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Bending Optimization of Composite Sandwich Panels with Second-Order Corrugated Cores

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Abstract: Second-order corrugated cores are one type of hierarchical cores that use the common corrugated cores as constituent elements for the main core. This paper attempts to identify and optimize the bending properties of composite sandwich panels with second-order corrugated core. To this end, both first- and second-order corrugated cores are constructed and force-displacement diagrams are extracted in three-point bending tests. Finite element models are created and the deflection results are validated by experiments. Based on the Taguchi method, various finite element models with different geometrical parameters are modeled and reaction force and stiffness are determined. Stiffness formulas for first- and second-order corrugated cores are determined by using regression analysis. The constrained-optimization results are determined to optimize the stiffness of sandwich panels with first- and second-order corrugated cores, separately. The global optimization problem is implemented to compare the first- and second-order configurations.

Keywords: Design of Experiments, Optimization, Sandwich Panel, Second-Order Corrugated Core, Stiffness

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Research paper

1 INTRODUCTION

Hierarchical structures are novel structures that have multi-level organization of materials and are widely used in advanced engineering fields such as aerospace, civil, and ocean engineering. These structures have nature-inspired design origins and commonly improve load-bearing capability and crashworthiness compared to traditional structures. Second-order corrugated cores [1] are novel hierarchical cores that use the common corrugated cores as constituent elements for the main core. These structures have the advantages of sandwich panels such as high bending stiffness and low weight at the same time [2].

There are several investigations that studied the mechanical behavior of sandwich panels with corrugated cores. Liang et al. [3] determined the correlation between the transverse displacement of the corrugated panel and external uniform pressure load by implementing normality theory and a simplified beam model. Wang [4] studied the compressive behavior of sandwich panels with multi-layer corrugated linerboards as cushioning media. Bartolozzi et al. [5] present equal properties for sinusoidal corrugated cores based on beam theory and validate them by finite element results. Åslund et al. [6] performed experimental uniaxial compression tests on sandwich panels with corrugated cores to study their buckling. They provided finite element models and validated them with experiments. Berdichevsky and Yu [7] employed asymptotic expansion of the field of the shell theory to determine the equal model for corrugated structures. Kiliçaslan et al [8] exposed multi-layer metal corrugated cores to an axial compression test to determine their energy absorption at different strain rates. They developed a finite element model to extract the stress-strain diagram and compared numerical results with experiments. In the review paper of Dayyani et al. [9], the application of corrugated structures especially in morphing wings is provided.

Blandzi et al. [10] studied sandwich beams with sinusoidal corrugated cores and presented an analytical formulation for bending and buckling them by using the classical Euler–Bernoulli theory. Park et al. [11] used the energy method to determine equal properties for corrugated sheets. In the work done by Kheirikhah and Babaghasabha [12], corrugated sandwich panels with composite faces are modeled and analyzed by using the finite element method. They showed that critical buckling loads increased notably by using corrugated faces. In another work, Kheirikhah et al [13] considered the free vibration of corrugated sandwich panels. Paczos et al. [14] constructed five-layer corrugated beams consisting three corrugated and two facing layers. They determined their vertical displacement by using a three-point bending test. They developed finite element models and validated numerical results with experiments. Dayyani and Friswell [15] optimized trapezoidal corrugated morphing skins with an elastomeric coating. Han et al. [16] investigated the vibration and buckling of sandwich panels with corrugated cores. They considered that the core is made from composite and filled with foam. They developed shear deformation theory to obtain equal properties of panels. In the work done by Lurie et al. [17], a sandwich panel with a corrugated core is used to design optimum geometry for rescue vehicles in thermal conditions. Shaban and Alibeigloo [18] extended the previous analytical formulation of corrugated cores and determined out-of-plane equal properties of them. They [19] added a piezoelectric sensor and actuator to sandwich panels with corrugated cores to achieve a smart structure.

Du et al. [20] applied three-point bending tests to curved sandwich panels with corrugated cores to determine their failure modes. They also provided analytical formulas for predicting the failure of panels. Zhang et al. [21] studied the failure behavior of sandwich panels with second-order corrugated cores in compression loads. The internal corrugation pattern in their work is similar to the overall pattern. Taghizadeh et al. [22] investigated the effect of corrugated shapes on the energy absorption of sandwich panels with foam-filled corrugated cores.

