Experimental investigations of the energy absorption capacity of coconut mesocarp core sandwich panels

Khảo sát thực nghiệm khả năng hấp thụ năng lượng của các tấm vật liệu nhiều lớp dạng sandwich với cốt lõi xơ dừa

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Crashworthiness; coconut; energy-absorption; mesocarp; sandwich.

Abstract

Finding out the low cost, environment-friendly and good at energy absorption materials are received an increasing interest in recent years. The sandwich panels with skins (or face sheets) made of steel and the core of coconut mesocarp were firstly manufactured and conducted under quasi-static compression with the speed of 2mm per minute. The nominal thickness of mesocarp core is 20mm. SUS 304 stainless steel and mild steel were both selected to be panel face sheets. The peak force F_{max} and the energy absorption E_j were computed based on the quasi-static experimental result. The result revealed that SUS 304 stainless steel face sheet panel absorbs energy better than the mild steel sheet panel. The deformation and failure of specimens under compression were also analyzed clearly. The comparative study was also made between mesocarp core sandwich panels and aluminum corrugated core sandwich panels. Comparative results showed that the natural, environment-friendly and recyclable mesocarp core sandwich panels absorbed more energy than aluminum corrugated core sandwich panels.

Từ khóa:

Cấu trúc vật liệu nhiều lớp; Hấp thụ năng lượng, Xơ dừa

Tóm tắt

Việc tìm ra các loại cấu trúc vật liệu có chi phí thấp, thân thiện với môi trường và hấp thụ năng lượng tốt đang nhận được sự quan tâm ngày càng tăng trong những năm gần đây. Các loại vật liệu nhiều lớp với mặt tấm làm bằng thép và cốt lõi làm bằng xơ dừa lần đầu tiên được tạo ra và thực hiện thí nghiệm nén dưới tải trọng gần như tĩnh với tốc độ 2mm mỗi phút. Chiều dày danh nghĩa của lõi xơ dừa là 20mm. Thép tấm không gỉ SUS 304 và tôn cán được chọn làm vật liệu lớp mặt. Lực nén cực đại F_{max} và năng lượng hấp thụ E_j được tính dựa trên kết quả thử nghiệm nén gần như tĩnh. Kết quả đo được trong biểu đồ hình 6 (a, b) và bảng 1 cho thấy cấu trúc vật liệu nhiều lớp dạng tấm với lớp mặt là thép không gỉ SUS 304 hấp thụ năng lượng tốt hơn so với loại có lớp mặt làm bằng tôn. Sự biến dạng và phá hủy của mẫu thử dưới dạng nén cũng được phân tích rõ ràng. Nghiên cứu so sánh cũng được thực hiện giữa cấu trúc vật liệu nhiều lớp có lớp lõi là xơ dừa với cấu trúc vật liệu nhiều lớp có lõi nhôm tấm mỏng dạng gấp sóng. Kết quả so sánh cho thấy cấu trúc vật liệu nhiều lớp dạng sandwich với lớp lõi là xơ dừa tự nhiên, thân thiện với môi trường và có thể tái chế được có khả năng hấp thụ nhiều năng lượng hơn so với cấu rúc vật liệu nhiều lớp có lõi nhôm tấm mỏng dạng gấp sóng.

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1. INTRODUCTION

The sandwich structure has been in use for about one century of history. Till now, it has still been popularly used in the fields of aerospace, marine, automobile, windmills, construction and other industries due to its improved stability, high strength/weight ratio, high stiffness/weight ratio, energy absorption characteristics and ease of machining and repairs. The sandwich panels are often used where weight-savings is priority [1,2,3,4]. Sandwich panel is usually comprised of two thin face sheets, which are separated by a thick, lightweight core to sustain strong faces. The faces are usually made of metals or laminated fiber reinforced plastics, while as the core is usually made of polymeric foam, honeycomb or corrugated core and balsa wood etc.

