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Structural Characterization of Anisotropic Plate Using A Predictive Model.

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ABSTRACT
This project aims to simplify the process of solving the anisotropic plate, with a specific emphasis on the sandwich plate with corrugated cores. The Integrated Thermal Protection System's in-plane extensional stiffness and out-of-plane bending and twisting stiffness are sandwich plates analyzed using a combination of classical laminate assumption, parallel axis theory of axis rotation, and structural smearing. The finite series assumption, classical laminate theory, and structural smearing are used to determine the bending and twisting moments of the Integrated Thermal Protection System, as well as its deflection. A computer program has been developed to handle the proposed model more efficiently for the given sandwich construction. To validate the research, the model's results are compared to those of other researchers who used finite element methods. The model outlined in this work can handle the characterization of any sandwich construction with various corrugation patterns of any material. Therefore, this model is utilized to analyze and design sandwich plates with corrugated cores.
KEYWORD; *Anisotropic plate, Integrated Thermal Protection System. structural smearing*

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I. Introduction

Researchers worldwide are striving to develop innovative materials for construction purposes. Sandwich plates with corrugated cores usually display lower bending deflection, high critical buckling loads, high natural frequencies and more significant transverse load-carrying capacity compared to monolithic structures of equal weight. This proffers an enormous edge in structural usage. These advantages make sandwich constructions used in the transportation and industrial sectors. Its applications can be found in bridge decks, grillages, muffin wings of aircraft, storage systems, ship panels, vibration attenuation and sound insulation systems, and the packaging industries. Several methods available for analysing sandwich plates with corrugated cores are mathematically involved owing to their complicated geometry. Several homogenization methods have been evolved to deal with the difficulties in the analysis and design of sandwich construction. A review of various homogenization methods is presented by Igor et al. (2015), Aleksander et al. (2015), Arthur et al. (2012), Abbes et al. *(*2010), Talbei*etal* (2009), Buannic*et al* (2003), Naoki*et al* (1995).

In the same vein, various studies have been dedicated to developing alternative approaches, the most popular being the equivalent plate method, obtained by relaxing some of the stringent requirements of the homogenization method. Some of the authoritative works on equivalent plate models include Huimin*etal* (2019), Jian*et al* (2018), Young Jo *et al* (2015), Bartolozzi*et al* (2014), Zheng*et al* (2014), Bartolozzi*et al* (2013), Weng*et* (2011), Biancolini*et al* (2005), Brassoulis*et al* (1986).

On the other hand, several methods are available for the analytical solution of the bi-harmonic equation of transverse bending of the plate to obtain the stresses and displacements for transverse, shear and longitudinal loadings based on either the elastic or plastic theory. However, the flexible theories are usually associated with rigorous mathematics, while the plastic theories do not adequately track variation in moment, leading to over-reinforcement in concrete sections and the selection of more significant sections in steel, plastic, timber and other non-reinforced concrete materials. More so, the plastic theories do not predict deflection and can also not show clearly how loads are distributed.

II. Governing Equations

Theoretical Frame Work

The stiffness of a sandwich plate with a corrugated core for symmetric orthotropic laminated composites occurs at the neutral axis. This means that the stiffness matrices of each laminate in the composite need to be translated to the neutral axis before being summed up.

Determination of the Neutral Axis of the Sandwich Plate

The centroid of the unit cell in Figure 1 is given as:

$$h_s = \frac{A_{BP}h_{BP}+A_W h_W+ A_{TP}h_{TP}}{A_{BP}+ A_W+ A_{TP}} \quad (1)$$

Where A_{TP}, A_{BP}, A_W are the area of the top plate, the area of the bottom plate and the area of the web, respectively while

Z_{TP}- h_s: is the soffit of the top surface from the centroid y-axis

Z_{bP} - h_s: is the soffit of the bottom surface from the centroid y-axis

h_n : position from the bottom plate to the centroid y-axis

When the thickness of the bottom plate is equal to the thickness of the top plate

When the thickness of the bottom plate is equal to the thickness of the top plate

i.e $t_{BT} = t_{TP} = t$

Then, the centroid of the unit cell from the bottom of the unit cell of Figure 1 becomes:

$h_s = t / 2 + d\_c / 2$ (2)

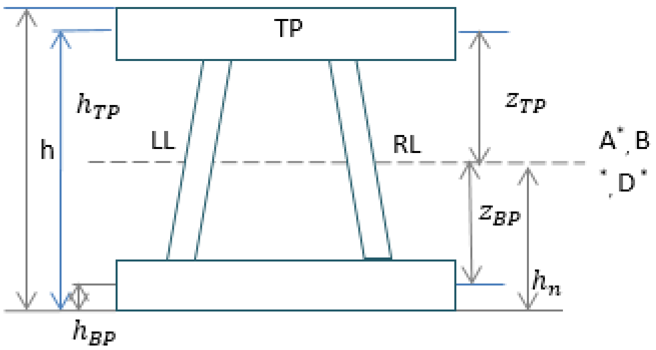

Figure 1: A Unit Cell of the Corrugated Core for Determination of Neutral Axis.

