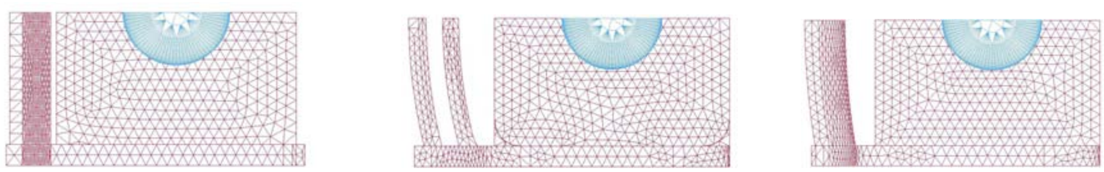


Fig.8. Isometric view



Design #1 Design #2 Design #3

Fig.9. Side view



Design #1 Design #2 Design #3

Fig.10. Top view

III. Results and Discussion

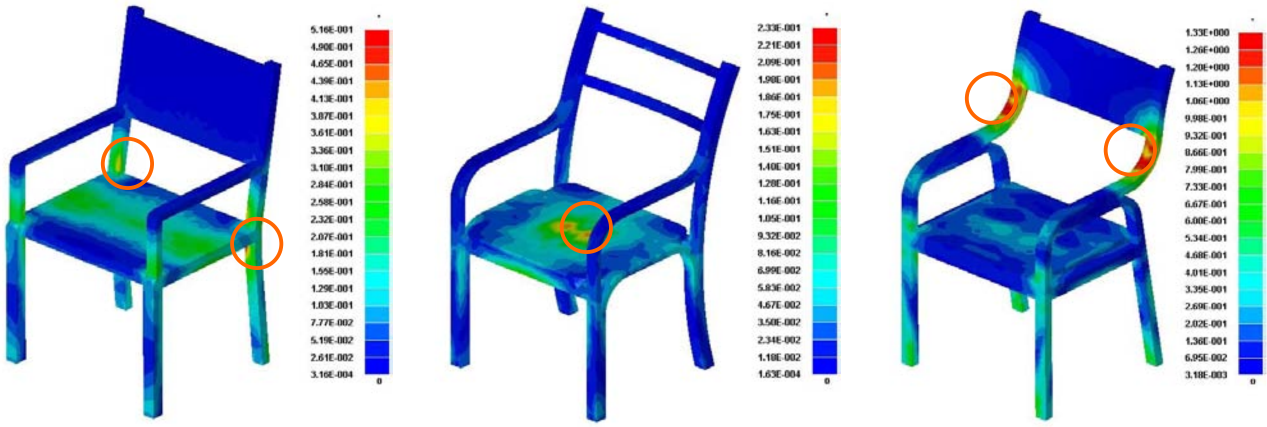
A. Static Simulation

Static simulation lasted for approximately 10 minutes. The results obtained from static simulation are illustrated in Figures 11-13. As show in Figure 11, the location of maximum von Mises stress is circled. In Design #1, the stress concentrated near the joint after the pad load is removed. Stress concentrated near the center of seat for Design #2, while Design #3 undergoes much stress concentration near base of back support of chair. In overall, Design #3 is subjected to higher maximum *von Mises* stress compared with Design #1 and #2. The distribution of total and Z-displacement illustrated in Figures 12 and 13 indicates Design #3 undergoes higher deflection after removal of static load. However, the amount of deflection is fairly small.

The predicted maximum Z-deflection and von Mises stress from each test are listed in Table 2.