Several uni-axial quasi-static and dynamic experimental investigations have been conducted by many researchers to study the deformation, to determine the energy absorbing capacity and to improve the crashworthiness of a sandwich panel [2,3,4,5,6,7]. Goldsmith and Sackman [8] have experimentally the static and dynamic loading to investigate the behavior of sandwich panels so as to find out the energy dissipation and force level transmission characteristics of them. Mouring et al [9] have studied how the composite skin and honeycomb core sandwich panels were affected by impact damage under edgewise compression tests. Burak Bekisli and Joachim L. Grenestedt [10] have developed the new arrangement of balsa blocks to be a sandwich core and analyzed the mechanical characteristics under shear loading. Xue Z and Hutchinson JW [11] have proposed a continuum constitutive model for compressible orthotropic metallic sandwich core. Their quadratic yield surface model is similar to that proposed by Deshpande et al. S Nemat - Nasser et al [12] have conducted quasi-static and dynamic test with aluminum foam core and steel skins sandwich panels. The high speed photography was used to understand the deformation behaviors of skins and core under high rate inertial loading in their research. Borellino and Bella [13] have researched the sandwich structures made of biomimetic cellular cores of recycle paper for evaluating the mechanical properties under flat-wise and edgewise compression tests. A. Lindström, S Hall Ström [14] have investigated the energy absorption of SMC/balsa sandwich panels with geometrical triggering features. They concluded that the peak load of SMC/balsa sandwich panels under in-plane compression was clearly reduced when triggering features were introduced. In addition, the specific energy absorption of sandwich panels with triggers was increased in comparison to that of panels without triggers. J.A. Kepler [15] have introduced a concept for improving the shear stiffness properties of balsa core material by cutting the balsa wood core with an angle α to the grain direction. B.G. Vijayasimha Reddy and K.V. Sharma et al [16] have experimentally investigated the deformation and impact energy absorption of cellular sandwich panels. They found that the energy absorption capacity of the cellular material increased with the increase of impact velocities. Energy absorption capacity of cellular materials increases under dynamic loading condition when compared to the quasi - static loading condition. G. Belingardi et al [17] have conducted a series of static compression tests; dynamic impact tests and bending tests run on the composite-foam sandwich structure. Results show that the structural response of sandwich depend primary on the strength properties of the foam core material. Cesim Atas and Cenk Sevim [18] are also presented an experimental investigation on impact response of sandwich composite panels with PVC foam core and balsa wood core through a series of various impact energy tests, then comparison between impact responses and damages mechanisms of sandwich composites with two difference cores, balsa wood and PVC foam. Damages process of sandwich composites was also analyzed from cross-examining load-deflection curves, energy diagrams and damages specimens. N. Jover et al [19] have researched on thin carbon fiber skins with the balsa wood core sandwich composites subjected to single and multi-site sequential ballistic impacts. The results showed a ballistic limit of 96 ms^{-1} and the results pointed that it was capable of withstanding impacts from small object debris from roads and runaways. The effect of prior damages in terms of residual and absorbed energies became more pronounced as number of impact increased. In the existing researches, most attentions are paid on wood, especially balsa wood.

In the recent years, the researches on new cellular sandwich core structures, typically involves a large amount specimen manufacture and testing to investigate the mechanical properties of the sandwich structure increasingly. Ali, Liu and Sou et al [20] had concentrated on investigation of the mechanical and dynamic properties of coconut fibers reinforced concrete. They concluded that coconut fibers have the highest toughness among the natural fibers so that they have potential to be used as reinforcement in low cost concrete structure, especially in tropical earthquake regions. Mulinari and et al [21] investigated the mechanical properties of coconut fibers reinforced polyester composites. The test result demonstrated that fatigue behavior decreases when was applied greater tension. R. Alavez-Ramirez et al [22] have studied and evaluated the potential use of coconut fiber as thermal isolating filler for ferrocement panel wall in sandwich configuration of school and houses' roofing in Mexico. The results revealed that the thermal conductivity of the coconut fiber filled ferrocement sandwich panels is lower than typical materials used home –buildings such as red clay brick, hollow concrete block or light weight concrete brick panels, etc.

The mesocarp of the coconut shell is the anisotropic discontinuous material, strength in the grain direction is considerably higher than in any other direction [1]. It also has many mechanical properties similar to the balsa wood such as light weight, good in absorption/dissipation impact energy, otherwise coconut shells are easy getting with cheap price, so that we can put it in the use of a sandwich core material. The most importance is, there are still lacks of researches, experiments and analysis on the sandwich structure with the core made of the mesocarp coming from coconut shell.