Constitutive Equations

In Figure 1, the sandwich plate has multiple layers of material, each with different levels of stiffness. We use the parallel axis theorem to properly analyse the plate to transform the stiffness values from each layer's axis to a common axis. This allows us to accurately account for the stiffness of each layer in the overall analysis.$(A^*_{ij}, B^*_{ij}, D^*_{ij})$.

In-plane Extensional Stiffness Model

The In-plane Extensional Stiffness of a sandwich plate with corrugated cores (as shown in Figure 1) equals the sum of the In-plane Extensional Stiffness of the individual face plates and the corrugated cores. This means that the A matrix for the sandwich plate with corrugated cores, which is the In-plane extensional stiffness per unit width, is obtained by adding the terms of the face plates and the corrugated cores considered separately.

$$[A^{S*}{}_{IJ}]_{equi..}=[A_{ij}]_{Faces} + [\bar{A}_{ij}]_{corr.cores..} \quad (3)$$

With the subscript ij denoting the ij element of the A matrix, also the corrugated cores in-plane extensional stiffness can be defined as:

$$[\bar{A}_{ij}]_{corr.cores..} = n_c[A_{ij}]_{cores} \quad (4)$$

Where n_c is a corrugated core factor and for the in-plane extensional stiffness, the factor is n/a in the $Longitudinal$ direction, 1/2f in the $Transverse\ direction,$ 1 in the in the diagonal and twisting direction.

Where;

a, n and f are the length in the longitudinal direction, the number of the laminae in a laminate and the distance of the web from either side of the bottom plate of the unit cell.

From the parallel axis for axis rotation equation 4 becomes;

$$[\bar{A}_{ij}]_{corr.cores..}=n_c s_c[A''{}_{IJ}]_{corr.cores} \quad (5)$$

And the in-plane extensional stiffness of the face plates is given as:

$$[A_{ij}]_{faces} = [A_{ij}]_{fTP} + [A_{ij}]_{fBP} \quad (6)$$

Substituting equations 5 and 6 into equation 3 yields the in-plane extensional stiffness of the sandwich construction given in equation 7.

$$[A^{S*}{}_{IJ}]_{equi..} = [A_{IJ}]_{FTP} + [A_{IJ}]_{FBP} + n_c s_c[A''{}_{IJ}]_{corr.cores} \quad (7)$$

Bending and Twisting Stiffness model

The Bending Stiffness of the sandwich plate with corrugated cores is equivalent to the sum of the Bending Stiffness of the individual face plates and the corrugated cores. This means that the D matrix for the sandwich plate with corrugated cores, which is the bending and twisting stiffness per unit width, is giving by the sum of the corresponding terms of the face plates and the corrugated cores considered separately.

$$\left[D^{S*}{}_{IJ}\right]_{equi..}=\left[D_{ij}\right]_{Faces}+\left[\bar{D}_{ij}\right]_{corr.cores..} \quad (8)$$

With the subscript ij denoting the ij element of the D matrix, also the corrugated cores bending and twisting stiffness can be defined as:

$$\left[\bar{D}_{ij}\right]_{corr.cores..}=n_c\left[D_{ij}\right]_{corr.cores} \quad (9)$$

Where n_c is a corrugated core factor and for the bending stiffness, the factor is 1/a in the $Longitudinal$ direction, 1/2f in the $Transverse\ direction,$ 1 in the in the diagonal and twisting direction.

From the parallel axis theorem for axis rotation equation 9 becomes;

$$\left[\bar{D}_{ij}\right]_{corr.cores..}=n_c\left(\frac{s_c^3}{12}\sin^2\varphi\left[A''{}_{IJ}\right]+S_c\left[D''{}_{IJ}\right]\right)_{corr.cires} \quad (10)$$

And the bending and twisting stiffness of the faces can be defined as:

$$\left[D_{ij}\right]_{faces}=\left[D_{ij}\right]_{fTP}+\left[D_{ij}\right]_{fBP} \quad (11)$$

substituting equations 10 and 11 into equation 8 yields the bending and twisting stiffness of the sandwich construction given in equation 12.

$$\left[D^{S*}{}_{IJ}\right]_{equi..}=\left[D_{IJ}\right]_{FTP}+\left[D_{IJ}\right]_{FBP}+n_c\left(\frac{s_c^3}{12}\sin^2\varphi\left[A''{}_{IJ}\right]+S_c\left[D''{}_{IJ}\right]\right)_{corr.cires} \quad (12)$$

Where the subscripts FTP and FBP , are the face of the top plate and face of the bottom plate of the sandwich plate respectively, while, h_{TP}, h_{BP} and φ are the seperation between the centre of the top plate to neutral axis,the separation between the bottom plate to the neutral axis and the angle of inclination of the web.