An et al. [23] optimized the stacking sequence of multi-region composite structures by using two-level problems. Fu et al. [24] studied the crush behavior of multilayer corrugated metal tubes subjected to axial impact loads. Zamanifar et al. [25] applied first-order shear deformation theory to the finite strip method to determine the thermal buckling of sandwich panels with the corrugated core. Bahrami-Novin et al. [26] implemented a genetic algorithm for optimizing the geometrical parameters of corrugated sheets.

Yüksel et al. [27] determined a truss model for obtaining equal in-plane stiffness of sandwich panels with corrugated core and filled with foam. Santos et al. [28] optimized Sandwich Panel with a rectangular core by implementing a gradient-based optimization method. They used a plate bending solution to estimate the internal stresses of each layer. Novin et al. [29] determined flexural behavior of sandwich panels with corrugated cores constructed from fiber-metal laminates. They also optimized the structural properties of them. Vakilifard et al. [30] analyzed bending behavior of five-layer sandwich panels with corrugated cores and introduced isotropic multi-layer sandwich panel to eliminate anisotropic properties. In the work of Wang et al. [31], crushing strength analysis of first- and second-order corrugated cores is investigated. Talaie et al. [32] determined out-of-plane core shear modulus for both first- and second-order composite corrugated core. They used first-order shear deformation theory to determine the deflection equation of the beam subjected to a three-point bending test and compared the analytical results with experimental and numerical results.

Surveying the literature, very few investigations have been found on the investigation of mechanical behavior of sandwich panels with second-order corrugated cores; none of them determine optimized panels. In continuation of the previous work [32], this paper attempts to identify and optimize the bending properties of composite sandwich panels with second-order corrugated core. To this end, the required molds for both first- and second-order corrugated cores are described. Based on the Taguchi method, several finite element models with different geometrical parameters are modeled and reaction force and stiffness are determined. Then, stiffness formulas for first- and second-order corrugated cores are determined by using regression analysis. After that, the constrained-optimization results are determined to optimize the stiffness of sandwich panels with first- and second-order corrugated cores, separately. Finally, the global optimization problem is implemented to compare the first- and second-order configurations.

2 EXPERIMENT MANUFACTURING AND TESTS

2.1. Geometric Characteristics of Sandwich Plates

Figure 1 presents a schematic depiction of sandwich panels with first- and second-order corrugated cores.

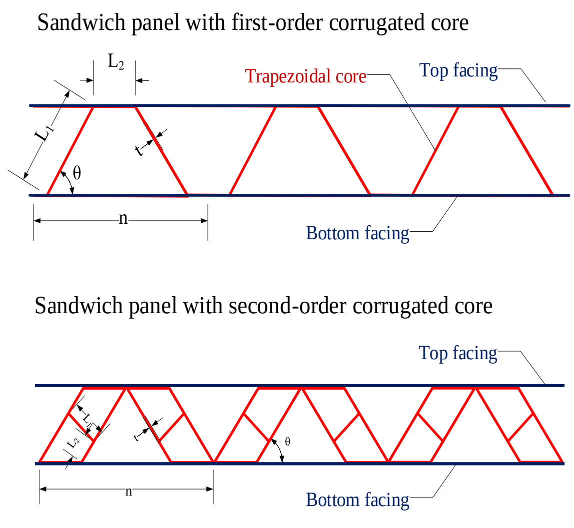


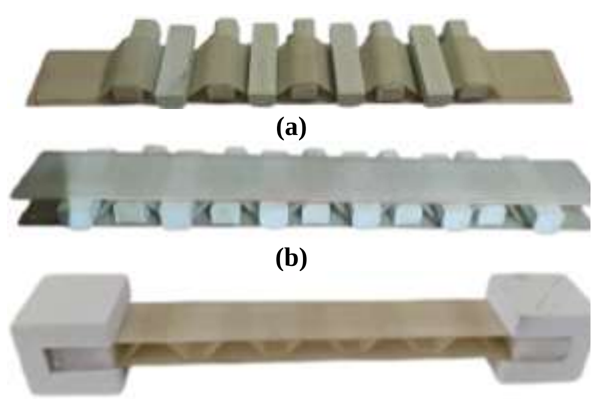
Fig. 1 Schematic representation of sandwich panel with second-order corrugated core.