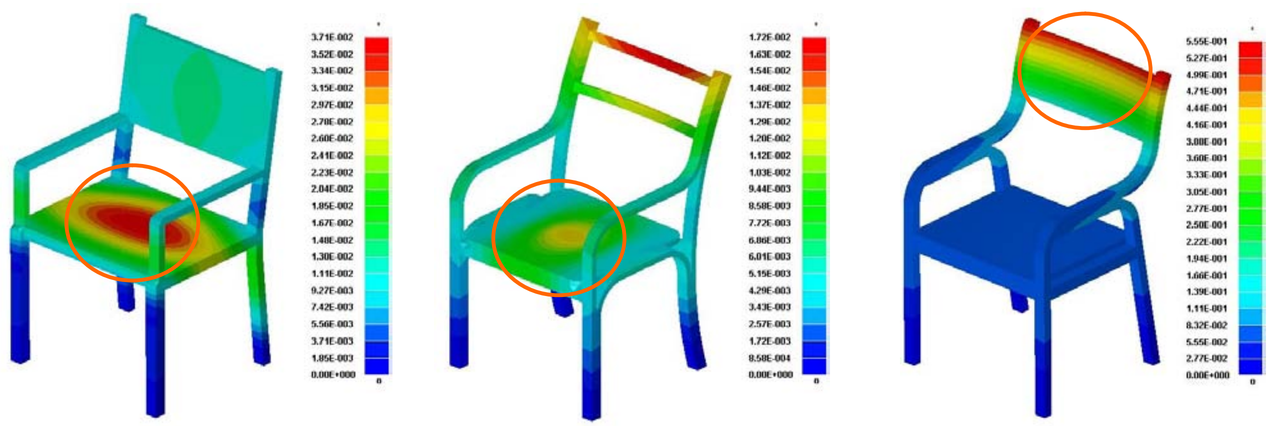
Table 2. Data recorded after removal of pad load

Design	Max. Z- Deflection (mm)	Max. *von Mises* Stress (MPa)
1	-0.0355	0.516
2	-0.0127	0.233
3	0.1860	1.330



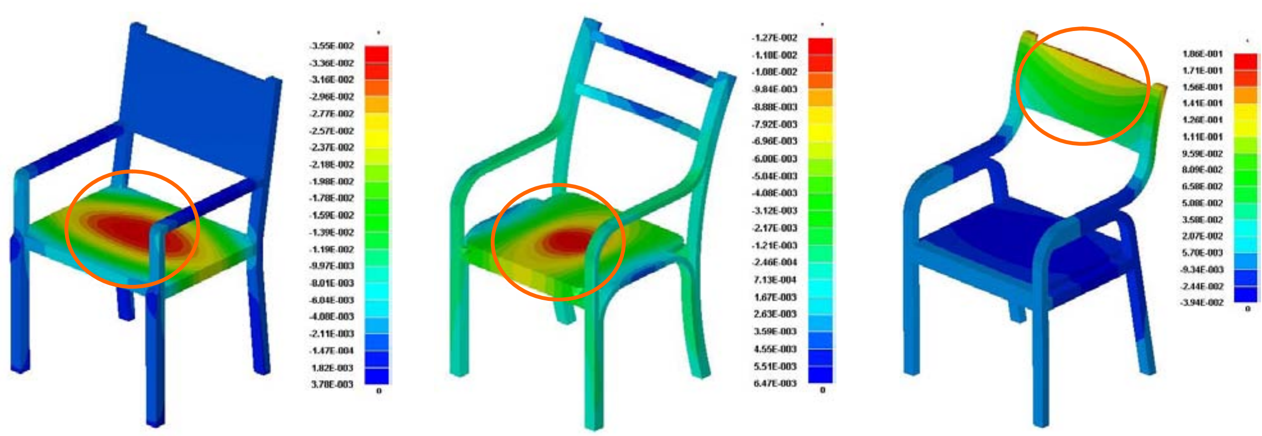
Design #1 Design #2 Design #3

Fig.11. Distribution of maximum *von Mises* stress (in MPa) in static analysis



Design #1 Design #2 Design #3

Fig.12. Distribution of total displacement (in mm) in static analysis



Design #1 Design #2 Design #3

Fig.13. Distribution of displacement in Z-direction (in mm) in static analysis

B. Dynamic Simulation

The cyclic dynamic loading reveals higher stress concentration near joints at the back of Design #1 laminated bamboo chair, as illustrated in Figure 14. In the case of Design #2 and Design #3, stress concentration occurs near the joints at the front of laminated bamboo chair. The simulations also indicate Design #2 laminated bamboo chair undergoes higher stresses during cyclic dynamic loading if compared with Design #1 and #3. This is probably due to flexible design compared to more rigid Design #1 and #3. The maximum *von Misses* stress recorded is listed in Table 3.