Equations 7 and 12, are used to evaluate the in-plane extensional stiffness, and the bending stiffness in the problem coordinate system for the unit cell in Figure 1.

For balanced laminate and symmetric lamina about its mid plane, terms in equations 7 and 12 can take the form in equations 13 and 14 respectively.

$$\begin{bmatrix} A_{11}^* & A_{12}^* & 0 \\ A_{12}^* & A_{22}^* & 0 \\ 0 & 0 & A_{66}^* \end{bmatrix} \quad (13)$$

$$\begin{bmatrix} D_{11}^* & D_{12}^* & 0 \\ D_{12}^* & D_{22}^* & 0 \\ 0 & 0 & D_{66}^* \end{bmatrix} \quad (14)$$

The Finite Strip Method

In SMR method, the twisting moment characterisation in the diagonal strip for deflections, gives results which does not compare to classical solution, except the poisons ratios are kept at zero.

This method is an elastic strip method that considers each term in Bi-harmonic equation separately with its amplitude $A_xA_y, A_{xy} and A_{yx}$as been equal to each other, for the compatibility criterion. It also assumes that, the load from the strip length multiplied by the perpendicular to the strip reaching the plate boundaries, are actually the load carried by each strip.

From the finite strip method, the following equations holds section.

$$f_x=\frac{q_x}{q}=\frac{n^4D_{11}}{(n^4D_{11}+D_{22}+2n^2{}_{xy}D_{xy})} \quad (15)$$

$$f_y=\frac{q_x}{q}=\frac{D_{22}}{(n^4D_{11}+D_{22}+2n^2{}_{xy}D_{xy})} \quad (16)$$

$$f_{xy}=\frac{q_x}{q}=\frac{2b^2n^4D_{xy}}{(n^4D_{11}+D_{22}+2n^2{}_{xy}D_{xy})l_{xy}} \quad (17)$$

$$M_x=f_xm_x+vf_ym_y \quad (18)$$

$$M_y=vf_xm_x+f_ym_y \quad (19)$$

$$M_{xy}=f_{xy}m_{xy} \quad (20)$$

$$\Delta_s=f_{xy}\Delta \quad (21)$$

Where $f_x, f_y, f_{xy}, m_x, m_y, m_{xy}, \Delta$ and $\Delta_s$are the load fraction in the short strip, load fraction in the long strip, load fraction in the diagonal strip, primitive moment in the short span, primitive moment in the long span,

primitive moment in the diagonal strip, primitive deflection and deflection in the sandwich plate, while $M_X,\ M_Y\ and\ M_{XY}\ are\ the$ bending and twisting moments in the sandwich construction.
And

$$D_x = D_{11}\ , D_y = D_{22}, D_{xy} = (D_{12} + 2D_{66}), n = \frac{l_y}{l_x}\ , n_{xy} = \frac{l_{xy}}{l_x},$$

$$l_{xy} = \sqrt{{l_x}^2 + {l_y}^2}, \Delta = \frac{5ql^4}{384EI}, l_x = a, l_y = b$$

III. Presentation of the Model

Based on the classical laminate theory, structural smearing and the finite series assumption.

i. Obtain the in-plane material stiffness from equation (i) of Appendix A
ii. obtain the transformed stiffness matrix $\bar{Q}_{11}, \bar{Q}_{22}, \bar{Q}_{12}, \bar{Q}_{66}, \bar{Q}_{16},$ and $\bar{Q}_{26}$ from equations (ii) to (vii) in Appendix B
iii. Substitute values from Appendix B respectively into equation (ix) of Appendix C, knowing the thickness of constituent plies, gives the in-plane extensional stiffness for the composite laminas.
iv. Terms in equation 13 (the in-plane extensional stiffness) are resolve by substituting Values from the in-plane extensional stiffness for the composite laminas. Gotten above into using equations 7, knowing that sc = $\frac{d_c}{\sin\varphi}$
v. Substitute values from Appendix B respectively into equation (x) of Appendix D, knowing the Thickness of constituent plies, $t_{k\,,}\ \ and$ $\check{Z}^2$to get the bending stiffness of the composite laminas
vi. Terms in equation 14 (the bending and twisting stiffness of the sandwich construction) are resolve by substituting Values from the bending stiffness of the composite laminas gotten above into using equations 12.
vii. Compute $l_{xy},\ n_{xy}$ and substitute into equations (15),(16),(17) with values of D_{11},D_{22},D_{12},D_{66} to get f_x, f_y, f_{xy}.
viii. The values of $f_x, f_y\ and\ f_{xy}$ are then substituted into equations (18), (19) and (20) to obtain the $(M_x, M_y\ , M_{xy})$ bending and twisting moment of the sandwich construction.
ix. Finally, the deflection of plate is obtained by substituting the strip coefficient f_{xy} into equation 21.

