STATIC ANALYSIS OF CORRUGATED PLATE MADE COMPOSITE MATERIAL BASED ON THE EQUIVALENT ORTHOGONAL PLATE MODEL

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ABSTRACT

Folding plates with wavy shapes made of composite materials have been widely applied, hence designing this type of structure is significant in practice. In this research work, the results of static calculation of the sinusoidal corrugated composite plates will be analyzed. Instead of calculating the displacements on the actual corrugated plate, it can be analytically obtained from the equivalent orthogonal plate. Both bending and membrane stiffness constants are equivalently converted according to the suggestion of the early researcher in the literature. The displacements given by the analytical method on the equivalent plate are compared with those resulting from the finite element method on the real sinusoidal corrugated plate. The results show that the difference in the values of displacements along the x and y directions of the center between the two methods is small. The maximum relative error is 7.33%. From this, it can be seen that the proposed model can be extended to static as well as dynamic calculations for corrugated plates with trapezoidal, triangular shapes, or can be applied to calculate the natural frequency of the corrugated plate on an equivalent orthogonal flat plate.

PHÂN TÍCH TĨNH TẤM COMPOSITE LƯỢN SÓNG DỰA TRÊN MÔ HÌNH TẤM TRỰC HƯỚNG TƯƠNG ĐƯƠNG

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TỪ KHÓA

Tấm lượn sóng
Phương pháp Phần tử hữu hạn
Tấm tương đương
Độ cứng màng và uốn
Vật liệu composite

TÓM TẮT

Các tấm gấp dạng lượn sóng làm bằng vật liệu composite đã được ứng dụng rộng rãi nên việc thiết kế dạng kết cấu này có ý nghĩa trong thực tế. Trong bài báo này, các giá trị chuyển vị của các điểm dọc theo đường ở giữa mỗi cạnh của tấm composite sóng hình sin sẽ được tính toán dựa trên hai mô hình. Mô hình phần tử hữu hạn tính toán trên kết cấu lượn sóng 3D, trong khi đó phương pháp giải tích được sử dụng trên mô hình tấm phẳng trực hướng tương đương. Các hằng số của độ cứng màng và độ cứng uốn sẽ được quy đổi đồng thời trong nghiên cứu này. Chuyển vị được xác định từ hai phương pháp kể trên sẽ được so sánh với nhau. Kết quả cho thấy tỉ lệ phần trăm sai khác nhau lớn nhất của chuyển vị tính được từ hai phương pháp là 7,33%. Kết quả sai khác này có thể chấp nhận được trong phạm vi cho phép, và khẳng định độ tin cậy của mô hình đề xuất nhằm giảm thời gian tính toán tĩnh của kết cấu lượn sóng 3D thông qua một mô hình tấm phẳng tương đương, giảm thời gian tính toán, tăng hiệu quả sản xuất. Ngoài ra, có thể thấy rằng mô hình đề xuất có thể mở rộng để tính toán động cho các tấm sóng có dạng hình thang, tam giác hoặc có thể áp dụng để tính tần số tự nhiên của tấm sóng trên một tấm phẳng trực giao tương đương.