NOMENCLATURE

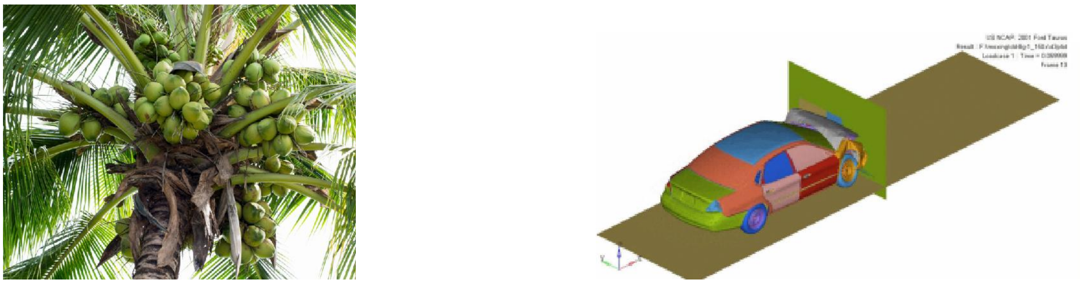
SEA	specific energy absorption
E_j	energy absorption
F	compressive force (load)
Fmax	peak force
l/l_0	compressed length
m_j	mass

2. MANUFACTURING OF SANDWICH PANELS WITH COCONUT MESOCARP CORE

2.1. Why do we select coconut mesocarp as sandwich core?

In this paper, the coconut shells which are used for machining specimens come from Vietnam. In Vietnam, the height of coconut trees is from 15m to 30m. The freefalling velocity of coconut impacting ground is from 17.15m/s to 24.25m/s. This can also be written from 61.73km/h to 87.30km/h. Here the air resistance has been ignored.

As we know, the frontal collision speed of safety rules and regulations is from 45km/h to 56kn/h. In a different region, there is a corresponding specific value. Therefore, coconut peel is a kind of natural materials automatically satisfying the collision safety rules. The speed comparison was shown in Figure 1. Coconut peel includes exocarp, mesocarp and endocarp. Among three, mesocarp is the thickest layer, and is also the main energy-absorption layer [1]. Therefore, coconut mesocarp was selected to be the bio core for further study.



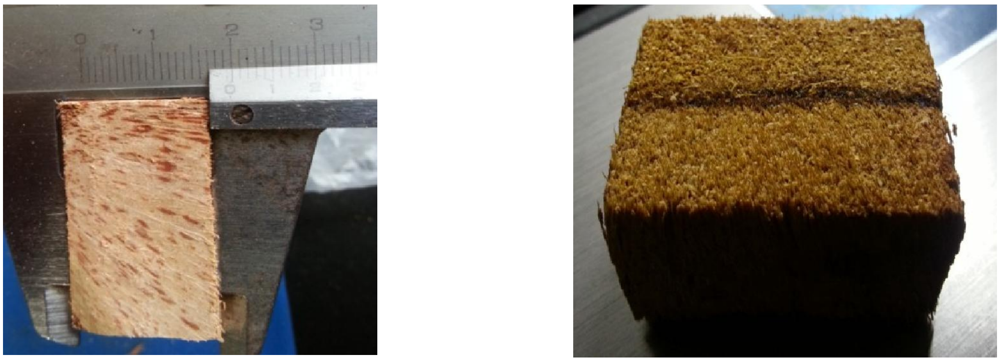
(a) Free falling speed 61~87km/h (b) Frontal collision speed of safety rules 45~56km/h [23]

Figure 1. Two speed comparison of free falling and safety rules

2.2. Preparation of mesocarp core

The mesocarp of coconut shell is demonstrated that it has best energy-absorption characteristics along the grain direction [1] so that the mesocarp core will be machined in the grain direction which are oriented through the thickness. Coconut shells are gathered from Bentre province in the southern of Vietnam, have age of 7-8 months [1]. Firstly rectangular parallelepiped mesocarp blocks in grain direction were cut from well dried coconut shells with the nominal height of 20mm, the other dimensions are free cut depends on dimension specification such as the thickness of the coconut shell, etc. as shown in Figure 2(a). Tools in use for machining mesocarp blocks are frame saw and thin sharp knife [1]. Secondly, every two small mesocarp blocks are commonly glued together side by side to form the bigger block like Figure 2b by using 7205 AB adhesive glue. The way of adhering every small block together is that the coir fibers of the two blocks nearly symmetrical to each other through inter bonded face like Figure 2c.

