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Development and Modeling of Multi-phase Polymeric Origami Inspired Architecture by Using Pre-molded Geometrical Features

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ABSTRACT

Using Origami folded cores in sandwich structures for lightweight applications has attracted attention in different engineering applications, especially in the applications where the stiffness to weight ratio is a critical design parameter. Recently, common sandwich cores such as honey-comb and foamed cores have been replaced with origami core panels due to their way of force redistribution and energy absorption; these unique characteristics give origami cores high stiffness to weight ratio and high bending and twisting resistance. This paper presents the results of experimental investigations of the effect of base material on the mechanical properties and the impact resistance of Miura-Origami sandwich cores; then, the experimental results are compared with FEA simulation results. The materials used in the study for the origami cores were polymer blends composed of polylactic acid (PLA) and thermoplastic polyurethane (TPU). PLA/TPU blend compositions are (100/0, 80/20, 65/35, 50/50, 20/80, and 0/100) as a weight percentage. The geometrical parameters of the unit cell, base material thickness, and the panel thickness were considered to be constants in this study. The study shows the behavior of the origami cores under impact test and the energy absorbed by the origami folded cores. It was found that 20/80 PLA/TPU blend demonstrated the highest specific energy absorption efficiency both in quasi-static compression and impact tests. Fractured Origami structures were observed to fail at folded edges (creases lines), while the facets exhibit rigid body rotations. The FEM simulation showed a consistency in the impact behavior of the origami cores, and the directional deformational of origami core units which explain the ability of the structure to redistribute the applied force and absorb energy. In this work the origami folded core features were molded directly from the blended material.

Keywords: Origami, Sandwich, Folded, Cores, Polymers, Compression, Impact, Modeling, Stress.

1. INTRODUCTION

Sandwich core structures, usually composed of a thick lightweight core covered by two thin and stiff faces [1], are widely used for energy-absorption applications. Conventional sandwich core structures with honey-comb, foam, and ribbed stiffened cores have been used for such applications for many years. The mechanical performance of honeycomb cores deteriorate over time due to the moisture accumulation inside the sealed cells [1,2]. Recently, many new types of core structures have evolved for lightweight structures, such as truss core panels, open and closed cell foamed cores, functionally graded foams, and folded cores [3]. The global mechanical properties of two dimensional sheets can be enhanced by introducing a local texture to the material sheet [4]. The new manufacturing methods have allowed folded cores to be more promising for such applications [3]. Origami is the art of paper folding in which complex spatial objects can be created from a flat sheet [5]. It has an intrinsic source of inspiration for innovation of mechanical metamaterials, for which the material properties are defined more by the geometry and the way the materials are arranged than from the properties of its parent materials [5,6]. Rigid origami, in which the faces between the crease lines remain rigid and only the creases deform during the folding process, has an advantage over other classes of origami patterns that require faces bending and crumpling. During the load application, only crease lines deform while the faces have rigid body rotation [7]. Most previous studies have focused on periodic origami patterns; however, the non-periodic origami patterns have not yet received attention because of their complexity in theoretical modeling [7,8]. The main idea behind origami folded cores is their ability to absorb impact and compression energy through deformation of tessellation patterns, which is due to the collapse mechanism of the tessellation faces along folding lines without causing material rupture [4]. The origami pattern of origami tessellation is periodic in the planar direction, and the unit cell geometry, which consists of four identical faces joined through the crease lines, is characterized by the faces' dimensions and folding angles. The mechanical properties of the origami cores are characterized in a partly folded state [7,9]. The geometrical mechanics and characteristics of origami patterns have been studied by many researchers [7,9]. Furthermore, many research studies have provided mathematical and analytical models for the origami folded cores, including computer simulations and finite element analysis [5,7]. Extensive work has been carried out in the progress and development of folded cores in Tupolev State Technical University [10–14], in which different folded cores with different folding patterns have been investigated for mechanical properties and engineering applications [3]. Alekseev [15] has presented a simulation of geometrical parameters of both regular and irregular folded cores using CAD systems for designing the structure. A theoretical and experimental study to determine the characteristics of Z-Crimp cores has been introduced by Paimushin, et al. [15], while Shabalin et al. [16] provided a simulation of Z-Crimp shaping using the ANSYS finite element package. The effect of the geometrical parameters of Z-Crimp origami pattern on strength under transverse compression and longitudinal shear at the same volumetric density made of different materials has been investigated by Dvoeglazov et al. [17]; the authors outlined valuable

recommendations for the selection of structural parameters concerning origami structures for high strength. Tolman et al. [18] have introduced a three-stage strategy for material selection of Miura-origami structure. A numerical investigation of Miura-origami cores under quasi-static loads has been done by Zhou et al. [1], in which they found that the performance in compression and shear of the models with curved lines higher than the flat faced origami cores.