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1. Introduction

In order to improve the load carrying capacity of thin sheets, several methods have been utilized to enhance stiffness such adding reinforcement ribs, or forming a corrugated shape. Since it is only necessary to create a cyclic corrugated shape, without the need to create an assembled reinforcement ribbed element, corrugated sheets are increasingly used. Waveform can be trapezoidal shape [1], [2], sinusoidal shape [3], [4]. To ensure that the structure is durable and stable enough, static and dynamic calculations are essential. The methods used are typically numerical [5] - [7], or analytical ones [8] - [10]. For numerical methods, the finite element method is used mainly, in which the static and dynamic calculations are performed directly on the real corrugated plates model. Meanwhile, for the analytical method, due to the complexity of the geometrical structure, the authors often simplify the geometric configuration of the plate to get an approximate solution. One of the approximate transformations is to calculate statically and dynamically the corrugated sheet on an orthogonal plate which has the equivalent stiffness constants including bending and membrane stiffness [5], [6], [11], [12]. It can be seen that static and dynamic calculations for corrugated sheets with isotropic elastic materials have been studied quite fully [2], [6], [7]. However, there are still very few publications dealing with corrugated composite plates [9], [10]. Dao et al. [8] conducted the non-linear analysis on stability of corrugated cross-ply laminated composite plates where the corrugated plates in the form of a sine wave were considered as equivalent plat plates to analyze the stability of the structures. The transformation from the real structure to the equivalent ones based on the approach of Seydel [13]. In this technique the bending stiffness of a corrugated plate are determined through the equivalent flat plate. Khuc et al. [9], [10] applied the same approach presented in the study [8] to analyze natural vibration of the sinusoidal wave plate with various boundary conditions. The results showed that natural frequencies can be effectively determined in the equivalent flat plates. However, it is noticed that the bending stiffness is only equivalently transmitted, while the membrane stiffness is omitted in the previously mentioned studies.

This study presents the results of calculating the bending displacement of the sine wave composite plate by analytical method on the equivalent orthogonal flat plate model. In addition to equivalent bending stiffness values, equivalent membrane stiffness constants are also included based on the proposal of Briassoulis [3] for corrugated plate metal. The displacements of points on the plate along the x and y directions at the mid positions are obtained from the analytic method and the finite element method.

2. Method of establising the governing equations

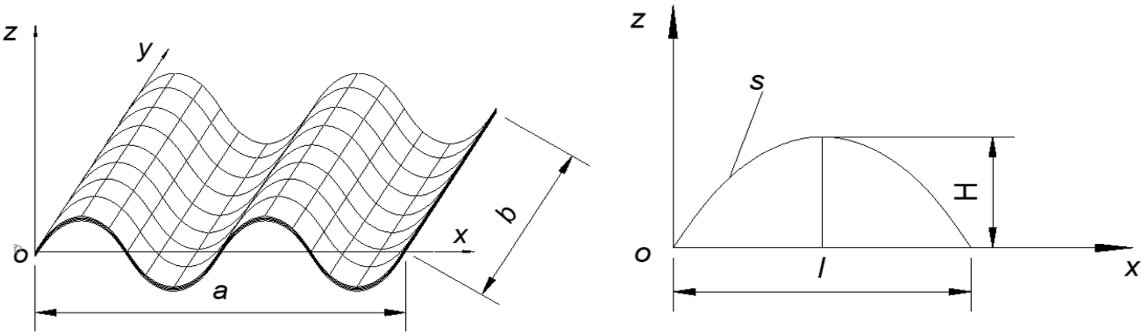

Figure 1. *Model of sinusoidal corrugated metal plate*

A symmetrically laminated metal corrugate plate which has the form of a sine wave in the plane (*x, z*) is considered in this case. The model of the plate is presented in Figure 1. The plate is subjected to uniform contribution load in the z direction.

$$z = H\,\mathbf{sin}\frac{\pi x}{l} \tag{1}$$

Where: H – wave amplitude.

l - half wave.

When studying the stress-strain state of thin-layer composite panels, the following assumptions are taken into account:

- The thin composite plates satisfy the Krichohoff - Love hypothesis.
- The layered material is an ideal bonded uniform fiber-reinforced composite material.
- Ignoring transverse shear: $\gamma_{xz} = \gamma_{yz} = 0$

Based on the assumptions above, the linear strain-displacement relationships for a such corrugated plate proposed by [8] are:

$$\begin{aligned}
\varepsilon_x &= \frac{\partial u}{\partial x} - kw & \qquad k_x &= -\frac{\partial^2 w}{\partial x^2} \\
\varepsilon_y &= \frac{\partial v}{\partial y} & \qquad k_y &= -\frac{\partial^2 w}{\partial y^2} \\
\gamma_{xy} &= \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} & \qquad k_{xy} &= -2\frac{\partial^2 w}{\partial x \partial y}
\end{aligned} \tag{2}$$