A comparison of total and Z displacement also reveals Design #2 exhibits bigger deflection when it's subjected to cyclic loading. In Design #1, deflection takes place near the front and back of seat pad after removal of cyclic load. The deflection is higher near the arm rest for Design #2. Again, this characteristic is contributed to the more flexible design. In Design #3, high deflection takes place near the back support of chair. The maximum Z deflection is listed in Table 3.

Table 3. Data recorded after removal of pad load

Design	Max. Z- Deflection (mm)	Max. *von Mises* Stress (MPa)
1	0.0047	0.094
2	0.0134	0.460
3	0.0096	0.182

C. Impact Simulation

The impact simulation for Design #1 and #3 lasted for approximately 6 hours, while Design #2 takes approximately 10 hours. The long simulation time in Design #2 is caused by a several small tetrahedron elements from its complex geometry. The results obtained from impact simulation are illustrated in Figures 17-19. The stress response of laminated chair during impact simulation is quite similar to cyclic loading with exception of much higher degree stress concentration. As illustrated in Figure 18, total displacement is higher near the arm rest of all chair designs as a result of higher impact loading causing arm rest to cave inwards. The impact loading also increase deflection in Z direction. The maximum deflection in Z direction is listed in Table 4.

Higher impact force is recorded in Design #1 as a result of rigid structure which provided harder landing surface. The peak impact force is approximately 21.60 kN. In impact simulation for Design #2, the peak impact force is 16.10 kN. The peak impact force is 18.75 kN for Design #3.

Table 4. Data recorded after removal of impacter

Design	Max. Z- Deflection (mm)	Max. *von Mises* Stress (MPa)
1	-0.583	26.50
2	-0.846	23.20
3	0.232	23.90

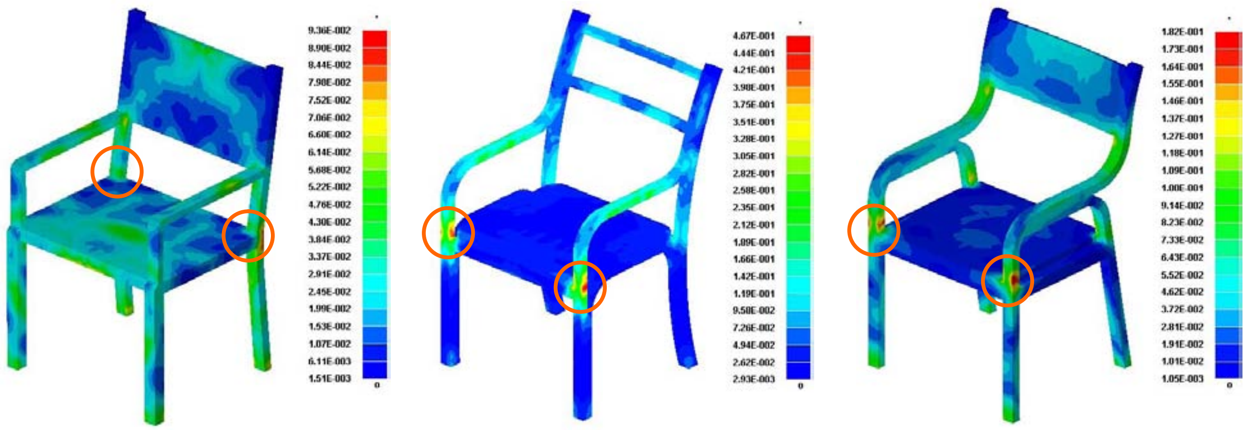
IV. Conclusion

The application of CAE technology has been proven to help improving product quality, reducing time and lowering cost of developing new products. In this study, the CAE technology is employed to investigate the performance and durability of laminated bamboo chair designs. The virtual tests including static, impact and dynamic loading cases are conducted using multi-physics FEA solver with explicit and implicit capabilities. The static loading case is conducted using the implicit algorithm, while both dynamic and impact loading cases are performed using explicit algorithm. The virtual test procedure is complied with the International Standard.

