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Experimental and Numerical Evaluation of the Fundamental Natural Frequency of a Spherical Core Sandwich Structure.

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Abstract

Background:

This study investigates the effect of the variation of the geometrical factors on the fundamental natural frequency of the novel spherical core sandwich structure numerically and experimentally. These novel structure are made up by using carving wax. The geometrical factors are diameter of sphere, skin thickness and spacing between spheres.

Materials and Methods:

Fifteen specimens according to response surface methodology - design of experiments and using Box-Behnken method were manufactured from unsaturated polyester material with different geometry while maintaining a 20 cm effective length. The fundamental natural frequency was evaluated according to two methods numerically by using finite element analysis and experimentally by using the modal test. ANOVA statistical analysis was used to evaluate the effect of the geometrical factors on the natural frequency

Results:

The results show that the discrepancy between these methods was less than 15%. The spacing between the spheres was a dominant factor that influence the fundamental natural frequency. The sphere diameter is a less dominant factor while the skin thickness has a minor influence on the fundamental natural frequency of the spherical core sandwich structure.

Conclusions:

This study provides a better understanding of the influence of the geometrical properties of the structure on the fundamental natural frequency. The most influential factor on the fundamental natural frequency is the spacing between the spheres while The diameter of the sphere has less influence, while the skin thickness has a minor effect on the fundamental natural frequency.

Keywords: Vibration, Composite Materials, FEA, Lightweight structure, Sphere-core sandwich.

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1. Introduction

Composite sandwich structures are limited in application because their sensitivity to impact-loading damage and low impact energy can cause structural failure to the core, while the skin doesn't damage [1]. Many research studies have been achieved to decrease impact-loading damage which included the development of manufacturing methods and new materials. The first course of the research is adding nanoparticles, nanofibers, and nanoclays for traditional core materials [2], while the other was focusing on the core shape and structure design evaluation.

Studying the behavior of the sandwich structure under mechanical vibration is essential to have a better understanding of its structural dynamics' properties and its dynamic stability. Many approaches were used to modulate the sandwich structure. The equivalent single-layer approach (ESL) and classical models were used to modulate these structures in the varicose vibrational analysis [3]. Unfortunately, the results obtained by those traditional; methods were inaccurate especially when a flexible core was used in the sandwich structure [4]. Good accuracy was achieved when first-order shear deformation theories (FSDT) is used by modeling the thin skin with a flexible core [5]. Other researchers evaluated the free vibration of the double curve open deep sandwich by using mixed theories with the Rayleigh-Ritz method [6]. Simply supported composite and sandwich doubly curved shells free vibration was studied by using Sander's theory based on an equivalent single-layer approach [7]. High-order Sandwich Panel Theory (HSAPT) is used to evaluate the free vibration of three-dimensional models' dynamics [8]. The latter method was used to evaluate numerous sandwich structure problems, such as open single curved composite with softcore sandwich-free vibration [9].

Unfortunately, the free vibration of the spherical core sandwich structure was not reported in the literature due to the difficulty in manufacturing a model without using bonding materials between the skin and the core to investigate the free vibration experimentally by using the modal test. This study focuses on evaluating the fundamental frequency of sphere core sandwich structure composite by using experimental and numerical methods. The impact of different geometrical factors on the natural frequency is also evaluated.

2.Materials and Methods

The samples of testing materials are unsaturated polyester (USP) material. The mechanical properties of the USP material are listed in the table (1).

Table 1: Mechanical properties of USP material [10].

Material	Young's Modulus (MPa)	Poisson's Ratio
USP	1900	0.33

Fifteen specimens of the spherical core sandwich structure were designed according to design of experiment (DOE)-response surface methodology (RSM) by Minitab 18. The responses in RSM can be expressed as polynomial equation of second-order, according to equations (1) and (2) [11 and 12].