Where *u*, *v*, and *w* denote displacement of a point along x, y and z directions respectively, ε_x, ε_y, γ_{xy} are strains; k is the curvature of the portion line in (x, z) plane, which is defined as:

$$k = \frac{z''}{\left(1 - z'^2\right)^{\frac{3}{2}}} \approx z'' = \frac{-H\pi^2}{l^2}\mathbf{sin}\frac{\pi x}{l} \tag{3}$$

u, v, z is the displacement of any point on the middle face of the plate in the directions of the x, y, z axes and, s is the length of the half-wave.

$$s = \int_0^l \sqrt{1 + \frac{H^2\pi^2}{l^2}\cos^2\frac{\pi x}{l}} = l\left(1 + \frac{H^2\pi^2}{4l^2}\right) \tag{4}$$

Because the investigated plate is symmetrical, the bending stiffness $B_{ij} = 0$ and membrane stiffness A_{16}, A_{26}, D_{16}, D_{26} are very small and can be ignored.

From (1) and (2), extending Briassoulis [3] approach to composite materials, the force and moment expression of a symmetrical corrugated composite plate can be obtained as follows:

$$\begin{aligned}
N_x &= A^*_{11}\varepsilon_x + A^*_{12}\varepsilon_y \\
N_y &= A^*_{12}\varepsilon_x + A^*_{22}\varepsilon_y \\
N_{xy} &= A^*_{66}\gamma_{xy} \\
M_x &= D^*_{11}k_x + D^*_{12}k_y \\
M_y &= D^*_{12}k_x + D^*_{22}k_y \\
M_{xy} &= D^*_{66}k_{xy}
\end{aligned} \tag{5}$$

According to the suggestion of Briassoulis [11], the sinusoidal corrugated plate as previously mentioned is considered as a thin orthotropic plate with uniform thickness (Figure 2) possessing equivalent membrane stiffness and flexural stiffness as follows:

Membrane stiffness constants

$$\begin{cases} A_{11}^{*} = \dfrac{A_{11}\left(1-\mu_{12}^{2}\dfrac{E_2}{E_1}\right)}{\left[1+\dfrac{6H^2}{h^2}\left(1-\mu_{12}^{2}\dfrac{E_2}{E_1}\right)\left(\dfrac{s^2}{l^2}-\dfrac{s}{2\pi l}\mathbf{sin}\dfrac{2\pi s}{l}\right)\right]} \\ A_{22}^{*} = A_{22}\left(1-\mu_{12}^{2}\dfrac{E_2}{E_1}\right)\dfrac{s}{l}\mathbf{;}\; A_{66}^{*} = \dfrac{Eh}{2\left(1+\mu_{23}\right)} = A_{66} \\ A_{12}^{*} = \bar{\mu}_{12}^{m}A_{22}^{*} \\ \bar{\mu}_{12}^{m} = \dfrac{l\mu_{12}}{s\left[1+\left(\dfrac{H}{h}\right)^{2}6\left(1-\mu_{12}^{2}\dfrac{E_2}{E_1}\right)\left(\dfrac{s^2}{l^2}-\dfrac{s}{2\pi l}\mathbf{sin}\dfrac{2\pi s}{l}\right)\right]} \end{cases} \quad (6)$$

Bending stiffness constants

$$\begin{cases} D_{11}^{*} = \dfrac{E_1h^3}{12\left(1-\mu_{12}\mu_{21}\right)}\dfrac{l}{s} = D_{11}\dfrac{l}{s} \\ D_{22}^{*} = D_{22}\left(1+6\left(1-\mu_{12}^{2}\dfrac{E_2}{E_1}\right)\left(H/h\right)^{2}\right) \\ D_{66}^{*} = 2\dfrac{Eh^3}{24\left(1+\mu_{12}\right)} = 2D_{66} \\ D_{12}^{*} = \bar{\mu}_{12}^{u}D_{22}^{*} \\ \bar{\mu}_{12}^{u} = \dfrac{l}{s\left(1+6\left(1-\mu_{12}^{2}\dfrac{E_2}{E_1}\right)\left(H/h\right)^{2}\right)}\mu_{12} \end{cases} \quad (7)$$

Where:

A_{ij}^{*}, D_{ij}^{*} are the membrane and bending stiffness constants of the equivalent orthogonal composite flat plates respectively.