In static simulation, Design #1 undergoes maximum Z-deflection of -0.0355 mm at the center of seat area. The maximum *von Mises* stress is recorded as 0.516 MPa near the corner of rear legs of laminated bamboo chair. Though amount of recorded stress is below yield stress, design change is recommended to remove stress concentration at these regions to improve strength of chair. Design #2, the maximum Z-deflection and *von Mises* stress are -0.0127 mm and 0.233 MPa, respectively. Both maximum Z-deflection and *von Mises* stress takes place at the center of seat area. Comparison of static loading simulation between Design #1 and #2 reveals the latter performs much better by allowing lower stress concentration and deflection. For Design #3, the maximum Z-deflection and *von Mises* stress are 0.186 mm and 1.33 MPa, respectively. Higher deflection is observed near the back support of seat, while stress concentrated near the arm rest.

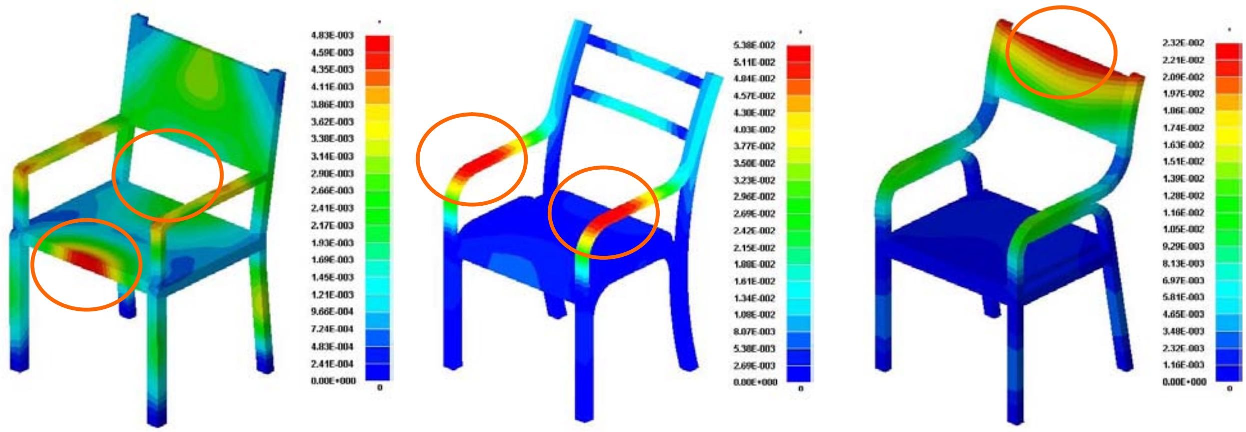
The dynamic cyclic loading indicates the maximum Z-deflection and *von Mises* stress for Design #1 is 0.0047 mm and 0.094 MPa, respectively. The stress concentration takes place near the joints between rear legs and seat area of chair, while maximum Z-deflection occurs near the front edge of seat area. For Design #2, the maximum Z-deflection and *von Mises* stress are 0.0134 mm and 0.46 MPa, respectively. Design #2 exhibits larger deflection near the arm rest and back support of chair due to its flexible design. Furthermore, design #2 exhibits higher stress concentration near the joints between front legs and seat area of chair when subjected to cyclic loading. For Design #3, the maximum Z-deflection and *von Mises* stress are 0.0096 mm and 0.182 MPa, respectively. Fatigue assessment is not yet evaluated due to lack of experimental data of fatigue parameters.

When subjected to impact condition, the characteristics of both chairs are quite similar those subjected to dynamic cyclic loading. The maximum Z-deflection and *von Mises* stress for Design #1 are 0.583 mm and 26.5 MPa, respectively. For Design #2, the maximum Z-deflection and *von Mises* stress are 0.846 mm and 23.2 MPa, respectively. Again, Design #2 undergoes higher deflection due to flexible design. In Design #3, the maximum Z-deflection and von Mises stress are 0.232 mm and 23.9 MPa, respectively.