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$$Y = f\,(x_1 ,x_2 ,.......,x_k) \pm \varepsilon \;................................(1)$$

$$Y = b_o + \sum_{i=1}^{k} b_i\, x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i<j=2}^{k} b_{ij} x_i x_j \pm \varepsilon \ldots\ldots\ldots\ldots (2)$$

where:

Y = the system response.
f = function of response.
$x_1, x_2, \ldots.. x_k$ = independent input variables.
k = number of parameters.
ε = fitting errors.
b_o = constant
b_i, b_{ii} and b_{ij} = linear, quadratic and interaction coefficients.

The dimension limit of factors as shown in table 1 and samples fabricate by using carving wax to get spheres panels mold, as shown in figure 1. The contact area between the skin and the sphere was kept the same in all the specimens (4.15 mm^2). The specimens were made in different dimensions while fixing the effective length in all specimens, to evaluate the influence of each geometrical factor on the fundamental natural frequency. According Box-Behnken method in RSM the run of the specimens is 15 as shown in table (3).

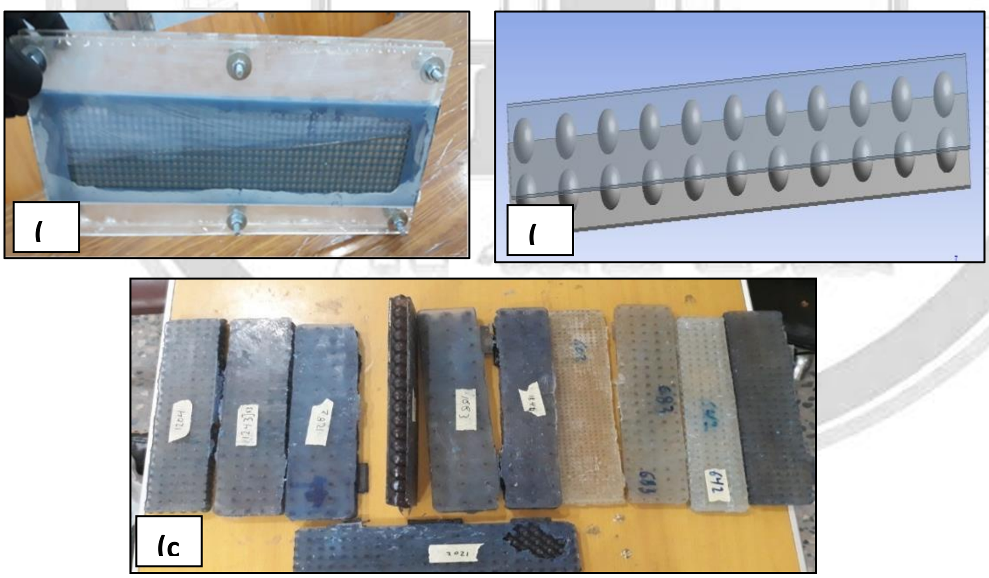

Figure 1 : (a) mold of wax with spheres cavities, (b) sandwich sphere structure, (c) fifteen samples of sandwich sphere structure.

Table 2: DOE by Box-Behnken Method

Box – Behenkin Method			
Factors	Sphere Diameter(mm) D	Space (mm) X	Skin Thickness(mm) K
Levels	6	0	2
	12	4	3
	18	8	4

Table 3: Specimens geometrical dimension.

Specimen Number	Sphere Diameter (mm) D	Space (mm) X	Skin Thickness (mm) K
1	6	0	3
2	6	4	2
3	6	4	4
4	6	8	3
5	12	0	2
6	12	0	4
7	12	4	3
8	12	4	3
9	12	4	3
10	12	8	2
11	12	8	4
12	18	0	3
13	18	4	2
14	18	4	4
15	18	8	3

2.1Finite Element

The fundamental natural frequency of the spherical core sandwich structure was evaluated numerically by using finite element analysis (ANSYS/ Modal). The three-dimensional model was generated by using the design modeler. Tetrahedral 4 elements were used for the meshing of the three-dimensional model. The boundary conditions assumed in this solution were