IV. Results Using a Numerical Example

Considering a square ITPS plate shown Figure 2, evaluate the optimal angle of inclination for the greatest bending stiffness and minimum centre deflection as well as the out of plane bending and twisting moment, given that d = 80mm, t_t = 1mm, tb =1mm, tw = 1mm, a = 640mm, b =640mm, P=80mm and the panel is composed of four unit cells, made out of graphite epoxy / T7300/934 with $E_1 = 138GPa, E_2 = 9GPa, G_{12} = 6.9GPa, v_{12} = 0.3$, with four laminate in each component and a stacking sequence of $(0/90)_s$

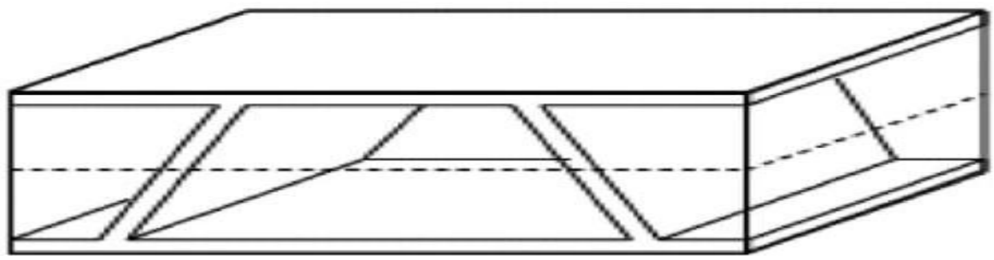

Figure 2: Unit Cell for ITPS Panel to be Sought for Membrane and Bending Stiffness

In 2007, Martinez et al. successfully solved this example by utilizing the finite element model to verify their findings. In this study, the problem has been solved by introducing the developed model. Tables 1 through 3 display the results of the computations, which include flexural stiffness, out-of-plane bending, twisting moments, and deflections with changes in the angle of inclination of the core. Moreover, the results have been visualized in Figures 3 to 14.

Table 1: Compressed Values of In-plane Extensional Stiffness and the Inclination of Web for an ITPS Sandwich Panel Using Classical Laminate Theory and the Finite Strip Model with that of Martinez (2007), for a=0.64, b=0.

Angle of Inclination of web (deg.)	A_{11} Analytical 10^8N/m	A_{11} Martinez 10^8N/m	A_{22} Analytical 10^8N/m	A_{22} Martinez 10^8N/m	A_{12} Analytical 10^8N/m	A_{12} Martinez 10^8N/m	A_{66} analytical 10^8N/m	A_{66} Martinez 10^8N/m
40								
45	1.7865	2.200	1.479	1.425	0.0543	0.0542	0.138	0.140
50	1.8146	2.210	1.479	1.435	0.0543	0.0542	0.138	0.140
52	1.8283	2.215	1.479	1.446	0.0543	0.0542	0.138	0.140
60	1.8954	2.221	1.479	1.465	0,0543	0.0542	0.138	0.141
70	2.0055	2.225	1.479	1.477	0.0543	0.0542	0.138	0.141
75	2.0718	2.230	1.479	1.478	0.0543	0.0542	0.138	0.142
80	2.1465	2.234	1.479	1.479	0.0543	0.0542	0.138	0.142
90	2.3246	2.235	1.479	1.479	0.0543	0.0542	0.138	0.142

Table 2: Compressed Values of Flexural Stiffness VS Inclination of Web for an ITPS Sandwich Panel Using Classical Laminate Theory and the Finite Strip Model with that of Martinez (2007), for a=0.64, b=0.64.

Angle of Inclination of web (deg.)	D_{11} Analytical 10^5 N.m	D_{11} Martinez 10^5N.m	D_{22} Analytical 10^5 N.m	D_{22} Martinez 10^5 N.m	D_{12} Analytical 10^5 N.m	D_{12} Martinez 10^5 N.m	D_{66} analytical 10^5N.m	D_{66} Martinez 10^5N.m
40								
45	2.2955	2.60	2.2799	2.15	0.08422	0.0877	0.2140	0.2210
50	2.3598	2.62	2.2806	2.20	0.08422	0.0877	0.2140	0.2210
52	2.3873	2.63	2.2808	2.22	0.08422	0.0877	0.2140	0.2210
60	2.5075	2.64	2.2814	2.25	0,08422	0.0887	0.2140	0.2210
70	2.6816	2.65	2.2819	2.35	0.08422	0.0877	0.2140	0.2210
75	2.7799	2.76	2.2821	2.37	0.08422	0.0877	0.2140	0.2210
80	2.8669	2.78	2.2824	2.42	0.08422	0.0877	0.2140	0.2210
90	3.1324	2.84	2.2828	2.43	0.08422	0.0877	0.2140	0.2210

Table 3: Computed Deflections and Load Fractions for Varying Angle of Inclination of Web of Sandwich Panel

