TEST Engineering & Management

March-April 2020
ISSN: 0193-4120 Page No. 11028 - 11038

Manufacturing and Optimization Strength and Stiffness of Novel Lightweight Spheres Sandwich Structure by Carving Wax Method

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Article Info
Volume 83
Page Number: 11028 - 11038
Publication Issue:
March - April 2020

Article History
***Article Received**: 24 July 2019*
***Revised**: 12 September 2019*
***Accepted**: 15 February 2020*
***Publication**: 13 April 2020*

Abstract:
Sphere Sandwich Structures (SSS) are a new structure which may have the potentials to provide the energy absorption as compared with monolithic specimen material. By using carving wax plate, fifteen specimens have been prepared according to RSM optimize method and it machined by CNC-3axis machine with sphere end screw.Three variables sphere diameter(D), distance between spheres(X) and skin thickness(K) have has been studied. The relative density of the samples has been calculated and compared with the reference sample Monolithic, the lowest relative density is 0.35, 65% which is lower than the monolithic sample. The bending test has been achieved bythree-pointtest on the designed samples. The sample 603 has the highest stress value and an improvement of 62% compared with the reference sample. The optimal value of this test is 19.35 Mpa2/3 of the sample 602 (diameter = 6, distance between spheres = 0, skin thickness = 2 mm).The stiffness has been calculated by known the modulus of elasticity of the designed samples, it is known as the Performance Index. The specimen 642has the highest modulus value and the improvement 116% compared with the reference sample, the optimal value for this test is 2.28 Gpa0.5 for sample 602 (diameter = 6, distance between spheres = 0, skin thickness = 2 mm).

Keywords: *Carving Wax, Sphere Sandwich Structure, Lightweight Materials, RSM-Optimization*

I. INTRODUCTION

Sandwich structure is one type of lightweight composite structure which consist from three elements skins, core and adhesive to bond skins and core.Skins are stiffmaterials like Aluminum panel and core is low density materials as foam whereas adhesive like epoxy to transform shear and axil load from skins to core and viseversa[1].Forces on skins are tension and compression whereas shear on core[2].The main purpose of sandwich structure are high flextural stiffness, high strength, low weight and thermal insulation properties[3]. Energy absorption application also has associated sandwich structure in

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transportation[4].In recent years, sandwich sphere structure(SSS) has interested in ballistic application as personal or vehicle armors. So, Andrews (2012)gave a detail description of sphere structure at three dimension in his multi-layer composite armordesign. This study shows that the primary advantage of sphere structure is dispersion of associated energy with ballistic projectile toward the perimeter of the layer of sphere structure rather directing all of the energy straight through the protecting layers.

Yibin Fu et al (2013) innovates Square Based Pyramid Unit Cell (SBPUC) to describe the 3D-arrangemnt of new sandwich sphere structure.In their research, they studied a design an numerical simulation in three models and concluded that the new structure can absorb at least 11.6% more impact kinetic energy than the monolithic plate.

Another research to Yibin Fu et al (2013), shows that the diameters relation between the incoming projectile and the spheres in sandwich core, the projectile initial impact velocity and the sphere arrangement. This research showed the diameter of spheres in different layers in one sandwich core should either decrease or increase monotonically, and there exists critical impacting speed.

A research by Pandyaraj V. et al(2018) innovates a novel plate structure with half sphericalprotrusion. They experimentally investigate of compression properties for different models Regular, Inverted, Interlock, Stagger with chopped and woven glass fibers. They concluded the interlock design have higher value of strength and compression than other designs and glass chopped specimens have higher value of strength and compression than Glass woven specimens at all designs.

The aim of this study is to investigate the strength and stiffness of sphere sandwich structure(SSS) which may be affected by three variables including the diameter of sphere, distance between sphere and skin thickness. The SSS is manufactured without used any adhesive between skins, however, the spheres are self-bonded with skins.

The process used to fabricate SSS is innovation method and based on carving wax.Shortly,the spheres are machined on the carving wax panel by CNC-3axis machine with end sphere screw to get hollow spheres which distributed according to experimental design method (RSM)and then the fluid resin (unsaturated polyester resin) has poured inside it. After the casting has been finished, the model immersed in a boiled water bath to melt the wax, which comes out from the polyester sample by the gravity force, and the result will be formed a model of self-adhering solid balls between two skins and as a form of a sandwich panel.