We call the new bonded block from two small mesocarp block (as seen in Figure 2b) as the name “basic block”. When all basic blocks were well bonded (as seen the bonded line shown in Figure 2c), they were all arranged alternately and glued together to manufacture the sheet core as seen in Figure 2d. This arrangement avoids the same bent to one side under the external force and simultaneously increases the stiffness and the strength of the mesocarp sheet. The mesocarp sheet as seen in figure 2d will be used as new core material in the sandwich panel.



(a) Machining mesocarp block (b) Gluing two mesocarp blocks together

(c) The side view of two bonded blocks (d) The mesocarp core being glued

Figure 2. Machining mesocarp core

2.3. Preparation of panel skins

Sandwich panel skins (or called face sheets) were made of SUS 304 stainless steel and mild steel with dimension of 60mmx60mmx1mm as shown in Figure 3(a), which were used for the quasi-static compression tests. Sandwich beam skins were made of SUS 304 stainless steel and mild steel with dimension of 25mmx120mmx1mm as shown in Figure 3(b).

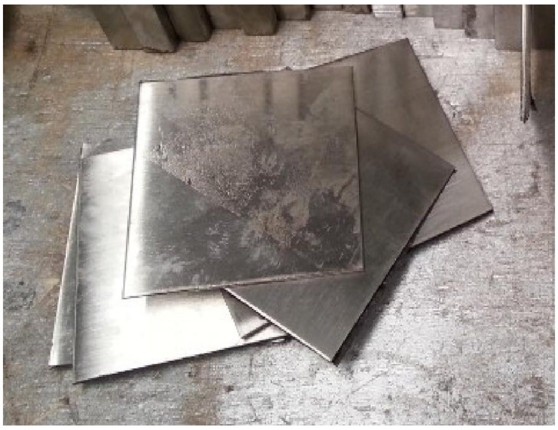


Figure 3. Cutting the sandwich panel skins

When all the skins were well machined, they are all rough grinded for reducing the surface rust (mild steel sheet) and for making the surface much more roughs with the aim to enhancement the work of adhesion between the skins and core by glue. After that, they are covered by nylon paper in the waiting time of bonding to the mesocarp sheet core, as shown in Figure 3(b).

2.4. Bonding skins to the mesocarp core

After all the mesocarp cores and steel skins were completely manufactured, two steel skins were also adhered to one mesocarp core together by 7205 AB adhesive-one kind of epoxy-basic glue as seen in Figure 4(a). The specimens were kept by attachment for one day to make sure they were bonded adhesively, then left them dried in the room temperature for more than five days [16] as shown in Figure 4(b). This helps to enhance the coherent among mesocarp blocks between the core and skins. Nevertheless, it limits the effect of moisture to degrade mechanical properties of mesocarp.

(a) Machining sandwich panels

(b) Drying sandwich panels

Figure 4. Machining sandwich panels and sandwich beams with mesocarp core

Meticulousness was taken to ensure that the specimens did not span the glued interfaces so that the measured properties represent the real properties of coconut mesocarp. When all the specimens were well dried enough, they were trimmed burrs and cleaned the surfaces. After that, they were all weighed and their dimensions were measured (as shown in Table 1 and 3). The medium thickness (height) of specimens was about 24mm. The tiny difference in thickness was caused by different of deviation amount of epoxy resin layer used during the laminate manufacturing [17] and the deviation of machining mesocarp blocks.

There were four sandwich panels with SUS 304 stainless steel skin and four sandwich panels with mild steel skin for the quasi-static compression. There were totally five sandwich beams with SUS 304 stainless steel skin and five sandwich beams with mild steel skin for the bending tests.

3. QUASI-STATIC COMPRESSION OF SANDWICH PANELS WITH MESOCARP CORE

The specimens were marked from M1 to M4 for mild steel skin sandwich panels and S1 to S4 for SUS 304 stainless steel skin sandwich panels so as to consistent with the corresponding deformation or curves data. The uniaxial quasi-static compression experiments were carried out by using Instron 5985 universal material testing machine [1]. The all specimens were placed in the center of the load cell surface in order to eliminate the influence of eccentric compression load during the test. The quasi-static compression was performed at a constant loading speed of 2 mm per minute, which is commonly used speed in the quasi-static compression test. The experimental curves of force versus time were automatically collected by a computer connected to Instron 5985