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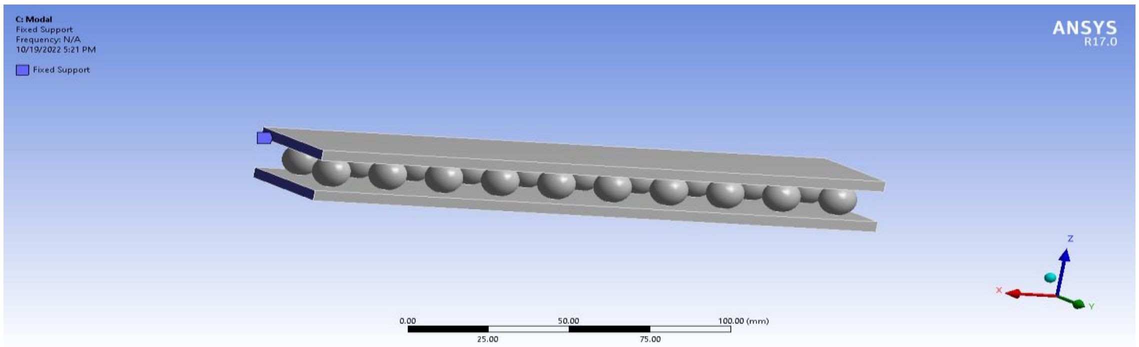
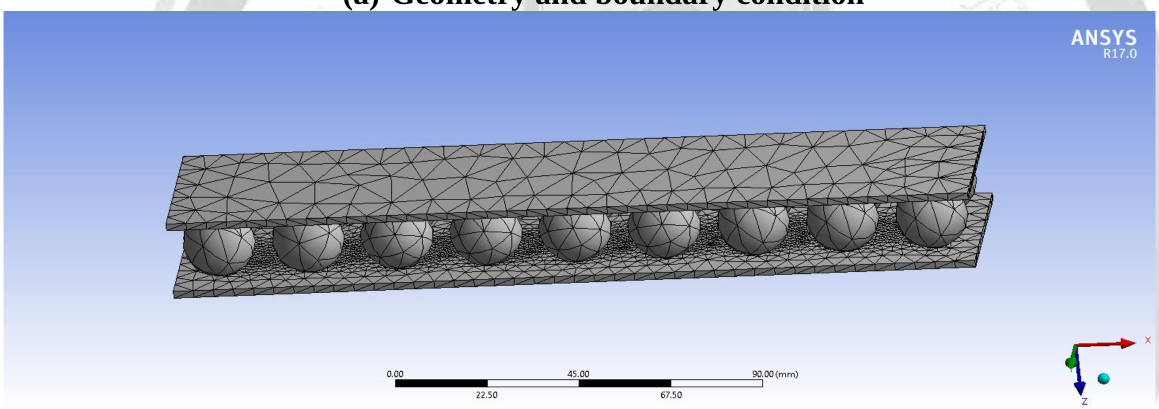
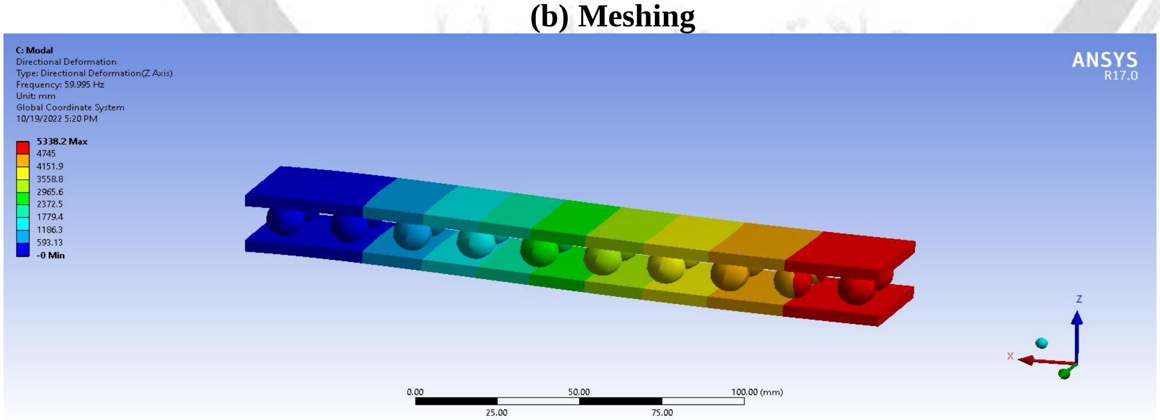
fixed-free as shown in figure 2. Fifteen models were constructed to reflect the variation of the geometry (skin thickness, sphere diameter, spacing between spheres). Modal Analysis was carried out to evaluate the fundamental natural frequency for each the 15 specimens.