As shown in "Fig. 1", the sandwich panel consists of a top facing, bottom facing, and core. The geometrical parameters of corrugated cores are L1, L2, θ, and n. L1 and θ are the web length of corrugation and angle of web, respectively. L2 denotes the top length of corrugation. n is the unit cell length that represents a full period of trapezoidal corrugation. The thickness of the corrugated core and facings are shown by t and tc. As shown in "Fig. 1", the core of the second-order corrugated sandwich panel consists of interior trapezoidal cores. These interior cores rested on the bottom and top facings and created the same angle as the corrugated core, i.e., θ.

2.2. First-Order Sandwich Panel

In this section, the building of a sandwich panel with first-order corrugated core is described. The overall length and width of the panel are 300 mm and 35 mm, respectively. For every component, the E-glass woven is used as fiber. Araldite LY 5052 with Aradur 5052 hardener is used as a resin matrix. For first-order corrugated core, five layers of composites are located in the lower mold. It is noted that the put layer should be impregnated with resin before placing the next layer in the mold. Then, extra fibers out of the mold are cut and the upped mold is placed on the specimen. The trapezoidal corrugated core is exposed to pressure and prepared after the complete curing of the specimen. The constructed specimens have a thickness of 1.25 mm, L1=L2=10 mm, and θ=45º.

To assemble the facings and core components and obtain a perfect bonding surface between facings and core, the same resin and hardener are used as the adhesive. For achieving a perfect bonding surface between facings and core, the bonded surfaces should be exposed to pressure. But when the corrugated core is subjected to pressure, it deforms and loses its initial form. To overcome this problem, inserts from PVC are provided and used to cause the pressure implemented into the bonding surface without deformation in the shape of a corrugated core. Figures 2(a, b) show how to place inserts into empty cavities of cores. As shown in "Fig. 2(c)", a reinforced region including internal and external U-cap PVC inserts in both ends is considered to prevent local failures, debonding, and deformations in two ends.



(a)

(b)

(c)

Fig. 2 Manufactured first-order sandwich panels and their inserts.

Based on ASTM D7250, three-point bending tests of the fabricated sandwich panels with first-order corrugated core were conducted in the electronic testing machine SANTAM STM-150 with a loading speed of 0.5 mm/min.

2.3. Second-Order Sandwich Panel

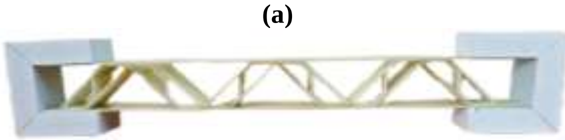
This section describes the manufacturing of sandwich paned with second-order corrugated core. The corrugated parameters are the same as that are used for first-order one. In the first stage, the interior cores should be made. To this end, a couple of molds are provided by using a 3D-printing process. The laminates are positioned in the lower mold and then the upper mold is placed on the laminates. The interior trapezoidal cores are prepared after curing of resin. Figure 3(a) shows the steps of manufacturing interior trapezoidal cores. Next, upper and lower facings should be bonded to trapezoidal cores to provide complete unit cells as shown in "Fig. 3(b)".

(a)

(b)

Fig. 3 Interior trapezoidal cores of the second-order corrugated core.

(a)



(b)

Fig. 4 Manufactured second-order sandwich panels and their inserts.

Similar to first-order corrugated cores, triangle inserts are required to assemble the interior cores as shown in "Fig. 4(a)". Two outer U-caps are provided to provide local failure of the panel in bending as shown in "Fig. 4(b)".

3 DESIGNS OF EXPERIMENTS

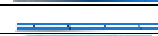
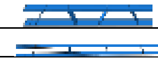
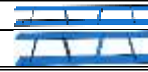
In this section, empirical formulas are derived for cores shear modulus of first- and second-order corrugated cores based on finite element results that are validated by experiments in previous sections. To investigate the relationship between geometrical parameters of corrugated core, design of experiments (DOE) that is a systematic and effective method is used. Here, Taguchi design method which is one of the famous design methods is used to generate an orthogonal array for four input factors, namely, L1, L2, θ, and t is used. "Table 1" presents the level values of design parameters.