Angle of Inclination	Deflection Analytical	Deflection Martinez	Deflection FE	α	B	γ
45	1.253E-08	1.100E-08		0.38824	0.33868	0.10606
50	1.362E-08	1.65E-08		0.38888	0.33712	0.10642
52	1.486E-08	1.70E-08	1.74E-08	0.38903	0.33663	0.10655
60	1.533E-08	1.68E-08		0.38927	0.33522	0.10700
70	1.551E-08	1.65E-08		0.38923	0.33422	0.10740
80	1.555E-08	1.66E-08		0.38913	0.33373	0.10763
90	1.525E-08	1.60E-08	1.652E-08	0.38908	0.33336	0.10771

Table 4: Computed Strip Coefficients and Bending Moments for Varying Angles of Inclination of Web

Angle of Inclination	M_x (N.m)	M_y (N.m)	M_{xy} (N.m)
45	2.303 E-02	2.295E-02	1.854E-02
50	2.330 E -02	2.287E-02	1.817E-02
52	2.341 E -02	2.284E-02	1.810E-02
60	2.390 E -02	2.271E-02	1.778E-02
70	2.458 E -02	2.253E-02	1.736E-02
75	2.494 E -02	2.243E-02	1.710E-02
80	2.533 E -02	2.233E-02	1.684E-02
90	2.618E -02	2.210E-02	1.629E-02

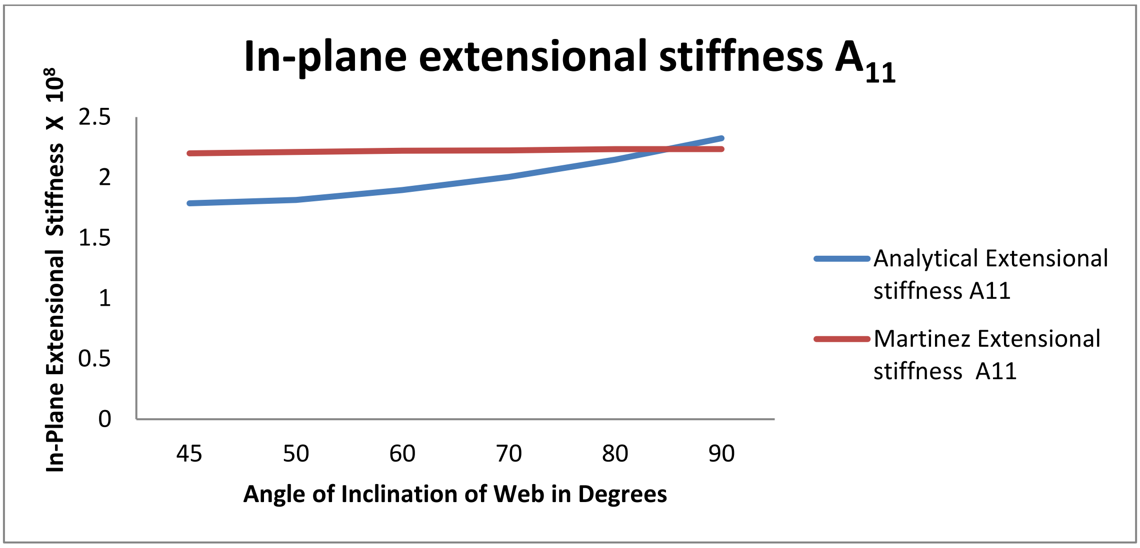

Figure 3: In-plane Extensional Stiffness A_{11}vs Angle of Inclination of Core ∅ for the Analytical Model and Martinez (2007) *et al*.

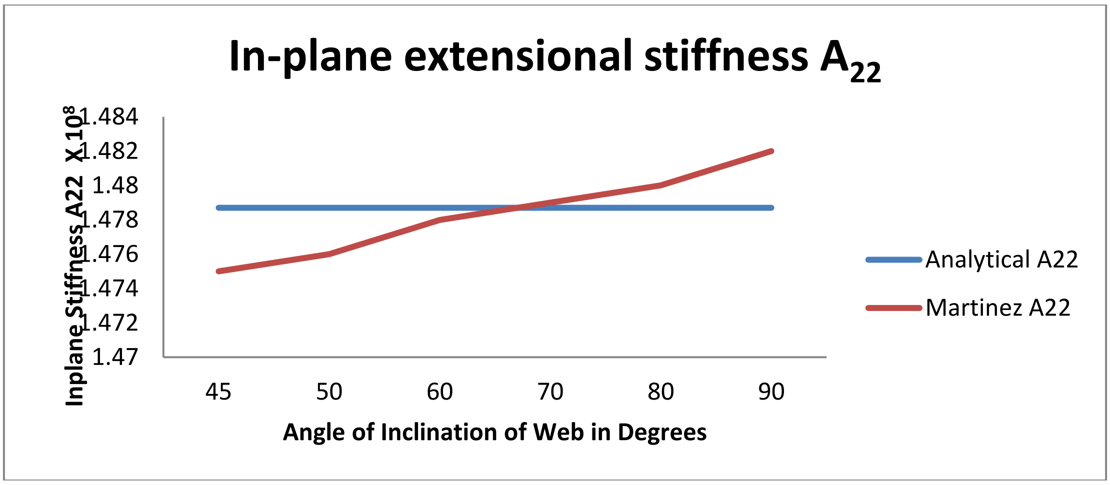

Figure 4: In-plane Extensional Stiffness A_{22} vs Angle of Inclination of Web ∅ for the Analytical Model and Martinez (2007) *et a*l