(a) Geometry and boundary condition



(b) Meshing



(c) Modal test

Figure 2: Finite element analysis

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3. Experimental Part

3.1 Modal Test

The fundamental Natural frequency was evaluated experimentally by using an impulse hammer, dynamic signal analyzer (DSA), and accelerometer. The specimen was tested in a cantilever supporting condition as shown in figure (3). The sampling frequency of the test was selected based upon the results obtained from the numerical analysis to evade Nyquist effect (estimated frequency multiplied by 4).

The values and the waveform of the excitation force exerted by the impulse hammer of the spherical core structure were recorded by using channel 1 of the DSA. The response of the structure was recorded by using channel 2 of the DSA via the accelerometer. Figure (4) shows the excitation force and system response in the time domain of the spherical core structure.

Figure 3: Modal Test.

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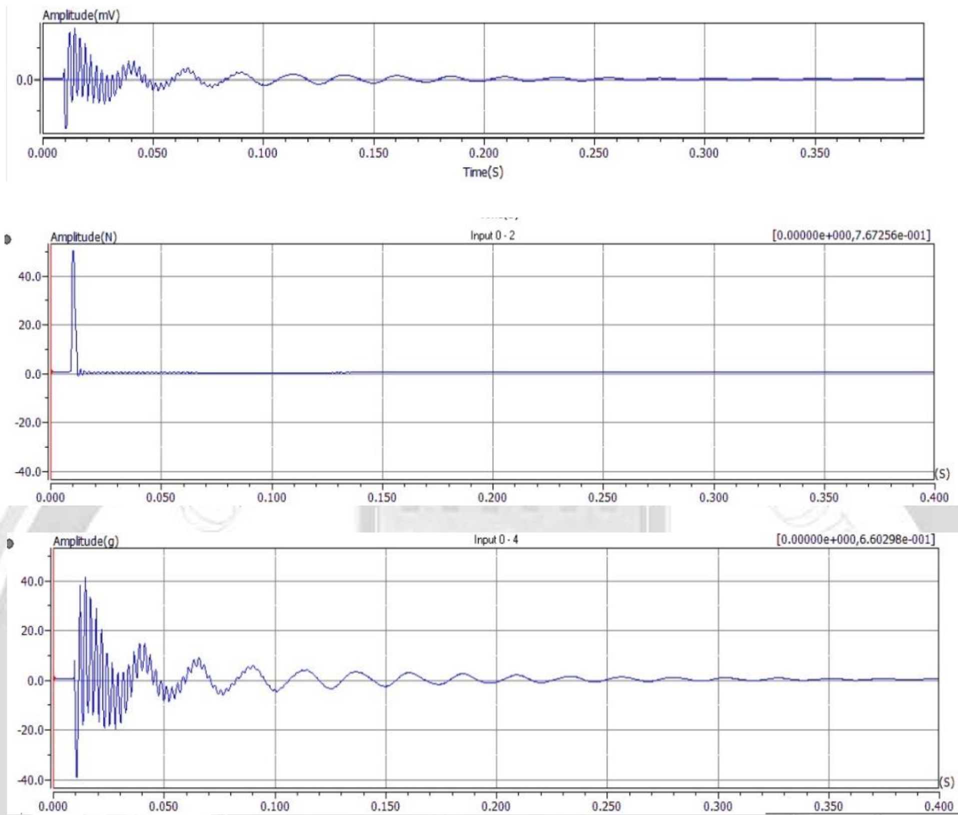

Figure 4: The excitation force and structure response in the time domain.

The test integrity was evaluated by using coherence function and the fundamental natural frequency was identified by using frequency response function (FRF) as shown in figure (5). The integrity of the test was decided base on the value of the coherence function (1 and 0).