$\bar{\mu}_{12}^{m}$, $\bar{\mu}_{12}^{b}$ are the equivalent constant Passion of the membrane and bending stiffness constant of the orthogonal plate.

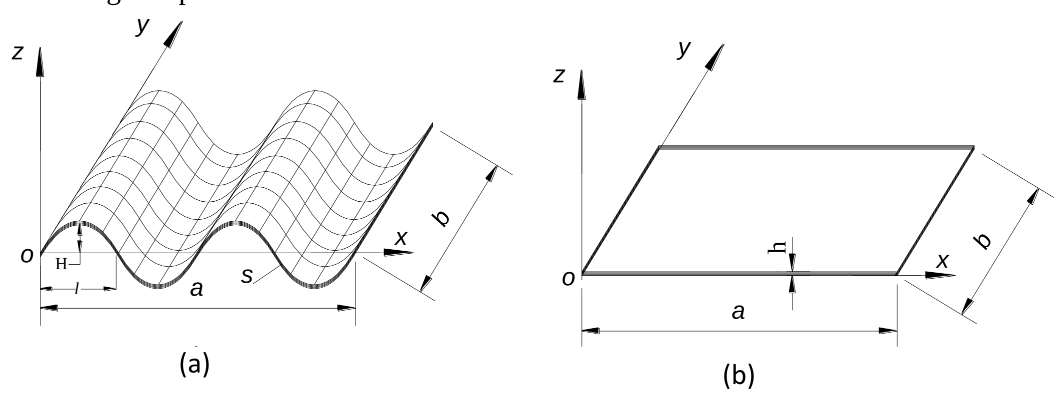

Figure 2. *The sinusoidal corrugated metal plate (a) and its thin equivalent orthogonal model (b)*

Substituting (2) into (5):

$$
\begin{aligned}
&N_x = A^*_{11}\left(\frac{\partial u}{\partial x} - kw\right) + A^*_{12}\frac{\partial v}{\partial y}\\
&N_y = A^*_{12}\left(\frac{\partial u}{\partial x} - kw\right) + A^*_{22}\frac{\partial v}{\partial y}\\
&N_{xy} = A^*_{66}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\\
&M_x = -D^*_{11}\frac{\partial^2 w}{\partial x^2} - D^*_{12}\frac{\partial^2 w}{\partial y^2}\\
&M_y = D^*_{12}\frac{\partial^2 w}{\partial x^2} - D^*_{22}\frac{\partial^2 w}{\partial y^2}\\
&M_{xy} = -2D^*_{66}\frac{\partial^2 w}{\partial x \partial y}
\end{aligned}
\tag{8}
$$

Consider a layered composite plate with a wavy shape, the plate is subjected to a uniformly distributed force p(x,y). Then, the equation describing the plate statics problem for the linear problem has the form:

$$
\begin{aligned}
&\frac{\partial \mathrm{N_x}}{\partial \mathrm{x}} + \frac{\partial \mathrm{N_{xy}}}{\partial \mathrm{y}} = 0\\
&\frac{\partial \mathrm{N_{xy}}}{\partial \mathrm{x}} + \frac{\partial \mathrm{N_y}}{\partial \mathrm{y}} = 0\\
&\frac{\partial^2 \mathrm{M_x}}{\partial \mathrm{x}^2} + 2\frac{\partial^2 \mathrm{M_{xy}}}{\partial \mathrm{x}\partial \mathrm{y}} + \frac{\partial^2 \mathrm{M_y}}{\partial \mathrm{y}^2} = \mathrm{p}
\end{aligned}
\tag{9}
$$