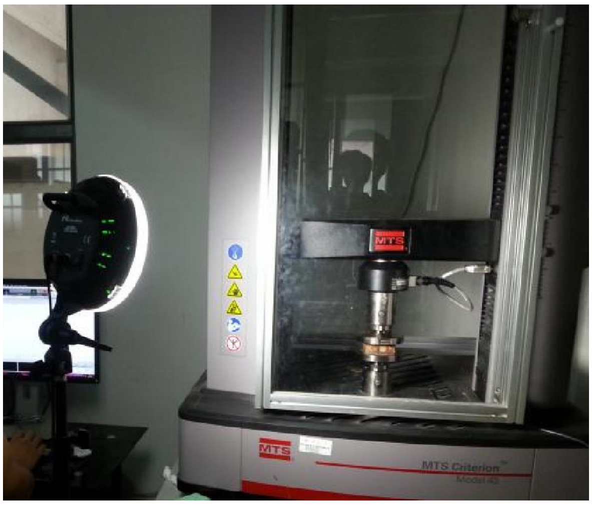
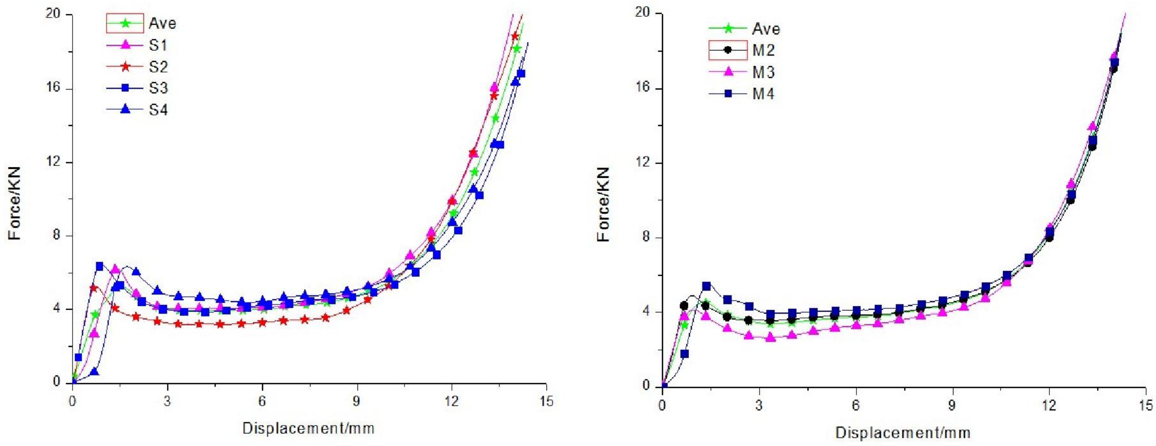


Figure 5. The MTS Criterion- model 43 material testing machine

universal testing system. When the M1 specimen was in the process of compression, suddenly the computer met errors so that the test result could not be saved. After that the left specimens were changed to conducted quasi-static compression by the MTS Criterion-model 43 testing system as seen in Figure 5. The set up condition for testing specimens were similar to the Instron 5985 material testing machine. The MTS Criterion-model 43 testing system has a maximum force of 20 KN in this experiment conducting in accordance with ASTM standard. The specimens were machined to dimension of $60x60x24mm^3$ and placed between the upper and lower pressure head in the universal testing machine. The specimens were applied to normal pressure by the indenter. Computer in the MTS Criterion-model 43 testing system can collect parameters of load and displacement resulting in the force - displacement curve.

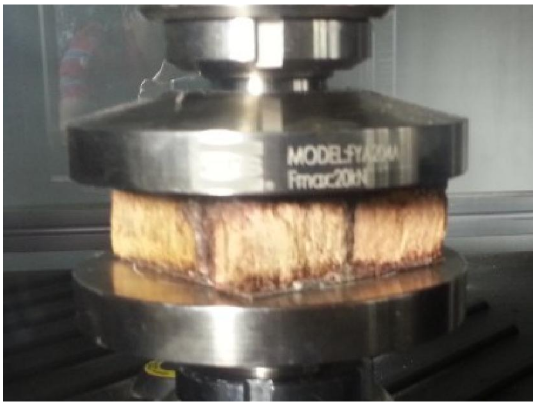


(a) Stainless steel skin panel (b) Mild steel skin panel

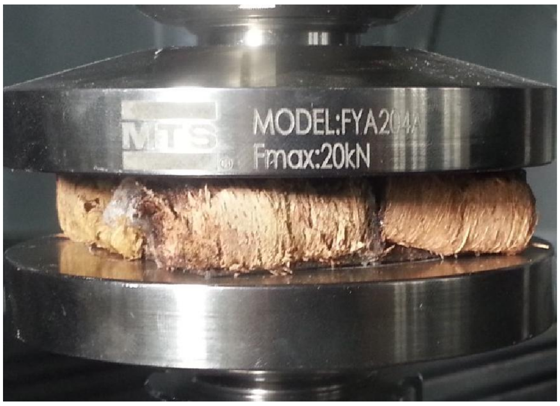
Figure 6. The Force -displacement curves of the mesocarp core sandwich panels under quasi-static compression