Surface response methodology RSM (Box-Behenkin method) is used to get optimization values and modeling parameters. In Box-Behenkin method 3 variables and 3 levels for each variable have been used so the runs number are 15

II. STRUCTURE CONFIGURATION

All structures of samples (Fig-1)are built according to the experimental design

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method (Box-Behenkin method) as table follow (table-1)

Table-1: The Box-Behenkin runs

No	Code	Spheres Diameters (D) mm	Distance between spheres (X) mm	Skin Thickness (K) mm
1	642	6	4	2
2	603	6	0	3
3	683	6	8	3
4	644	6	4	4
5	1202	12	0	2
6	1282	12	8	2
7	1243	12	4	3
8	1243	12	4	3
9	1243	12	4	3
10	1204	12	0	4
11	1284	12	8	4
12	1842	18	4	2
13	1803	18	0	3
14	1883	18	8	3
15	1844	18	4	4

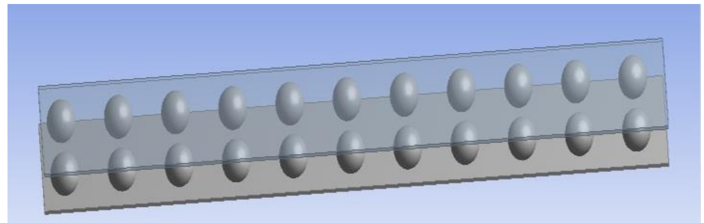

Figure (1): Sandwich sphere structure model

III. FABRICATION OF SPECIMEN

The SSS was made by innovation method as steps follow:

1. Wax Ingot Preparation

By using carving wax cubics, it has made wax panel (36*21*X cm) by re-melting of wax cubics which Pakistani's made from Dentirakcorporation asFigure (2).

A B

Figure 2: A-Carving wax fingers, B-carving wax panel

2. Shape Design of Wax Panel

Depends on Table-1, thickness of wax panel has been calculated by equation (1),as table (2):

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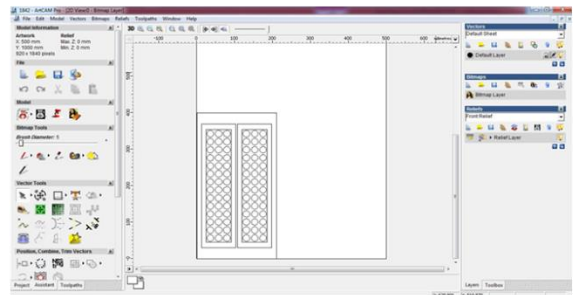
$T_{wax\ panel}$= Skin Thickness(K) + Radius (R) …………..(1)

Table-2: Thickness of wax panel

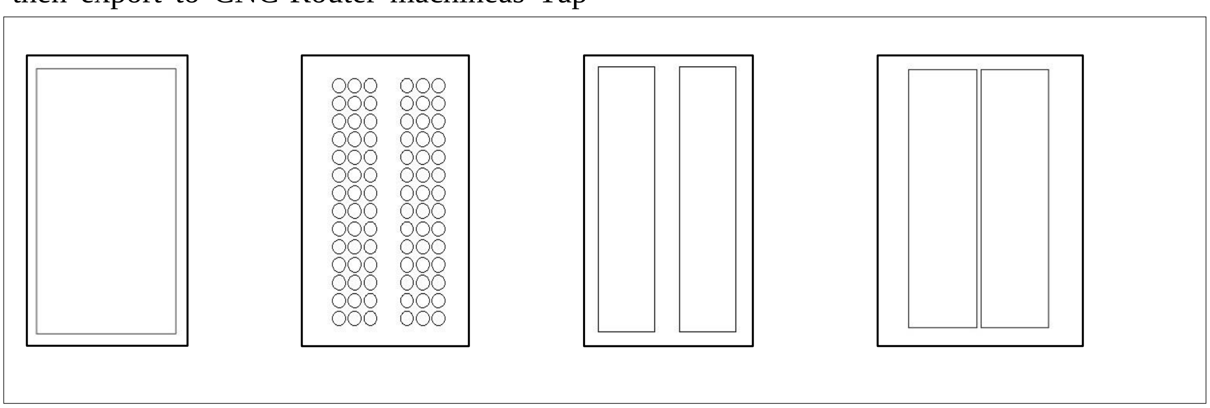
No	Code	T_{wax} mm
1	642	5
2	603	6
3	683	6
4	644	7
5	1202	8
6	1282	8
7	1243	9
8	1243	9
9	1243	9
10	1204	10
11	1284	10
12	1842	11
13	1803	12
14	1883	12
15	1844	13