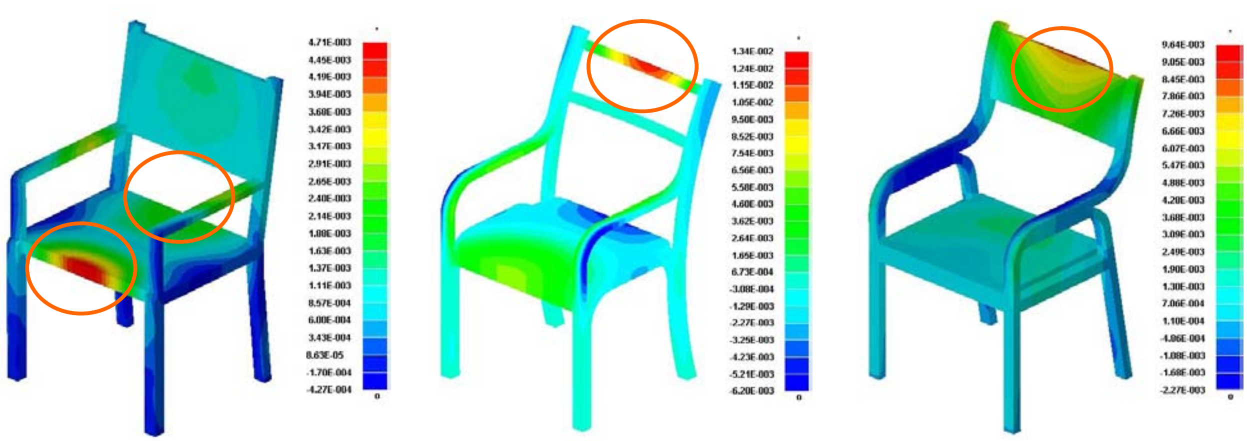
Design #1 Design #2 Design #3

Fig.14. Distribution of maximum *von Mises* stress (in MPa) in dynamic analysis



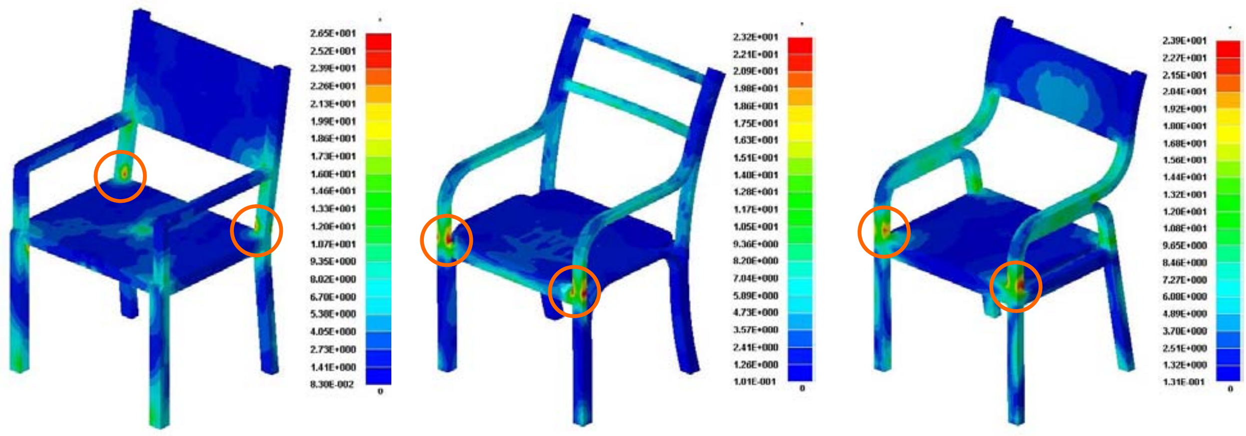
Design #1 Design #2 Design #3

Fig.15. Distribution of total displacement (in mm) in dynamic analysis



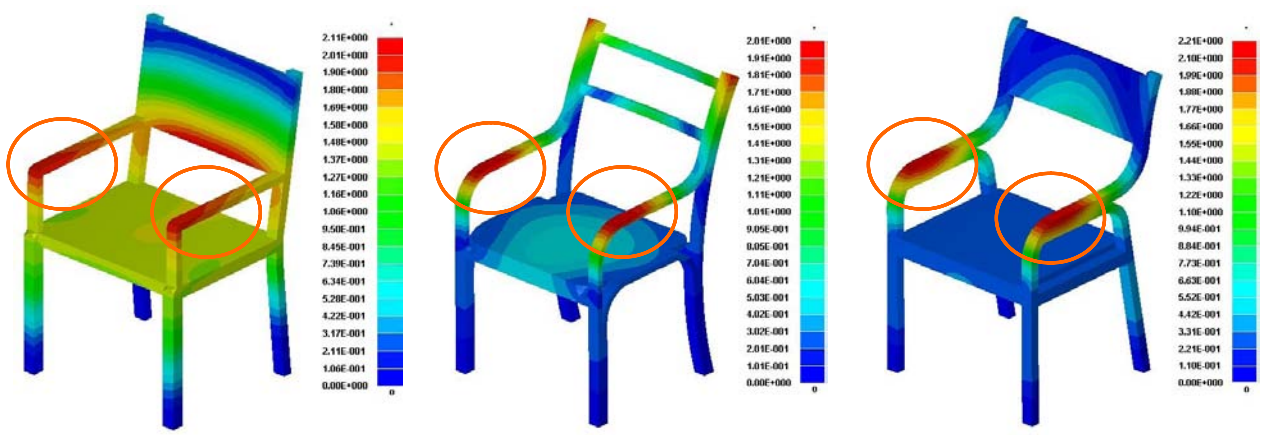
Design #1 Design #2 Design #3

Fig.16. Distribution of displacement in Z-direction (in mm) in dynamic analysis