The objective of this study is to introduce an experimental investigation supported by finite element evaluation of the effect of base material on the mechanical properties and the impact resistance of Miura-Origami cores. The origami structures were geometrically molded at the fabrication stage without post folding of flat sheets. The materials used in the study for the origami cores are polymer blends composed of polylactic acid (PLA) and thermoplastic polyurethane (TPU). PLA/TPU blend compositions are (100/0, 80/20, 65/35, 50/50, 20/80, and 0/100) as a weight percentage. The origami pattern is periodic in the planar direction, and the unit cell geometry is characterized by four identical faces and folding angles. The mechanical properties of the origami cores are characterized in a partly folded state. The geometrical parameters of the unit cell, base material thickness, and the panel thickness are considered constants in this study. The study presents the results of the compression test, the impact resistance, and the energy absorbed by the folded cores in the impact test. The finite element simulation has been conducted by modeling the origami structure as a sandwich, using the explicit dynamics solver provided by ANSYS software, the shell element type used to represent the origami cores and the sandwich faces, the impactor modeled as a rigid part.

2. EXPEREMENTAL WORK

2.1 Materials Processing

The materials used to produce polymeric blends for origami samples are Poly-Lactic Acid (PLA) (3052D) obtained from Natureworks LLC (USA), the reported melting temperature range of PLA is 145 – 160 °C and the density is 1.24 g/cm³. PLA is a bio-based polymer has advantage mechanical properties, low energy processability, and it is also bio-degradable [19]. The main drawbacks of PLA are its high brittleness, low impact strength and toughness [19]. There have been a number of studies to improve these limitations; one of the effective ways is to form PLA blends with other polymers like Thermoplastic polyurethane (TPU) which features by strength, ductility, impact resistance and toughness [19]. TPU is grade (55D) obtained from Lubrizol Engineering Polymers (USA). The reported melting temperature of TPU is 181 °C and the density is 1.16 g/cm³. Both polymers are in pellet form, the weight percentage of PLA/TPU blend compositions used were 80/20, 65/35, 50/50, 20/80, in addition to the neat PLA and TPU. A twin screw micro-compounder (DSM; Geleen, Netherlands) (MICRO15) was used to fabricate the material blends, by melting and mixing the pellets at a temperature range of (185 – 195° C) with the screw speed of 30 rpm for 10 min. Then, the blends were extruded and pelletized.

2.2 Fabrication of Origami Structures

Three samples from each batch have been fabricated using compression molding. The mold was designed in three parts, allowing the samples to be removed easily after molding (see figure 1- a). The molding temperature was kept at 205° C and pressure of 3 Tons. Silicon based mold release spray was used to help releasing the samples from the mold. During the first samples preparation, a lot of bubbles were observed in the produced samples, so the mold has been sealed using fiber reinforced rubber to prevent bubbles occurrence and to avoid polymer leak. The pelletized material blends were melted and compressed between the upper and lower jaws of the mold and then held at 3 Tons for 10 minutes to allow uniform distribution of the material. Tensile specimens were also prepared for tensile test from each blend according to ASTM 638.

Figure 1. a) Multi-stage compression mold used to fabricate origami cores
b) The geometrical parameters of fabricated origami cors

2.3 Miura Origami Unit Cell and Core Configuration:

Origami structure consists of a periodic tessellation of unit cells, which are made of thin-walled faces connected at fold lines; it gains its unconventional mechanical properties from the interaction between the fold lines and the deformation of the interlaying faces [4]. Periodic origami geometry is defined by a repetitive unit cell, characterized by specific geometric parameters. Figure 1-b shows the panel of Miura-origami in partially folded state. The unit cell can be characterized by a specified set of its face's parallelogram independent parameters and the folding angle. The pattern parameters can be calculated using equations (1-4) [8,10]:

$$H = a \cdot \sin \theta \sin \gamma, \quad (1)$$

$$S = b \cdot \cos \theta \tan \frac{\gamma}{\sqrt{1 + \cos^2 \theta \cdot \tan^2 \gamma}}, \quad (2)$$

$$L = a \cdot \sqrt{1 - \sin^2 \theta \sin^2 \gamma}, \quad (3)$$

$$V = b \cdot \frac{1}{\sqrt{1 + \cos^2 \theta \cdot \tan^2 \gamma}} \quad (4)$$

where H, a and b, γ , θ , S, L, and V are the height of the origami panel, the face dimensions of the unit cell, parallelogram angle, fold angle, surface area, unit cell height, and the overall volume, respectively [8,10]. The folded core panel is defined by the number of tessellations, which is defined by the size of the core panel (W, L, H) where W, L, and H are the width, length, and height of the core panel, respectively. The geometrical parameters used to generate the origami core samples are (a = b = 24 mm, W = L = 120 mm, H = 20 mm, $\gamma = \theta = 45^\circ$, and the thickness is 1.5 mm).