Substituting (8) into (9), the system of static equations for the layered composite plate with sinusoidal waveforms according to the displacement field u, v, w can be received as follows:

$$
\begin{aligned}
&A^*_{11}\frac{\partial^2 u}{\partial x^2} + A^*_{66}\frac{\partial^2 u}{\partial y^2} + \left(A^*_{12} + A^*_{66}\right)\frac{\partial^2 v}{\partial x \partial y} + A^*_{11}\frac{H\pi^2}{l^2}\sin\frac{\pi x}{l}.\frac{\partial w}{\partial x} + A^*_{11}\frac{H\pi^3}{l^3}\cos\frac{\pi x}{l}.w = 0\\
&A^*_{22}\frac{\partial^2 v}{\partial y^2} + A^*_{66}\frac{\partial^2 v}{\partial x^2} + \left(A^*_{12} + A^*_{66}\right)\frac{\partial^2 u}{\partial x \partial y} + A^*_{12}\frac{H\pi^2}{l^2}\sin\frac{\pi x}{l}.\frac{\partial w}{\partial y} = 0\\
&D^*_{11}\frac{\partial^4 w}{\partial x^4} + 2\left(D^*_{12} + 2D^*_{66}\right)\frac{\partial^4 w}{\partial x^2 \partial y^2} + 2D^*_{22}\frac{\partial^4 w}{\partial y^4} = p
\end{aligned}
\tag{10}
$$

The equation (10) is a system of partial differential equations of the wave-shaped plate theory. These equations are used to investigate the problem of statics of sine wave plate. In this study, the boundary condition of four edges of simply supported will be conducted.

The simply supported boundary condition will be described in this section. Consider a rectangular symmetrically metal corrugated plate having dimension of *a* and *b* in x and y direction respectively. The edges of the plate can be shown by the equation as follows:

+ At x = 0, x = a: w = 0, v = 0, M_x =0, $u \neq 0$

+ At y = 0, y = b: w = 0, u = 0 M_y =0, $v \neq 0$

The mode shape is represented by:

$$\left.\begin{aligned} u &= \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} U_{mn}\cos\frac{m\pi x}{a}\sin\frac{n\pi y}{b} \\ v &= \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} V_{mn}\sin\frac{m\pi x}{a}\cos\frac{n\pi y}{b} \\ w &= \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} W_{mn}\sin\frac{m\pi x}{a}\sin\frac{n\pi y}{b} \end{aligned}\right\} \tag{11}$$

Where m and n are the number of haft waves in the x and y direction respectively.

Substituting expression (11) into (10). In order to get the vibration equations corresponding to U_{mn}, V_{mn}, W_{mn} amplitudes, the Galerkin – Bubnov procedure are applied. The set of linear algebraic equations are gotten:

$$\begin{cases} \frac{1}{4}(A^*_{11}\frac{m^2\pi^2 b}{a}+A^*_{66}\frac{n^2\pi^2 a}{b})U_{mn}+\frac{1}{4}(A^*_{12}+A^*_{66})mn\pi^2 V_{mn} \\ -\frac{m^3 lbH\pi^2 A^*_{11}(\cos\frac{\pi a}{l}-1)}{(a+2ml)(a-2ml)a}W_{mn}=0 \\ \frac{1}{4}(A^*_{22}\frac{n^2\pi^2 a}{b}+A^*_{66}\frac{m^2\pi^2 b}{a})V_{mn}+\frac{1}{4}(A^*_{12}+A^*_{66})mn\pi^2 U_{mn} \\ -\frac{m^2 nH\pi^2 lA^*_{12}(\cos\frac{\pi a}{l}-1)}{(a+2ml)(a-2ml)}W_{mn}=0 \\ \frac{1}{4}[D^*_{11}\frac{m^4\pi^2 b}{a^3}+2(D^*_{12}+2D^*_{66})\frac{m^2n^2\pi^4}{ab}+D^*_{22}\frac{n^4 a\pi^4}{b^3}]W_{mn}=\frac{4ab}{mn\pi^2}p \end{cases} \tag{12}$$