3. Graphics Design

In this step, ArtCAM graphics software is used to draw specimens as figure (3) and then export to CNC-Router machineas Tap extent (G-code language). Specimen graphicisdivided to parts. Each part would achieve function such as edge cutting, sphere drilling and area clearance etc, as figure (4). The CNC-Router machine is XL-1325 China model with spheres end screw(figure-(5))



Figure(3): Graphics of specimen by ArtCAM software



(Part 1) (Part 2) (Part 3) (Part4)

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Figure (4): Four parts for export to CNC-Machine

Figure (5): The CNC-Machine and sphere end screw

4.

5. Execution Step

In this step, it has been executed Tap file by CNC-Router machine as steps in figure (6):

Step (1)-fixed wood plate and machined zero level on it.

Step (2)-fixed wax plate in 90º with respect z-axis (cutting axis).

Step(3)-machined the first face to mad spheres cavities

Step (4 ,5)-machined the second face to mad skins cavities

Step (6) – cutting edges to get two half wax plate to form at the same time completed mold.

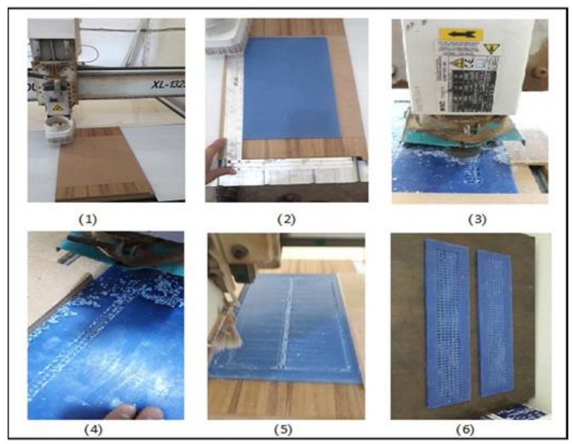

Figure (6): The steps of manufacture processing

6. Mold Preparation

In this step, Two half wax plate have been assembled in form one body and then trapped it between plastic or glass panels to get mold , as figure(7).

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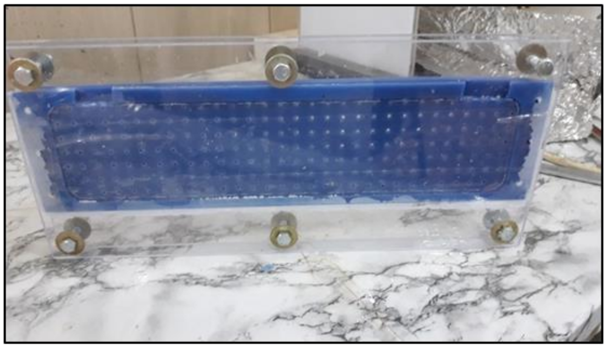


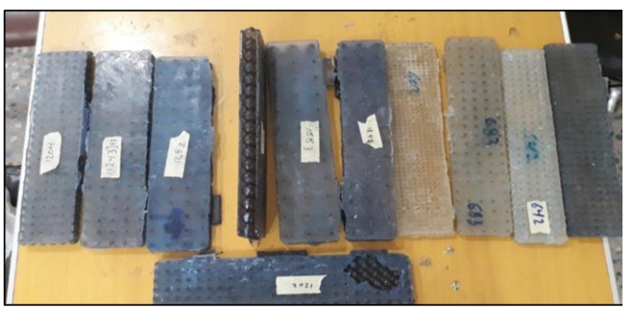
Figure (7): The mold for UPS casting

7. Casting Resin

In this step, UPS resin it has been poured with 1% hardener and then put the mold under vacuum nearly 9KPa at 5 min until casting finish.

8. Elimination Step

In this last step, wax has been eliminated by put it in water boiling paths nearly 30 min to get sandwich sphere structure as figure (8).