The volumetric density of the origami panel can be calculated using equation (5),

$$\rho_c = \frac{t \cdot S}{V} \rho_m \quad (5)$$

where ρ_c is core volumetric density, t is parent material thickness, and ρ_m is parent material density [8,10]. Table 1 shows the values of blended materials densities and the origami core volumetric densities made from PLA/TPU blends.

Table 1. Material blends density and origami volumetric density

Material Blends (PLA/TPU) w %	Material Blends Density (g/cm ³)	Volumetric Origami Density (g/cm ³)
Neat PLA	1.24	0.161
80/20	1.220	0.158
65/35	1.213	0.157
50/50	1.198	0.155
20/80	1.175	0.152
Neat TPU	1.16	0.150

2.4 Compression Test

A compression test, which measures the capacity of origami cores to withstand compressive loads, was conducted to determine the strength of origami cores which. The origami core samples were tested using a compression testing general machine. Two thick steel plates have been assembled with the testing machine allowing the load to be uniformly distributed on the origami panel structure. The test was consistent with ASTM D1621/94 standard with 5 mm/min stroke. Three specimens were tested for each origami structure. Each sample has 9 periodical cells (see figure 1-b) with a cell size of (40*40 mm). A tensile test of base materials was conducted according to ASTM D638 standard to determine the tensile modulus.

2.5 Impact Test

Impact test conducted using a custom setup which was designed to measure the force and the energy transferred by the tested sample due to impact event. The origami core is sandwiched between two flat polycarbonate sheets with a thickness of (7 mm) (figure 2-a). Then the sandwich samples were placed on the flat disk of the test stand which is connected to a quartz based dynamic load sensor (Dytran, 1060V) see figure 2-b. By adjusting the dropped weight we vary the impact energy; in this study the impact weight is 1.104 kg while the drop height is 66.5 cm. The test was conducted based on ASTM D7136/D7136M standard. Force and time were recorded during the impact event.

Figure 2. a) Origami Sandwich core sample, b) Sandwich sample placed in the test stand

3. SIMULATION AND ANALYSIS

3.1 Compression Simulation

In order to simulate the compression tests, the Static Structural analyzer provided by ANSYS was used. In the simulation, the origami core placed on a thick steel plate, and it was represented by shell elements, and the thick plate was represented by solid elements. Frictions-less contacts between the origami core and the plate have been defined, and the lower side of the plate was constrained by fixed boundary condition. A compression strain of 10.1 mm was applied as a compression load. Figure 3-a shows the meshed geometry of the compression model.

3.2 Impact event simulation

For impact event simulation, the explicit dynamics solver provided by ANSYS was used: the origami core and sandwich faces were represented by shell elements, while the impactor was represented by solid elements. Fixed boundary condition was used in the bottom side of the lower plate, and free directional constraints were used for the impactor in the load direction. Frictionless contact has been defined between the impactor and the upper side of the upper plate of the sandwich, and bonded contacts between the sandwich faces and the origami core have been defined. Figure 3-b shows the meshed geometry of the origami sandwich structure. The mass of the impactor used to be 1.1014 kg and the contact velocity was $3571.137 \text{ mm s}^{-1}$. The impact event end time was 0.002 s.

Figure 3. The meshed geometry of the origami a) compression simulation, b) impact simulation

4. RESULTS AND DISCUSSION

4.1 Compression Test Results

The compression test of the origami cores shows that with the increase of the soft material (TPU), the origami core strength decreases while the origami core samples with high content of PLA have the higher strength. In contrast, samples with high percentages of TPU have higher compressive strains. Samples with high strength values experienced fracture along the crease lines, while high TPU content core samples were able to recover, but at the expense of the strength. Figure 4 shows the stress-strain behavior of the origami cores, and figure 5 shows the changing in elasticity modulus and the strength of the origami cores, respectively. Figure 6 compares the compressive deflection behavior at maximum stress and the maximum stress of the origami cores. The toughness of the origami cores illustrated in figure 7, PLA samples have the maximum values of toughness of about 1500 (J/m³), this value keeps decreasing by the increase of TPU amount to about 600 (J/m³) for 50/50 (PLA/TPU) sample, and to about 210 (J/m³) for the neat TPU samples. By the controlling the material blends weight percentage; it is possible to tailor the compression stiffness and strength.