Table 1 Level values of design parameters

Parameters	Parameter symbol	Level values (First-order)	Level values (Second-order)
θ (degree)	A	30,45,60,75	30,45,60,75
t (mm)	B	0.9, 1, 1.1, 1.2	0.9, 1, 1.1, 1.2
L_2 (mm)	C	10, 20, 40, 60	10, 15
L_1 (mm)	D	10, 15	10, 15

According to the number of factors and levels, L16 orthogonal array is selected and the FE models are provided. "Table 2 and Table 3" present FE models of first- and second-order corrugated cores.s

Table 2 Finite element models of first-order corrugated cores

Experiment number	FEM	Experiment number	FEM
1		9	
2		10	
3		11	
4		12	
5		13	
6		14	
7		15	
8		16	

Three-point bending test is performed in ABAQUS for first- and second-order corrugated sandwich panels. The stiffness of the panel is the slope of the force-displacement diagram and is calculated by dividing the reaction force of the reference point by displacement. The stiffness of first- and second-order corrugated sandwich panels is reported in "Table 4 and Table 5", respectively.

Table 3 Finite element models of second-order corrugated cores

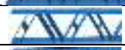
Experiment number	FEM	Experiment number	FEM
1		9	
2		10	
3		11	
4		12	
5		13	
6		14	
7		15	
8		16	

Table 4 Finite element results of first-order corrugated cores

Expt. No.	α	t	P_1	P_2	F (N)	S^{1st} (N/mm)
1	30	0.9	10	10	25/226	15/288
2	30	1.0	10	20	7/024	4/257
3	30	1.1	15	40	2/26	1/370
4	30	1.2	15	60	1/015	0/615
5	45	0.9	15	20	10/489	6/357
6	45	1.0	15	10	56/279	34/108
7	45	1.1	10	60	1/022	0/619
8	45	1.2	10	40	3/411	2/067
9	60	0.9	10	40	2/443	1/481
10	60	1.0	10	60	1/083	0/656
11	60	1.1	15	10	99/153	60/093
12	60	1.2	15	20	26/179	15/866
13	75	0.9	15	60	0/992	0/601
14	75	1.0	15	40	3/655	2/215
15	75	1.1	10	20	26/404	16/002
16	75	1.2	10	10	16/941	10/267

In the next step, regression analysis is used to generate an equation of force with respect to four design parameters. Regression analysis is carried out in Minitab for multiple orders, namely, linear, quadratic, and cubic polynomial. For each polynomial, the order corresponds with the degree of the equation. In “Table 6”, three statistical parameters are reported, that is, S, R-sq, and R-sq(adj). As shown in this table, the smaller standard error of the regression (S) is for a cubic polynomial that represents that the average distance from the predicted model is little on the other hand, R¬2 or R-sq value together with adjusted R2 or R-Sq(adj) value have higher values compared with linear and quadratic models. It means that the design variables, explain up to 94% of the variability of the force. This indicates that the cubic polynomial can suitably predict the reaction force of first- and second-order corrugated cores.

Table 5 Finite element results of second-order corrugated cores

Expt. No.	α	t	P_1	P_2	F (N)	S^{t2nd} (N/mm)
1	30	0.9	10	10	4/419	2/946
2	30	1.0	10	10	5/79	3/860
3	30	1.1	15	15	26/67	17/780
4	30	1.2	15	15	29/444	19/629
5	45	0.9	10	15	80/469	53/646
6	45	1.0	10	15	94/424	62/949
7	45	1.1	15	10	81/892	54/595
8	45	1.2	15	10	89/707	59/805
9	60	0.9	15	10	8/416	5/611
10	60	1.0	15	10	3/596	2/397
11	60	1.1	10	15	7/332	4/888
12	60	1.2	10	15	9/436	6/291
13	75	0.9	15	15	6/917	4/611
14	75	1.0	15	15	9/406	6/271
15	75	1.1	10	10	39/898	26/599
16	75	1.2	10	10	50/876	33/917