When specimens were uniaxial compressed, the material firstly exhibited a linear elastic deformation stage as shown in Figure 6. As the compression continues, following the attainment of peak force, initial failure occurs in a localized manner at the weakest sites and was accompanied by a drop in force level [6]. Following this drop, the specimens continue to deform at lower force level. Further deformation occurs under almost plateau force along the proceeds of deformation. After a long stage of plateau deformation, the force-displacement curve went into nonlinear stage, the cellular microstructure was sufficiently crushed and voids of mesocarp material became smaller and smaller until disappeared. Meanwhile, material density got higher and higher during the compressive progress. After a period of slow increasing, force began to rise steeply. The core material then went into its densification stage as shown in Figure 6. Crushing energy was absorbed by mesocarp material during the deformation process [1]. The force - displacement curves results show that the coconut mesocarp core sandwich panels has three stages of compression. They are linear elastic deformation, plateau region and densification scheme, which are similar to the phenomenon of mesocarp specimens under compression along the grain direction [1] or a porous foam-filler.

How did the mesocarp material absorb energy? The mesocarp is a typical natural composite material with anisotropic fibers and base material [1]. Therefore, the energy dissipation occurs by frictions between fibers and fibers, fibers and base materials, or material and material.



(a) Beginning stage of compression



(b) Under Compression

(c) Corner of specimen under compression

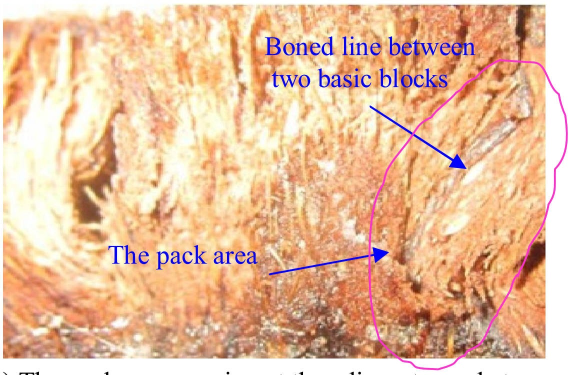
(d) Corner of post - mortem specimen

Figure 7. photographs showing deformation of mesocarp sandwich panel

By observing the specimens during procession of test, when the force increases, the mesocarp core sheet trended to bulge out in the horizontal direction (see the trend of deformation from Figure 7a to Figure 7c). At the outside, more and more fibers were burst as seen in Figure 7(c-d). The deformation of mesocarp blocks in the core were changing from buckling to kink band then at last they experienced densification regime as seen in the Figure 8. At the adjacent area of the inter bonded face between two mesocarp blocks (for each basic block), material trended to disengage and left a small hole there as seen in the Figure 8(b-d) due to the density of fibers closing to endocarp is lower than that of fibers far away from endocarp. This lead to the phenomenon that a specimen bent to the side closing to endocarp [1]. At the adjacent area of the inner bonded face between two basic blocks occurs the pack compression among material layers due to the swelling of each basic block to the horizontal as seen in Figure 8(c). For some places at outer edge where the glue did not adhere well enough also occurs the debonding between the skin and sheet core under compression as shown in Figure 8(d). This phenomenon might because of the cutting surface of mesocarp blocks there neither well nor smooth or glue did neither full fill enough nor dried enough before conducting the experiment.

(a) The densification regime of the mesocarp block at the left corner side of specimen

(b) Small hole between two mesocarp blocks appears due to the disengagement material



(c) The pack compression at the adjacent area between two basic blocks

(d) The skin/core debonding phenomenon

Figure 8. Photographs showing the deformation and failure of the mesocarp sheet core during the test.

4. RESULTS

After the uniaxial quasi-static compression results as shown in Table 1, the major mechanical properties and energy-absorption abilities of mesocarp were analyzed and calculated. It is noted that the energy was dissipated during the compression process.