Figure(8):The SSS specimens

IV. RELATIVE DENSITY ρr

Relative Density is a very important property to express the amount of materials with respect 100% dense solid in lightweight structure. It is between 0.02-0.9. The equations (1,2) is represented the relative density of our structure.

$$\rho_r = \frac{\rho_{UPS\,shape}}{\rho_{UPS}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

$$\rho_{UPS\,Shape} = \frac{W_{UPS\,shape}}{V_{UPS\,effective}} \quad \ldots\ldots\ldots\ldots\ldots\ (2)$$

Where is:

ρ_r:Relative density

$\rho_{UPSShape}$:Density of Unsaturated Polyester shape structure (g/cm^3)

ρ_{UPS}: Density of Unsaturated Polyester (1.277 g/cm^3)

$W_{UPS\ Shape}$:Weight of Unsaturated Polyester shape structure (g)

$V_{UPS\ effective}$: Effective Volume of Unsaturated Polyester shape (cm^3)

V. TESTS

The Flextural experiments are carried out in a Universal Testing Machine and by C-790 ASTM.The size of specimens as in Table -3.All specimens under the same speed load which is 2 mm/min.The load-deformation behavior was recorded. Flextural strengthis calculated by equation (3).The modulus of elasticity is calculated from equation (4) by damping test (cantilever model)and performance Index from equation (5)

$$\sigma_f = \frac{3PL}{2bd^2} \ldots\ldots\ldots\ldots\ldots\ldots\ (3)$$

Where is:

Ϭf:Maximum Bending Stress MPa

P:Maximum load N

L:Length of specimen mm

b:width of specimen mm

d:Thickness of specimen mm

$$\omega = 1.875^2 \sqrt{\frac{EI}{\rho L^4}} \quad \text{.........(4)}$$

Where is:

ω:Natural frequency Hz

ρ:Density Kg/m^3

I:EffectiveMoment of Inertia m^4

L:Length of specimen mm

E:Modulus of Elasticity MPa

$$\text{Performance Index} = E^{0.5} / \rho_r \quad \text{.........(5)}$$

Where is:

E:Modulus of Elasticity MPa

ρ_r:Relative Density Kg/m^3

Table-3:The dimension of specimen

No	Code	Span length mm	Thickness mm	Width mm
1	642	200	10.4	40
2	603	200	11.6	40
3	683	200	11.6	38.5
4	644	200	13	46.4
5	1202	200	14.8	46.8
6	1282	200	15.3	54
7	1243	200	17.5	44.9
8	1243	200	17.8	45.6
9	1243	200	17.7	44.8
10	1204	200	18.8	46.4
11	1284	200	18.3	56.7
12	1842	200	22.2	40.6
13	1803	200	22.7	51.9
14	1883	200	23.7	46.7
15	1844	200	23.4	39.6

VI. OPTIMIZATION METHOD

The design of experiments is carried out by Minitab17 according to RSM method (Box-Behinken method) to optimize parameters of Sphere Sandwich Structure (sphere diameter(D), distance between spheres(X) and skin thickness(K)).The number of runs is 15 and allowed the estimation of quadratic as table (4).It is used RSM method to analyze and model data and the results showed by main effect chart and contour chart.

Table-4: The RSM- runs

No	Code	Spheres Diameters (D) mm	Distance between spheres (X) mm	Skin Thickness mm
1	642	6	4	2
2	603	6	0	3
3	683	6	8	3
4	644	6	4	4
5	1202	12	0	2
6	1282	12	8	2
7	1243	12	4	3
8	1243	12	4	3
9	1243	12	4	3
10	1204	12	0	4
11	1284	12	8	4
12	1842	18	4	2
13	1803	18	0	3
14	1883	18	8	3
15	1844	18	4	4

VII. RESULT AND DISCUSSION

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The strength, stiffness and relative density are tabulated in Table-5.By comparing with UPS Block in figure (9), the specific strength percentage improvement is 62 and 116 for specific stiffness. The equation (6) represents modeling results for strength response with coefficient of determination R2 equal 78.22%.