Figure 4. Compression stress-strain relation of origami core structure

Figure 5. Modulus of elasticity and strength of origami cores

Figure 6. Comparison of maximum stress of origami cores and the deflection at maximum stress.

Figure 7. Comparison of origami cores' toughness

Compared with the specific modulus of elasticity of blended material, origami cores show low modulus values. Table 2 shows the comparison value of the specific modulus of elasticity. The values of origami strength are comparable with the honeycomb cores made of aramid fiber sheet (HRH10-3.2-144) [20], have the same density range ($144 \text{ Kg/m}^3 \pm 10\%$) (6.5 MPa) and the origami strength ranges between (4.6 ~ 0.5 MPa).

Table 2. Comparison of specific modulus of elasticity of solid blended material and origami cores

Material Composition (PLA/TPU) w%	E, of solid material blend (MPa.m ³ /Kg)	E, of origami cores (MPa.m ³ /Kg)
100/0 (PLA/TPU) w%	831.9	28.6
80/20 (PLA/TPU) w%	710.6	21.2
65/35 (PLA/TPU) w%	651.9	17.7
50/50 (PLA/TPU) w%	646.4	12.5
20/80 (PLA/TPU) w%	208.1	7.7
0/100 (PLA/TPU) w%	29.6	3.4

Figures 8 and 9 show the SEM images of fractured cores along crease lines for neat PLA and 80/20 PLA/TPU origami cores. PLA exhibits brittle-like fracture surface while the 80/20 PLA/TPU core shows cup-cone fracture surface that can be considered as ductile failure. This result illustrates brittle

to ductile transition with more percentage of TPU added to PLA for the origami core structures. This is important when designing origami structures where a balance between the brittleness and ductility in the material controls the compressive strength and energy dissipation, respectively. Increasing the brittle content (PLA) enhances compressive strength while the ductile content (TPU) promotes energy dissipation through plastic or large deformation.

Figure 8. SEM images of fracture surface of Neat PLA origami core with magnification **a)** 40X, **b)** 130X, **c)** 750X.

Figure 9. SEM images of fracture surface of 80/20 PLA/TPU origami core with magnification **a)** 40X, **b)** 130X, **c)** 750X.

4.2 Impact Test Results

In order to characterize origami structure during impact event, the procedure developed by Joshua has been adopted in our analysis [10]. Newton's second law is used and the solution for acceleration, $a(t)$, is given as:

$$a(t) = g - \frac{p(t)}{M} \quad (6)$$

where g is the gravitational acceleration constant, $P(t)$ is the load with respect to time, and M is the mass of the impactor. Zero time is considered when the impactor strikes the origami sandwich, so the following can be defined

$$v(t) = V, \quad \text{at } t = 0 \quad (7)$$

where V is the velocity just prior to impact.

Integrating equation (9) to obtain expression for $v(t)$ yields

$$v(t) = V + \int_0^t g - \frac{p(t')}{M} dt' \quad (8)$$

Once the previous quantities are obtained from our experimental setup, solving for the energy transferred as a function of time gives

$$\Gamma(t) = \int_0^t p(t') v(t') dt' \quad (9)$$

Figure 10 shows a sample of transferred impact force by neat PLA origami sandwich structure. There is force increase at the beginning of impact until a maximum value is reached, and then a decrease while the origami sandwich structure bounces back the impactor. This curve represents the $P(t)$ values in the equations above. V is calculated from Newton's equation of falling objects for an impactor mass of 1.104 Kg and drop height of 66.5 cm which reveals a value of 3.571134 m/sec. Maximum force and energy transfer is observed at high percentages of PLA which is attributed to the high compressive resistance due to brittle nature. The 20/80 PLA/TPU blend transfers force of 1.88 KN which is the lowest for all origami sandwich structures (see figures 11 and 12). As discussed in the previous section, the selection of the origami material depends on the application where the different percentages of PLA and TPU influence the amount of force and energy transfer. The reported values in this study are for the transferred force and energy where the receiver is our primary concern. Neat TPU provides low force transfer but it has the lowest compressive strength as noted in section 4.1. PLA can be added to enhance compressive strength while observing the transferred force, see figure 12. For example, 65/35 PLA/TPU blend increases the force transfer from 2.19 KN for neat TPU to 2.8 KN while also increasing the compressive modulus from 0.511 MPa to 2.79 MPa. So as discussed before, the origami structures can be designed for energy absorption while maintaining a required strength by controlling the amounts of PLA and TPU.