The above equations can be shortly written as below:

$$\begin{bmatrix} n_{11} & n_{12} & n_{13} \\ n_{21} & n_{22} & n_{23} \\ n_{31} & n_{32} & n_{33} \end{bmatrix}\begin{Bmatrix} U_{mn} \\ V_{mn} \\ W_{mn} \end{Bmatrix}=\begin{Bmatrix} 0 \\ 0 \\ \frac{4ab}{mn\pi^2}p \end{Bmatrix} \tag{13}$$

Where:

$$n_{11}=\frac{1}{4}(A^*_{11}\frac{m^2\pi^2 b}{a}+A^*_{66}\frac{n^2\pi^2 a}{b}) \qquad n_{12}=n_{21}=\frac{1}{4}(A^*_{12}+A^*_{66})mn\pi^2$$

$$n_{13}=-\frac{m^3 lbH\pi^2 A^*_{11}(\cos\frac{\pi a}{l}-1)}{(a+2ml)(a-2ml)a} \qquad n_{22}=\frac{1}{4}(A^*_{22}\frac{n^2\pi^2 a}{b}+A^*_{66}\frac{m^2\pi^2 b}{a})$$

$$n_{23}=-\frac{m^2 nH\pi^2 lA^*_{12}(\cos\frac{\pi a}{l}-1)}{(a+2ml)(a-2ml)} \qquad n_{33}=\frac{1}{4}[D^*_{11}\frac{m^4\pi^2 b}{a^3}+2(D^*_{12}+2D^*_{66})\frac{m^2n^2\pi^4}{ab}+D^*_{22}\frac{n^4 a\pi^4}{b^3}]$$

The equations (13) are the 3rd order algebraic equations. Solving these equations with the values of m and n vary from 1 to 5 can give the displacement values of the plates.

3. Results and discussion

In this section, the displacements of the sinusoidal corrugated plate made of laminated composite will be calculated by two methods, analytical and numerical. The former is based on the equivalent flat plate, while the numerical method, namely the finite element method, is directly analyzed in the real structure thanks to the ANSYS software. The results given by these methods will be compared to show the reality of the proposed approach.

Consider a corrugated plate in the form of a sine wave made of graphite/epoxy composite with a stacking sequence of [45^0/-45^0/-45^0/45^0]. The basic dimensions of the plate are shown in Figure 2. The dimensional parameters and material properties are as:

The young modulus in directions 1 and 2, and the shear modulus are E_1 = 144.8GPa, E_2 = 9.67 GPa, G_{12} = G_{13} = 4.14 GPa, respectively. The Poisson ratio μ_{12} = 0.3, the density of 389.23 kg/m^3; The plate includes four layers having similar thicknesses of 2 mm, H = 20 mm, l = 90 mm, a = 0.9 m, b = 0.9 m. The uniform distribution loading, p = 2000N/m^2. The corrugated plate has 5 half wavelengths.

The FEM model is performed by using ANSY with the chosen element of SHELL 99, the meshing elements including 35 and 20 in the x and y direction respectively. The total number of generated elements is 800. The CAD model of the corrugated plate is shown in Figure 3.

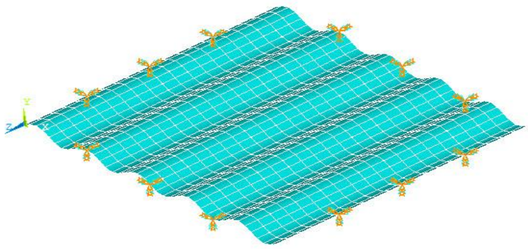

Figure 3. *Finite element model of the corrugated metal plate*

The displacements of the sinusoidal corrugated composite plate calculated from the two methods are compared with each other at the straight lines passing through the midpoint of the plate along the x-axis (y=0.9 m) and along the y-axis (x=0.9 m). Displacements of the plate along the x-axis (at y = 0.45 m) and y-axis (at x = 0.45 m) are shown in Table 1 and 2 respectively and in the graphical form are presented in Figure 4 and Figure 5.