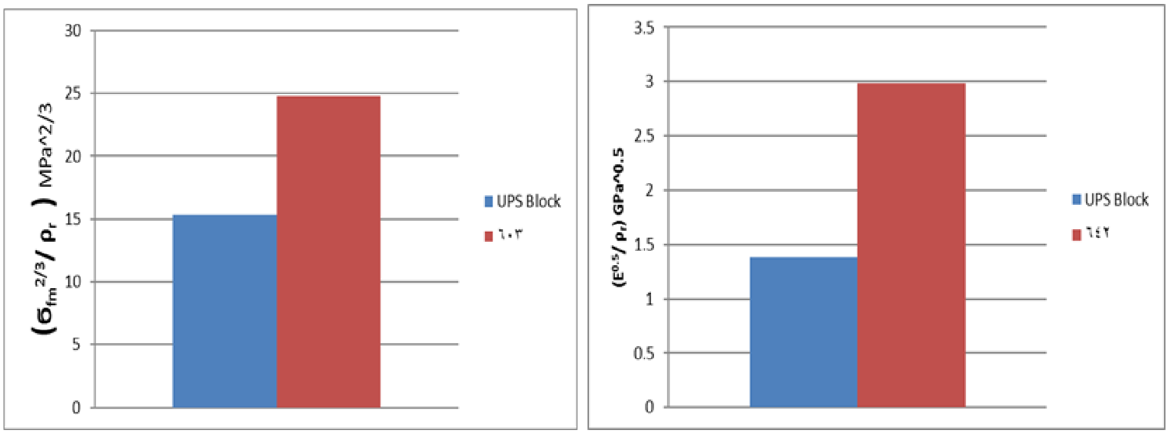

Figure (9): Comparison of max strength and stiffness value with UPS Block

Table -5:The results of relative density, strength and stiffness

No	code	ρ_r	σ_{fm} MPa	ρ_r	$(\sigma_{fm})^{2/3} / \rho_r$ MPa$^{2/3}$	E MPa	$E^{0.5} / \rho_r$ Gpa^0.5
0	UPS Block	1	62.5	1	15.33	1900	1.37
1	642	0.393979	10.17	0.393979	11.91	1379.04	2.980679
2	603	0.672101	68.06	0.672101	24.8	809.12	1.33836
3	683	0.55807	19.86	0.55807	13.14	1461.46	2.166236
4	644	0.611061	17.75	0.611061	11.14	1304.53	1.869147
5	1202	0.570446	10.01	0.570446	8.14	747.32	1.515448
6	1282	0.352617	5.22	0.352617	8.53	194.4	1.250509
7	1243	0.521782	6.39	0.521782	6.6	296.09	1.04286
8	1243	0.419378	6.08	0.419378	7.95	277.73	1.256634
9	1243	0.418351	6.26	0.418351	8.12	286.8	1.280132
10	1204	0.604244	16.08	0.604244	10.54	657.1	1.341557
11	1284	0.453969	6.94	0.453969	8.01	30.92	0.387383
12	1842	0.448869	4.39	0.448869	5.98	175.3	0.932603
13	1803	0.636075	18.62	0.636075	11.04	363.79	0.948201
14	1883	0.371891	3.91	0.371891	6.68	90.98	0.811079

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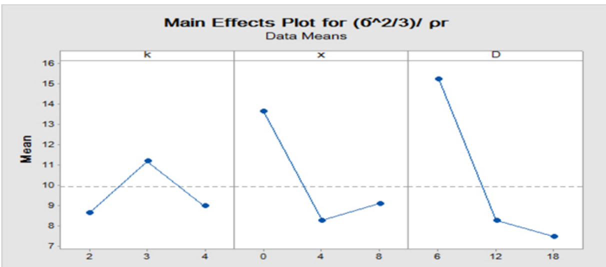
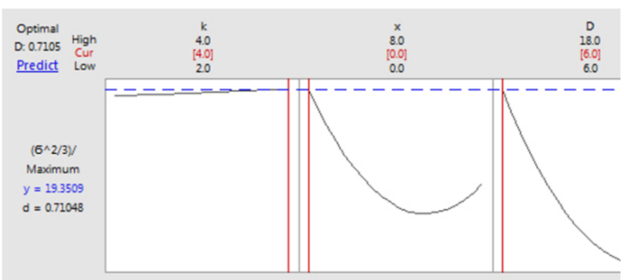
15	1844	0.409434	4.05	0.409434	6.21	104.25	0.788415

$$\frac{\sigma^{\frac{2}{3}}}{\rho_r} = 32.55 + 0.168\ k - 2.232\ x - 2.867\ D + 0.2079\ x*x + 0.0925\ D*D \text{.............(6)}$$



Figure(9):The main effects plot between strength and variables



Figure(10): The optimal value for variables with response

Figure (9) shows main effect plot for strength response with three parameters of study according to ANOVA. Here, the diameter(D) variable highly effects on strength with p-value less than 0.05and it decrease from 6 mm to 15 mm and then increase. The distance between spheres (X) also highly effects on strength with p-value less than and it decrease from 0 mm to 4 mm and then increase. The skin thickness (K) variable has low effects on strength and it increase from 2 mm to 3 mm and then decrease. Optimal value shows in figure (10) and denoted by Cur symbol, the it's values are ((D=6mm), (X=0 mm) and (K=4 mm)).Table (6) shows comparison between optimize value and practice value, there is2.5% error between these values since manufacture process.