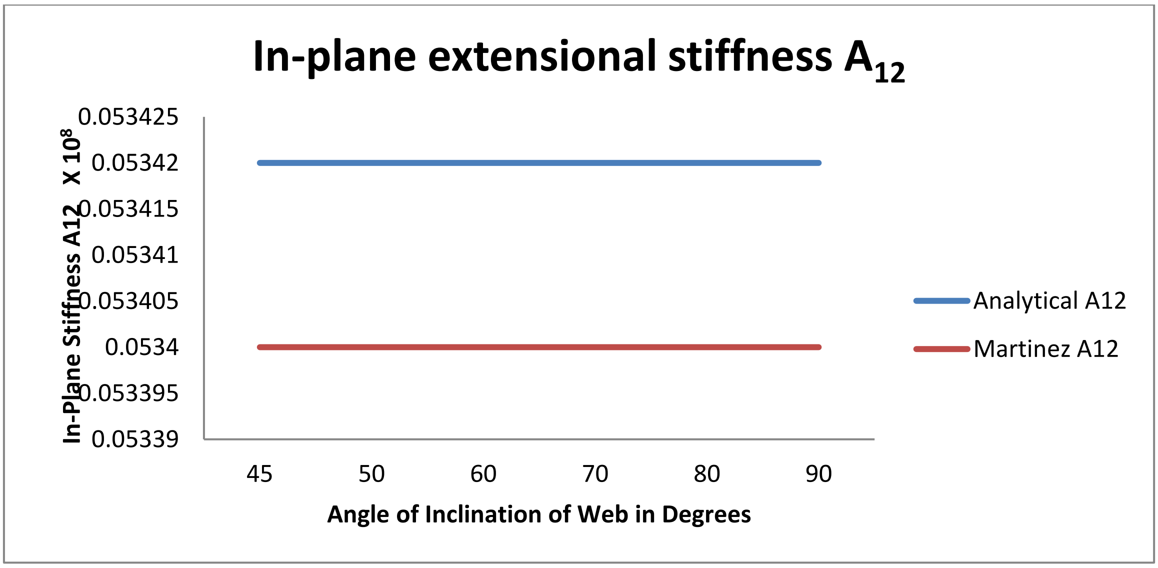

Figure 5: In-plane Extensional Stiffness A_{12} vs Angle of Inclination of Web ∅ for the Analytical Model and Martinez (2007) *et al*

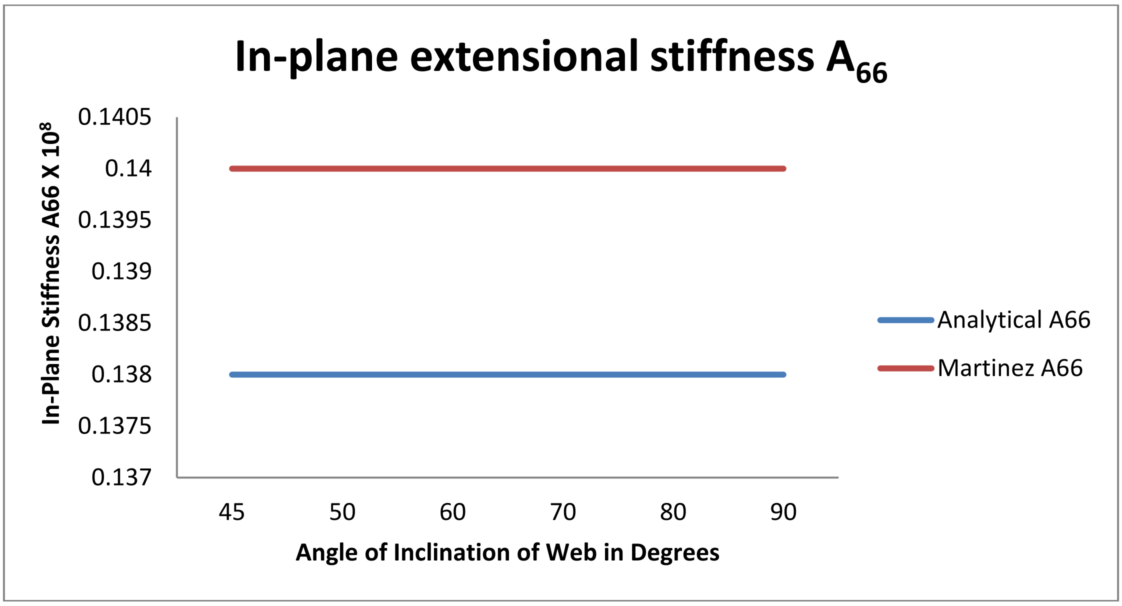

Figure 6: In-plane Extensional Stiffness A_{12}vs Angle of Inclination of Web ∅ for the Analytical Model and Martinez (2007) *et al.*