Table 1. *Displacement of composite plate [45^0/-45^0/-45^0/45^0] along the x-axis (at y position = 0.45 m)*

x (m)	y (m)	Displacement (mm)		Relative errors (%)
		Analytic	ANSYS	
0	0.45	0	0	0
0.045		0.0912	0.0962	5.19
0.15		0.2829	0.3051	7.28
0.3		0.3326	0.3487	4.62
0.3		0.4849	0.4865	0.33
0.45		0.5658	0.5945	4.83

Table 2. *Displacement of composite plate [450/-450/-450/450] along y-axis (at position x = 0.45 m)*

x (m)	y (m)	Displacement (mm)		Relative errors (%)
		Analytic	ANSYS	
0.45	0	0	0	0
	0.15	0.21621	0.2333	7.33
	0.18	0.33251	0.3399	2.17
	0.225	0.40000	0.41133	2.75
	0.3	0.48993	0.49200	0.42
	0.45	0.5658	0.5945	4.83

For this result, it can be seen that the maximum displacement values of 0.566 mm and 0.595 mm for the analytical method and the FEM, respectively, belong to the midpoint of the plate. This result is logical. The maximum error between two sets of results is 7.28%.

Similar to the displacements along the x direction, the maximum relative error between the two methods is 7.33%. It can be said that this error is small and it is acceptable to ensure the reality of the proposed modal. It is able to solve problems with other wave configurations such as trapezoids. In addition, the results can also be used to calculate free vibration, forced vibration, and stability problems. The relative errors obtained in these results may be due to the fact that the analytical problem on the equivalent orthogonal plate model only includes the equivalence along the x-length, i.e. the direction perpendicular to the sine waves. Meanwhile, the conversion expression along the y direction is not interesting. In addition, because the assumption of constants A_{16}, A_{26}, D_{16}, and D_{26} were ignored, this may affect the calculated values of the analytical model.

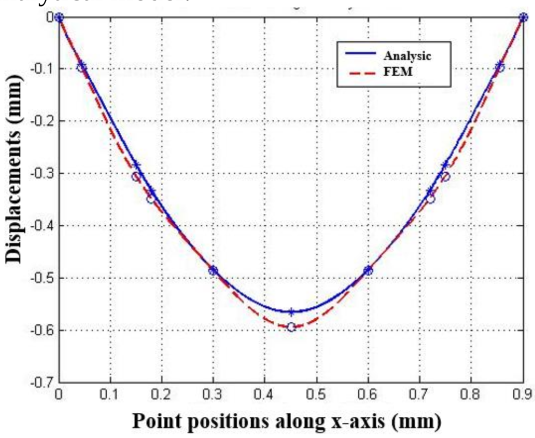

Figure 4. *The deflection of a sine waves composite plate along the x-direction*

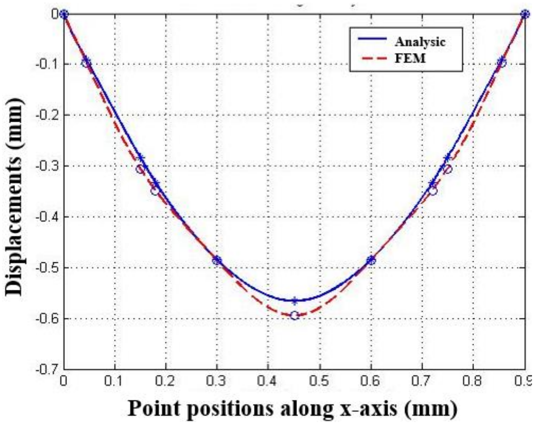

Figure 5. *The deflection of the sine waves composite plate along the y-direction*