Figure 10. Sample of impact force for neat PLA

Figure 11. Maximum transferred impact force

Figure 12. Maximum impact energy transferred

When compared with conventional materials, origami cores show better impact force damping. Table 3 shows the comparison of the transferred force of (PLA/TPU) origami cores with polycarbonate and steel sheets during the same impact event.

Table 3. Comparison of maximum impact force transferred

Material	Maximum Force Transferred (N)
100/0 (PLA/TPU) w%	3708.2
80/20 (PLA/TPU) w%	3085.4
65/35 (PLA/TPU) w%	2806.4
50/50 (PLA/TPU) w%	2584.0
20/80 (PLA/TPU) w%	1882.4
0/100 (PLA/TPU) w%	2195.8
Polycarbonate	11432.9
Steel	20852.0

4.3 Finite Element Results

The results of the FEM were converging by the decrease of the element size from 1.4mm to 1mm and then it started diverging (see figure 13), the number of shell elements of origami cores was 29198, and the number of nodes was 42514. The static structural analysis of the origami cores has showed that, the maximum Von-Misses stress was in the neat PLA cores with the value of 853.26MPa, and it keeps decreasing by the increase of the TPU content, which has the minimum value of 72.946MPa. Figure 14 shows the comparison of maximum Von-Misses stress values, and figure 15 shows the Von-Misses stress distribution on the origami cores of neat PLA, 80/20 PLA/TPU, 50/50 PLA/TPU, and neat TPU. It is clear that the high values of stresses occur in the crease lines, and they become the stress concentration zones, while the faces are the low stress areas, as a result the fracture always expected to happen along the crease lines.

Figure 13. The change of the results error (%) by changing the mesh size

Figure 14. Comparison of Von-Mises stress values for origami cores of different material blends

Figure 15. Von-Mises stress distribution on origami cores **a)** Neat PLA, **b)** 80/20 PLA/TPU, **c)** 50/50 PLA/TPU, and **d)** neat TPU.

The explicit dynamics simulation of the origami sandwich cores has showed the impact behavior of the origami cores, the total energy, the internal energy, and the reaction force have been demonstrated, see figure 16, it is clear that, cores with high percentage of TPU have higher internal energy than the cores with the high percentage of PLA. The force transferred (reaction force) was distinctly decreases by the increase of the TPU percentage as illustrated in figure 17. The directional deformations along the load direction were high in the cores with high TPU contents. Cores with 80% TPU have double

of the energy value of the 80% PLA cores, and the reaction force in the outer-side of the lower plate almost equals the half value, as shown in figure 13. Origami PLA samples can dissipate energy up to 2.6 J, while the value increases by the increase of the TPU content, where the maximum energy dissipated was in the 20/80 PLA/TPU samples with 3.3J, and it was slightly decreased in the neat TPU samples because of the densification behavior in the soft material (see figures 16 and 17). Figure 18 shows the directional deformation in the load direction of origami cores made of neat PLA and neat TPU respectively.

Figure 16. The total energy, internal core energy, and the energy dissipated by origami cores

Figure 17. Reaction force, and the directional deformation

Figure 18. Directional displacement of origami core a) PLA b) TPU

5. CONCLUSIONS

Origami metamaterial can offer many benefits to many engineering applications, most importantly high stiffness, high energy absorption efficiency, and light-weight. Miura Origami structures are fabricated in this work by direct molding of the geometrical features from PLA and TPU polymeric blends. Direct molding avoids the defects related to a conventional folding of flat sheets when typically making origami structures. The following blends were fabricated for PLA/TPU (100/0,

80/20, 65/35, 50/50, 20/80, and 0/100). Those different percentages of PLA and TPU reflect the increase in compressive strength or energy transfer respectively. The balance between PLA and TPU will depend on the intended application. PLA origami structure offers maximum force transfer of 686.1 N and highest compressive modulus of 4.6 MPa. The high compressive modulus of PLA resulted in fracture at crease lines. The high modulus of PLA origami structure can be reduced to 2.79 MPa by adding 35% of TPU which offers more elasticity and avoid failure at high compressive strains. The addition of 35% TPU also reduces the force transfer to 2.8 KN. The finite element modeling has been conducted using static structural for compression test and explicit dynamics for impact event. The compression results showed that the crease lines are the stress concentration zones, and it is subjected to fracture in the blends with high elastic modulus while the faces carry low-stress values. The FEA results also demonstrated that origami made structure made of a high percentage of 80% TPU has the highest values of energy absorption (up to 3.3 J), with directional deformation exceeded (1.6 mm), and it has the lowest Von-Misses stress in compression. This work provided numerical quantification of the compromise between compressive strength and energy transfer which can be used to design origami structure with target values for both.

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