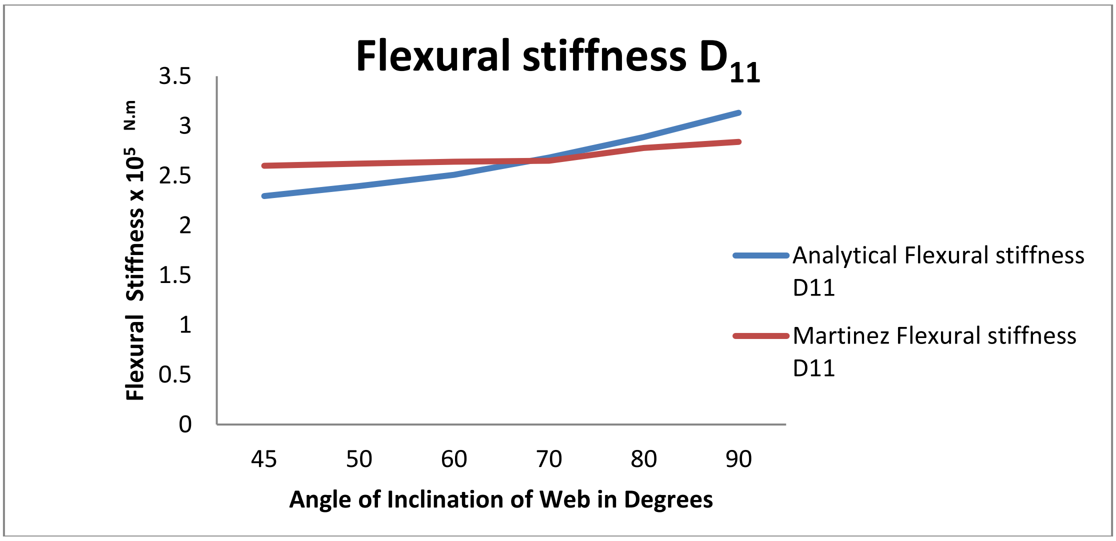

Figure 7: Flexural Stiffness D_{11} vs Angle of Inclination of Web ∅ for the Analytical and Martinez (2007) eta al.

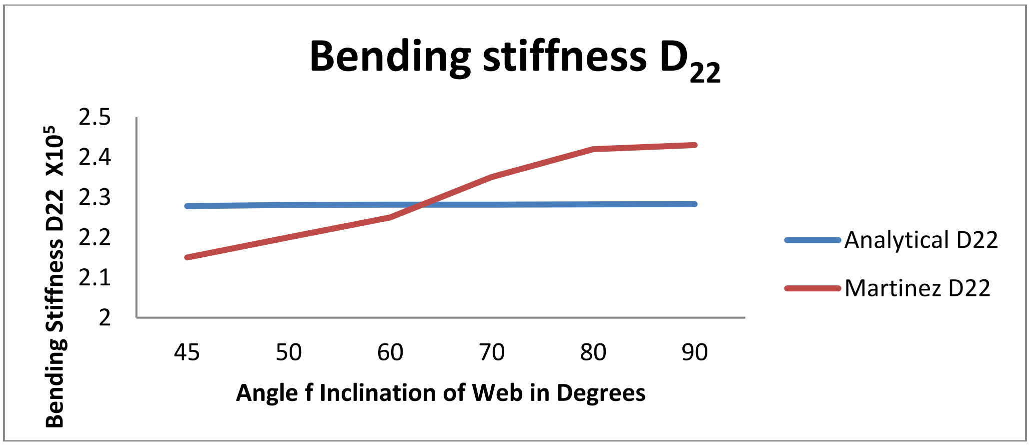

Figure 8: Flexural Stiffness D_{22} vs Angle of Inclination of Core ∅ for the Analytical and Martinez (2007) *et al*.