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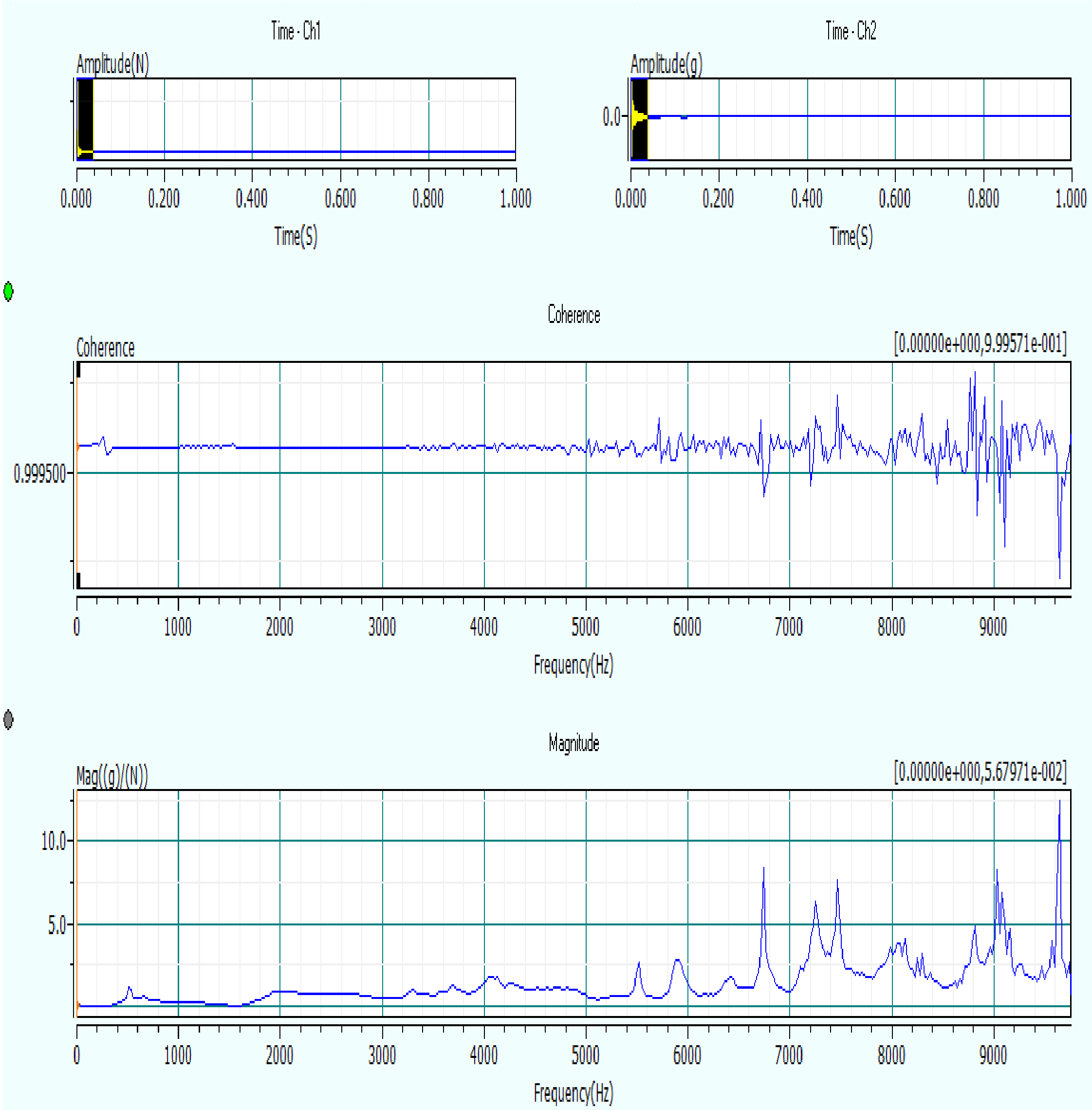

Figure 5: The FRF and coherence diagram.