4. Conclusion

In this study, the displacements of the sinusoidal corrugated composite plate were analyzed through the equivalent orthogonal model which has the membrane and bending stiffness equivalently considered those of the real structure. The small relative errors when comparing results obtained by the analytical solution in the equivalent model and those received by the ANSYS model show the reliability of the proposed model. Building the equation of equivalent membrane and flexural stiffness of the thin plate with thickness uniform which is equivalent to the real sinusoidal corrugated plate is conducted. Moreover, the constructing vibration equation of the problems is considered in terms of comparing two models. The displacements obtained by the two methods are compared. It is shown that the maximum relative error of 7.33%. The utilization of the equivalent orthogonal model of the real plate can reduce the computing time. Moreover, this proposed model can be widely the corrugated plate in the form of a trapezoidal shape made of metal of composite materials, as well as the static, dynamic problems with various boundary conditions.

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REFERENCES

[1] S. M. M. Asokendu, "Finite element static and dynamic analyses of folded plates," *Engineering Structures*, vol. 21, pp. 277–287, 1999.

[2] F. Emami, M. Mofid, and A. Vafai, "Experimental study on cyclic behavior of trapezoidally corrugated steel shear walls," *Engineering Structures*, vol.48, pp. 750-762, 2013.

[3] M. Malikan, R. Dimitri, and F. Tornabene, "Effect of Sinusoidal Corrugated Geometries on the Vibrational Response of Viscoelastic Nanoplates," *Applied Sciences*, vol. 8, no. 9, 2018, Art. no. 1432.

[4] K. Lang and M. Su, "Equivalent orthotropic model for corrugated plates based on simplified constitutive relation," *Heliyon*, vol. 8, no. 11, 2022, Art. no. e11264.
[5] K. M. Liew, L. X. Peng, and S. Kitipornchai, "Nonlinear analysis of corrugated plates using a FSDT and a meshfree method," *Computer Methods in Applied Mechanics and Engineering*, vol. 196, pp. 2358-2376, 2007.
[6] K. M. Liew, L. X. Peng, and S. Kitipornchai, "Vibration analysis of corrugated Reissner–Mindlin plates using a mesh-free Galerkin method," *International Journal of Mechanical Sciences*, vol. 51, no. 9-10, pp. 642-652, 2009.
[7] Y. Xia, M. I. Friswell, and E. I. S. Flores, "Equivalent models of corrugated panels," *International Journal of Solids and Structures*, vol. 49, no. 13, pp. 1453-1462, 2013.
[8] H. B. Dao and V. P. Khuc, "Non-linear analysis on stability of corrugated cross-ply laminated composite plates," *Vietnam Journal of Mechanics*, vol. 28, no. 4, pp. 197-206, 2006.
[9] V. P. Khuc, and V. D. Le, "Vibration of corrugated cross-ply laminated composite plates," *VNU Journal of Science, Mathematics - Physics*, vol. 23, pp. 105-112, 2007.
[10] H. B. Dao and V. P. Khuc, "A new approach for investigating corrugated laminated composite plates of wave form," *Vietnam Journal of Mechanics*, vol. 30, no. 3, pp. 133-141, 2008.
[11] D. Briassoulis, "Equivalent orthotropic properties of corrugated sheets," *Computers & Structures*, vol. 23, no. 2, pp. 129-138, 1986.
[12] L. X. Peng, K. M. Liew, and S. Kitipornchai, "Analysis of stiffened corrugated plates based on the FSDT via the mesh-free method," *International Journal of Mechanical Sciences*, vol. 49, no. 3, pp. 364-378, 2007.
[13] E. Sa, "Schubknickversuche mit Welblechtafeln," *DVL – Bericht*, vol. 12, pp. 9-19, 1931.