Table 6 Level values of design parameters

Model	S	R-sq	R-sq(adj)
First-order			
Linear	21.2784	52.47%	35.18%
Quadratic	17.5550	91.18%	55.88%
Cubic	6.06083	99.65%	94.74%
Second-order			
Linear	38.0590	8.97%	0.00%
Quadratic	26.8796	83.49%	38.08%
Cubic	5.50641	99.48%	97.40%

The cubic polynomial for first- and second-order corrugated cores are presented in “Eq. (1) and Eq. (2)”, respectively.

$$S^{1st} = 7441.8 - 26.42\alpha - 20377.58t + 40.18P_1 + 3.33P_2 + 0.64\alpha^2 + 19048.49t^2 + 0.034P_2^2 - 12.82\alpha t + 0.013\alpha P_2 - 13.273tP_1 + 2.885tP_2 - 0.873P_1P_2 - 0.003\alpha^3 - 5660t^3 \quad (1)$$

$$S^{2nd} = -1215.3 + 73.067\alpha - 8t + 5.667P_1 + 4.933P_2 + 1.409\alpha^2 + 44.67t^2 + 0.08\alpha t + 0.016\alpha P_1 - 0.141\alpha P_2 - 6.73tP_1 + 2tP_2 + 0.009\alpha^3 \quad (2)$$

Figure 5 shows Pareto chart of first- and second-order corrugated cores to determine the magnitude and the importance of the effects. As shown in “Fig 5(a)”, square of the bottom length of the first-order corrugated core, P2 2, has the most effective term in the formula of the first-order corrugated core. Thickness (either t, t2, and t3) is the second important parameter in bending analysis of the first-order corrugated core. Based on "Fig 5(b)", the angle of corrugation, α, plays the most important role in the bending of the second-order corrugated core.

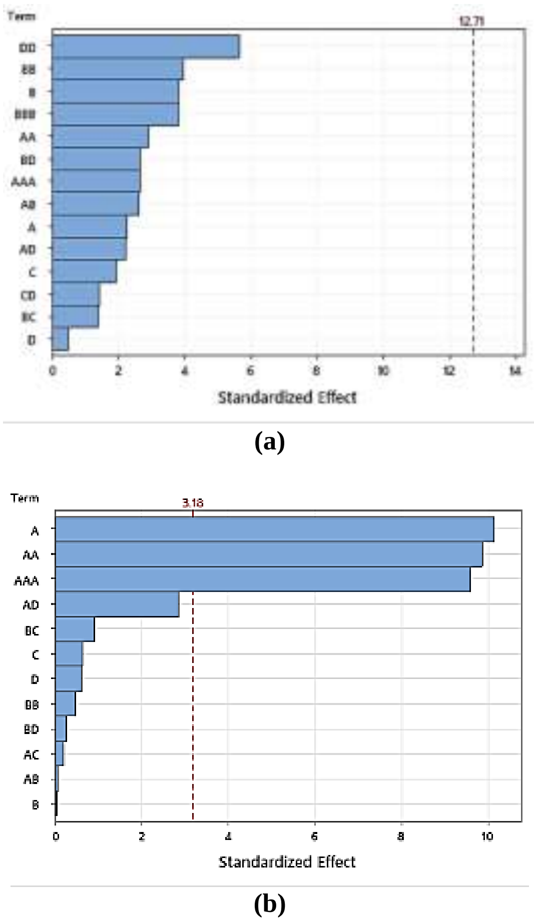


Fig. 5 Pareto chart of sandwich panels with: (a): first-order corrugated core, and (b): second-order corrugated core.