Results and Discussion:

The fundamental natural frequency of the spherical core sandwich structure was evaluated numerically and experimentally. The discrepancy between the numerical and experimental results is less than 14%. The difference in the results can be related to the slight variation between the specimen geometry and the three-dimensional model. The results are shown in table (3).

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Table 3: Fundamental natural frequency of the spherical core structure.

Specimen	Natural Frequency (Hz)		Discrepancy (%)
	Finite Element	Modal Test	
1	60.34	53.4	12%
2	39.874	35.095	12%
3	57.635	53.406	7%
4	59.253	54.932	7%
5	73.62	68.665	7%
6	61.278	54.932	10%
7	47.87	41.199	14%
8	47.87	41.199	14%
9	47.87	41.199	14%
10	47.87	45.776	14%
11	50.45	43.725	13%
12	55.21	51.88	6%
13	38.68	39.673	-3%
14	38.765	33.569	13%
15	35.851	33.569	6%

The data of natural frequency has been statistically modeled in equation 3 according to second order polynomial model as equation 2. A full quadratic model with a confidence level equal to 95%. This equation contains linear parametric, square parametric, and two-way interaction. Determination coefficient R^2 for this equation is equal to 88.7%.

Natural Frequency(Hz) = 36.8 - 2.5 k - 6.10 x + 4.86 D + 1.91 k + 0.620 x - 0.0742 D + 0.668 k*x - 1.017 k*D - 0.207 x*D…………(3)

Table 4 shows influential and insignificant P-value based on analysis of variation (ANOVA). To forecast the actual outcomes while maintaining hierarchy rules to get the prediction model (equation 4), the insignificant terms are eliminated in equation 3.

Table 4: Regression coefficients for natural frequency (insignificant *).

Term	F-value	P-value
K	0.08	0.782
X	10.9	0.021
D	5.89	0.05
K * K	0.44	0.538*
X * X	11.77	0.019
D * D	0.85	0.398*
K * X	0.92	0.38*
K * D	4.83	0.079*
X * D	3.19	0.134*
R^2	88.7%	

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Natural Frequency(Hz) = 68.47 - 0.57 k - 6.61 x - 0.795 D + 0.623 x^2……………(4)

The RMS analysis was executed again after the elimination process and the significant regression for the natural frequencies are shown in table 5. The new R^2 is equal to 73.65%.

Table 5: Regression coefficients for natural frequency after elimination.

Term	F-value	P-value
K	0.06	0.819
X	7.11	0.024
D	3.84	0.078
X*X	37.04	0.019
R^2_{pred}	73.65%	

Figure (5) shows the influence plot for each geometrical factor on the natural frequency. X factor has a major effect on response with an F-value equal to 7.11 and a greater value of response when there is no space between the spheres (0 mm). D factor has an F-value equal to 3.84 which is less than the F-value of the X factor. K factor has a low F-value and it has a minor effect on the response has shown.