Table 1. Mechanical properties of sandwich panel specimens

Specimen N^0	**Dimension axaxh (mm^3)**	**Mass (g)**	F_{max} **(kN)**	**Energy (J)**	**Specific energy(kJ/kg)**
m1	60x60x23.6	90.59	Non available (Na)	Na	Na
m2	60x60x24.5	93.03	4.90	39.02	0.42
m3	60x60x24.5	93.55	4.13	33.68	0.36
m4	60x60x23.7	91.85	5.48	41.12	0.45
s1	60x60x24.5	99.78	6.20	42.85	0.43
s2	60x60x24.0	98.82	5.21	36.07	0.37
s3	60x60x24.4	95.36	6.44	43.01	0.45
s4	60x60x24.4	100.82	6.31	44.36	0.44
Average	60x60x24.2	96.32	5.52	40.02	0.42
Standard deviation		3.33	0.79	3.66	0.0012
Variance		0.03	0.14	0.09	0.003

4.1. Mass of Specimens (gram)

Mass of each specimen includes the mass of two steel skins, mesocarp blocks and adhesive glue used adhere them all together. Among them, mass of two SUS 304 stainless steel skins is about 57.5-58.5 grams, two mild steel skins is about 56.5-57.5 grams, total mass of mesocarp blocks is about 10-11.5 grams, the left is mass of adhesive glue. Mass of eight specimens were weighed and documented as shown in Table 1.

4.2. Peak force Fmax

From the force versus displacement curve in the Figure 5, the first peak crushing force is the initial peak crushing fore, expressed as F_{max}. It is determined by calculating its height respond on the vertical axis (force axis), the result as shown in Table 1. The average of F_{max} for mild steel sheet panel is 4.84kN and the average of F_{max} for SUS 304 stainless steel sheet panel is 6.04kN. The mean value of peak forces of SUS 304 stainless steel skin is higher than that of mild steel skin.

4.3. Energy absorption

In crash or impact safety design, energy absorption is an important indicator. The energy absorption of the mesocarp in quasi-static compression process can be calculated by the equation [1,2].

$$E_J = \int_0^{l_0} F dl \tag{1}$$

where, l_0 is the compressed length before the specimen come to compacting stage, F is the compressive force of the specimen during the compression. The energy absorption of the specimen materials can also be calculated by the Specific Energy Absorption (SEA) of unit weight material defined as:

$$SEA = \frac{E_J}{m_i} \tag{2}$$

where, E_J is the total energy absorption of the specimen during compression, m_i is the total weight of a single specimen.

The energy absorption E_j as shown in the table 1 was computed by using the Origin 8 software. The average of energy absorption for mild steel sheet panel is 4.1kJ/kg and for SUS 304 stainless steel sheet panel is 4.2 kJ per kg. It is recognized that the energy absorption E_j and peak force F_{max} of SUS 304 stainless steel skin sandwich panel are higher than those of mild steel skin sandwich panels because density and young modulus of SUS 304 stainless steel are higher than those of mild steel.

4.4. Comparative studies of Energy absorption

Energy absorption characteristic of common structure was contrasted to the coconut sandwich structures. Aluminum corrugated sandwich panels [23] were selected to compare the difference from coconut mesocarp core sandwich panel. The values are shown in the Table 2 where *Li* means number of corrugated layers. From Table 1, we can conclude that SEA of mesocarp sandwich panel is higher than aluminum corrugated sandwich panels.

Table 2. Specific energy absorption contrast

Specimen	Mesocarp sandwich panel	*L2*	*L3*	*L4*	*L5*	*L6*
SEA(kJ/kg)	0.42	0.14	0.20	0.30	0.31	0.32

5. CONCLUSIONS

The mesocarp core sandwich panels were manufactured and conducted under the quasi-static compression, so as to investigate their energy absorption characteristics. Panels with 304 steel sheets showed a little higher energy absorption characteristic than that with the mild steel sheets. Mesocarp core sandwich panels exhibited much better energy absorbing ability than aluminum corrugated core sandwich panels.

The coconut shell is a natural, easy seeking and environment-friendly material. If it can be widely used in the industrial design, environment can be protected. In the following step, the research group is going to study its characteristics under such loading conditions as dynamic compression, and impact so as to investigate their crashworthiness and further application fields. This study will open the door of applications of natural, environment-friendly and recyclable materials.

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