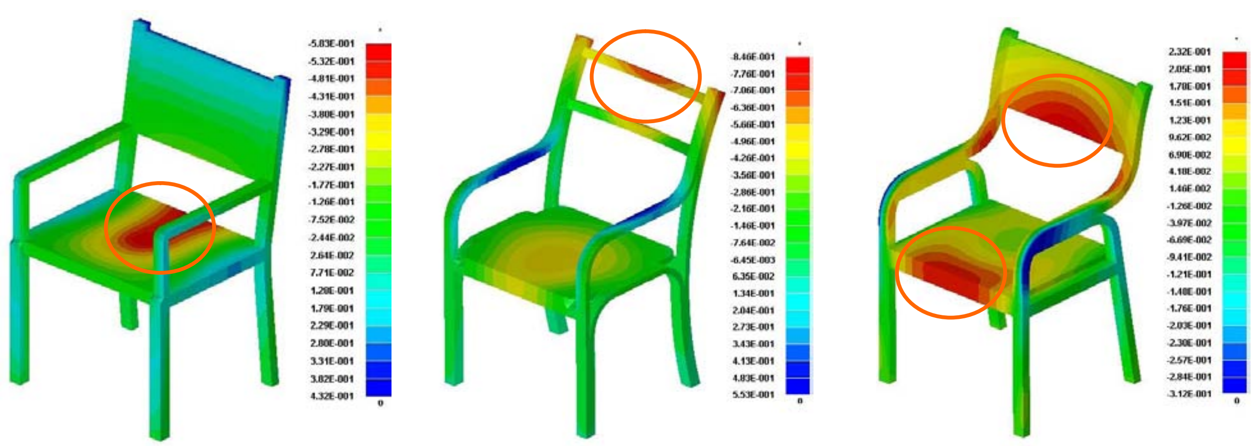
Design #1 Design #2 Design #3

Fig.17. Distribution of maximum *von Mises* stress (in MPa) in impact analysis



Design #1 Design #2 Design #3

Fig.18. Distribution of total displacement (in mm) in impact analysis



Design #1 Design #2 Design #3

Fig.19. Distribution of displacement in Z-direction (in mm) in impact analysis

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