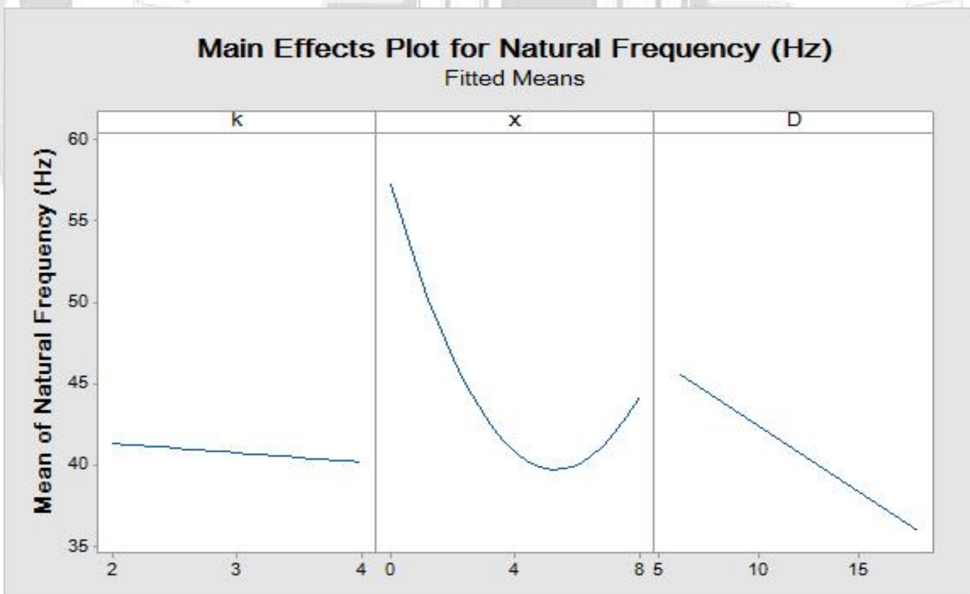

Figure 5: The main effects plot between natural frequency and variables

ANOVA statistical analysis shows clearly that the spacing between the spheres has a major effect on the fundamental natural frequency of the spherical core sandwich structure. It influences almost the entire frequency band. This influence can be related to the decrease in the number of spheres (reduce the mass and the total contact area) without influencing the moment of inertia of the cross-sectional area. The diameter of the sphere also influences the values of the

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natural frequency, but its influence is less dominant than the spacing. This effect can be related to the change in moment of inertia of the cross-sectional area and mass increases. The effect of mass and moment of inertia is opposite on the natural frequency. Therefore, the superposition of the influence of those two factors will reduce the variation in the natural frequency values due to the change in the sphere diameter. The skin thickness has a very minor effect on the natural frequency because of its effect on the mass and the moment of inertia of the sandwich spherical core structure is very low.

Conclusion

The application of the spherical core sandwich structure is wide due to its enhanced mechanical properties and lightweight. Most of those applications are exposed to mechanical vibration, therefore it's essential to investigate the structure dynamics properties and dynamic stability of those composite structures. This study provides a better understanding of the influence of the geometrical properties of the structure on the fundamental natural frequency. The most influential factor on the fundamental natural frequency is the spacing between the spheres. The diameter of the sphere has less influence, while the skin thickness has a minor effect on the fundamental natural frequency.

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التقييم العددي والتجريبي للتردد الطبيعي على لوح ساندويج ذو قلب كروي الشكل

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الخلاصة:

مقدمة:

الهدف من هذه الدراسة هو التحقق من تأثير متغيرات العوامل الجيومترية عدديا وتجريبيا على خاصية التردد الطبيعي لألواح ساندويج ذات قلب كروي . هذه الالواح مصنعة بطريقة أبتكارية بواسطة أستخدام شمع النحت التعليمي . العوامل الجيومترية هي قطر الكرة وسمك الوجه والمسافة بين الكرات.

طرق العمل:

طبقا لمنهجية استجابة السطوح – تصميم التجارب تم تصميم 15 عينة وفق طريقة بوكس–بيهنكن وأعتمادا على الظروف التجريبية لحدود قيم كل متغير. المادة الأساس في الصب هي البوليستر الغير مشبع . الطول الفعال لجميع العينات المصنعة كان ثابتا بقيمة 20 سم. تم تقييم التردد الطبيعي عدديا باستخدام نظرية العناصر المحددة وعمليا باستخدام الاختبار المشروط وحساب الفارق بينهما. تأثير المتغيرات الجيومترية تم تحليلها بأستخدام نظرية تحليل التباين الإحصائية.

الأستنتاجات:

بينت هذه الدراسة فهما جيدا لتأثير المتغيرات الجيومترية لألواح ساندويج ذات قلب كروي عل خاصية التردد الطبيعي. النتائج العملية والعددية بينت فارقا في القيم لم يتجاوز 15% أما النتائج الإحصائية فبينت ان المسافة بين الكرات كان لها تاثير كبير جدا ورئيسي على جميع المتغيرات الجيومترية الأخرى. سمك الوجه وقطر الكرة كان لهما تاثير أقل وفقا الى تلك البيانات.

الكلمات الدالة:الأهتزاز، مواد مركبة، FEA، التراكيب الخفيفة الوزن، ألواح ساندويج ذات القلب الكروي.