Table -6: Optimize and practice values of strength specimen

code	**Optimize Value** MPa$^{2/3}$	**Practice Value** MPa$^{2/3}$	**Error**
604	19.35	18.9	2.30%

The equation (7) represents modeling results for stiffness response with coefficient of determination R2 equal 70%.

$$\frac{E^{0.5}}{\rho_r} = 2.519 - 0.208\ k - 0.0120\ x - 0.0737\ D \text{.............(7)}$$

Figure (11) Shows main effect plot for stiffness response with three parameters of study.Here, The diameters(D) variable highly effects on stiffness and it decrease from 6 mm to 15 mm.The distance between spheres (X) also effects on stiffness but low and it increase from 0 mm to 4 mm and then decrease. The skin thickness (K) variable middle effects on stiffness and it decrease from 2 mm to 4mm.Optimal value showed in figure (12) and denoted by Cur symbol, the it's values are ((D=6mm), (X=7.5 mm) and (K=2 mm)).Table () shows comparison between optimize value and practice value, there are 9% error between these values since manufacture process.

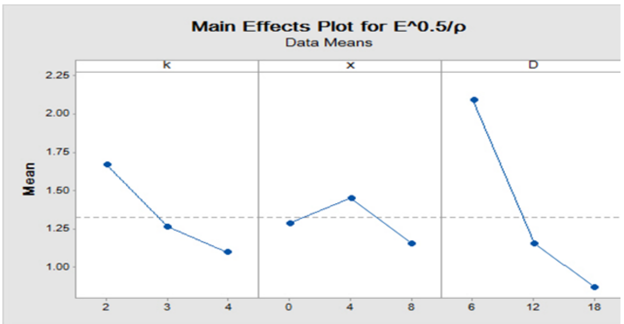


Figure (11): Themain effects plot between stiffness and variables

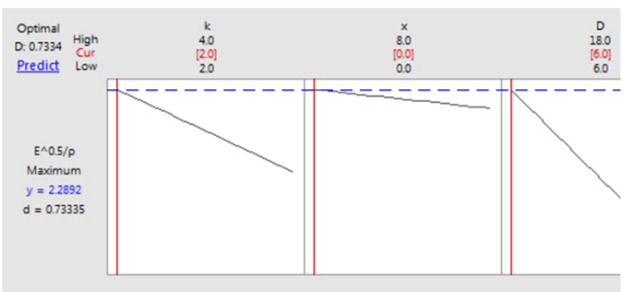


Figure (12): Theoptimal value for variables with response

Table -6: Optimize and practice values of stiffness specimen

code	Optimize Value GPa$^{0.5}$	Practice Value GPa$^{0.5}$	Error
602	2.289	2.1	8%

VIII. CONCLUSION

1-The carving wax method is innovation method to produce sandwich structure with a lot of benefits, these are:

Possibility of manufacturing various core shape such as rectangular, cubic, circular, and triangle in 3D arrangement.

Self-bonding of core to skins; no adhesive is needed.

Repeated layers are possible without using any adhesive.

Possibility of fulling hollow spaces by silicon rubber, foam or any liquid material for thermal or stiffness properties for examples.

This method is limited for thermosetting polymer such as epoxy and USP.

Possibility of employing any fillers materials to synthesize sandwich composite materials structure.

2-The maximum value of specific strength is 24.8 MPa2/3 for the specimen (603) and optimal value is 19.35 MPa2/3 for the specimen (602).

3-The improvement percentage is 62% as compare with monolithic sample.

4- The maximum value of specific stiffness is 2.9 GPa0.5 for the specimen (642) and optimal value is 2.28 GPa0.5 for the specimen (602).

5-The improvement percentage is 116% as compare with monolithic sample.

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