4 OPTIMIZATIONS

4.1. Constrained-Optimization

In the constrained-optimization problem, the constraints are mass and total length that should be satisfied. For the first-order core, the mass of the constructed specimen is 216.80 gr. In addition, it is assumed that the total length of the sandwich panel is 1m. Four design variables are considered in the optimization problem: α, t, L1, and n. To obtain a complete corrugation number, the variable n is considered instead of L2. For the first-order core, the parameter L2 is obtained as follows :

$$L_2 = \frac{L_{total}}{2n} - L_1 \cos(\alpha) \quad (3)$$

The total mass of the first-order core is:

$$m = n \times \rho \times v \quad (4)$$

Where ρ is density and v is the volume of one corrugated core that is calculated as follows:

$$v = 2(L_1 + L_2) \times b \times t \quad (5)$$

For obtaining solution space, the ±1.5% of reference mass tolerance which is about 3.25 gr is considered. The objective function is stiffness, S1st which is obtained from "Eq. (23)". The stiffness of the reference specimen is 148.48 N/mm. Code scripting in MATLAB software is used to optimize the objective function. "Table 8" presents the optimum parameters of the first-order corrugated core. It can be seen that the stiffness is increased by about 5% compared to the reference specimen. For second-order cores, the parameter L2 is obtained as follows:

$$L_2 = \left(\frac{L_{total}}{n} - 2L_1 - 2\right) / 4\cos(\alpha) - L_1 \cos(\alpha) \quad (6)$$

The volume of one corrugated core is calculated as follows:

$$v = 2\left[(3L_1 + 2L_2) + (2L_1 \cos(\alpha) + 2L_2)\right] \times b \times t \quad (7)$$

The stiffness of the reference specimen is 107.88 N/mm. The ±1.5% of reference mass tolerance, 329 gr, (about 5.9 gr) is taken into consideration and objective function, S, is obtained from "Eq. (24)". "Table 7" provides optimum parameters of the second-order corrugated core. It can be concluded that the stiffness is increased by about 24% compared to the reference specimen.

Table 7 Constrained-optimization of first- and second-order corrugated cores

	α	*t*	*P₁*	*n*	*S (N/mm)*
First-order					
	74	0.9	14	29	155.85
Second-order					
	32	1	12	4	134

4.2. Global-Optimization

In this section, the mass is minimized simultaneously to maximize the force. Thus, the objective function is assumed to be S/m. Strictly speaking, in global optimization, mass is not a constraint but is an objective function. "Table 8" presents the results for first- and second-order corrugated cores. As shown in this table, F/m in the second-order corrugated core is about twice of first-order one.

Table 8 Global-optimization of first- and second-order corrugated cores

	α	t	P_1	n	S/m
First-order					
	30	0.9	60	14	13.13
Second-order					
	74	0.9	52	14	28.64

5 CONCLUSIONS

The optimization of the bending behavior of sandwich panels with first- and second-order corrugated composite cores is investigated. For experimental specimens, a couple of molds are provided by using a 3D-printing process, and the corrugated cores are manufactured and then assembled to create sandwich panels. After selecting design parameters, the Taguchi method is used for the design of experiments. Based on Taguchi method results, finite element models are provided and the correspondent stiffness is extracted. The regression analysis is used to generate an equation of stiffness with respect to design parameters and the best stiffness formulas are selected.

In the next step, a constrained optimization problem is considered and the stiffness of sandwich panels is optimized. To compare the first- and second-order configuration, global optimization is considered by considering both the stiffness and mass of the panel and optimized parameters are determined. It is concluded that:

- The geometrical parameters do not have the same effect on the bending behavior of sandwich panels with first- and second-order corrugated cores. As shown, the corrugation angle is the most determinant factor in bending behavior of sandwich panels with second-order corrugated cores. On the other hand, the bottom length of first-order corrugated core is the most determinant factor in bending behavior.
- The influence of geometrical parameters in the increase of stiffness for sandwich panels with second-order corrugated cores is more notable compared with first-order one. In the considered constrained optimization, more improvement can be observed for the stiffness of the sandwich panel with a second-order corrugated core compared to the sandwich panel with a first-order corrugated one.
- By considering both the stiffness and mass of sandwich panels, it is determined that the sandwich panel with a second-order corrugated core has higher (more than twice) stiffness per unit mass than the sandwich panel with a first-order one. This means that sandwich panels with second-order corrugated cores are preferred candidates in structures that should endure high bending loads.

AUTHORS' CONTRIBUTIONS

Conceptualization, M. Sh; Methodology, M. Sh; experiments, software and validation, S. Kh and M.S. Sh.

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