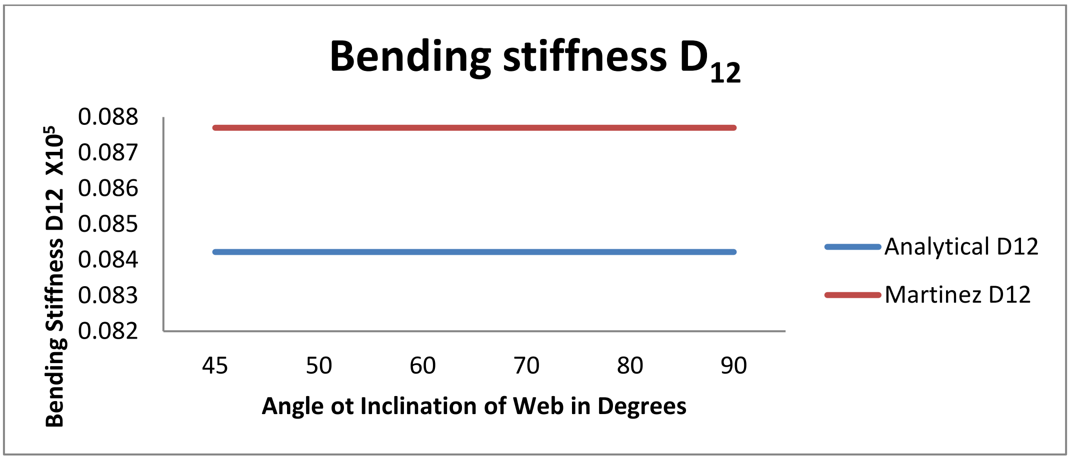

Figure 9: Flexural Stiffness D_{12} vs Angle of Inclination of Core ∅ for the Analytical and Martinez (2007) *et al*.

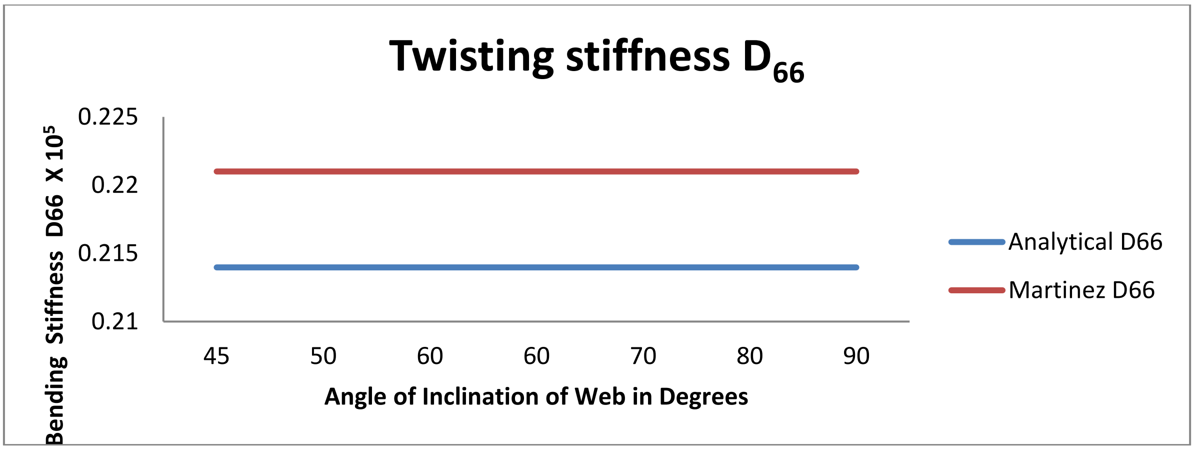

Figure 10: Flexural Stiffness D_{66} vs Angle of Inclination of Core ∅ for the Analytical and Martinez (2007) eta al.

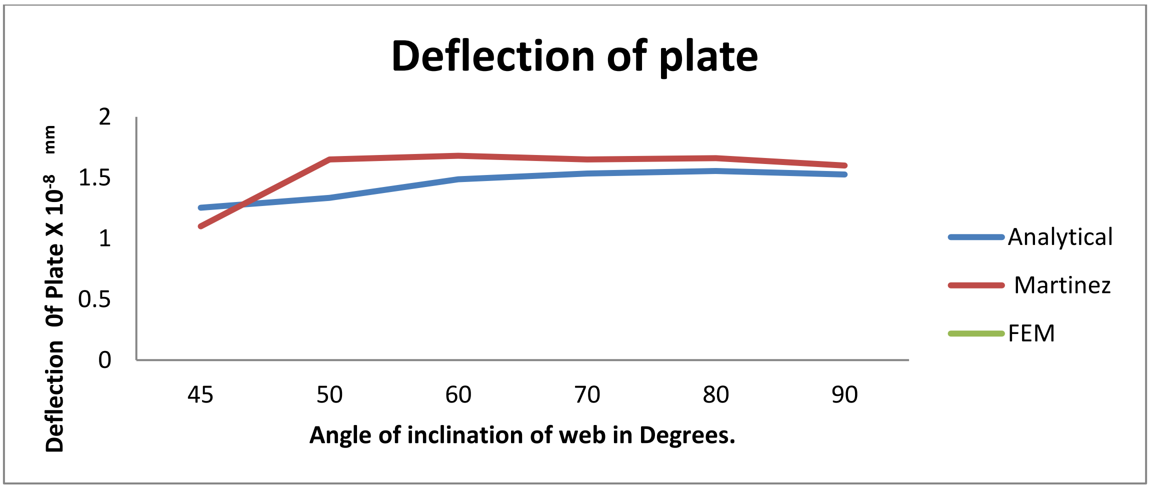

Figure 11: Deflections vs Angle of Inclination of Web

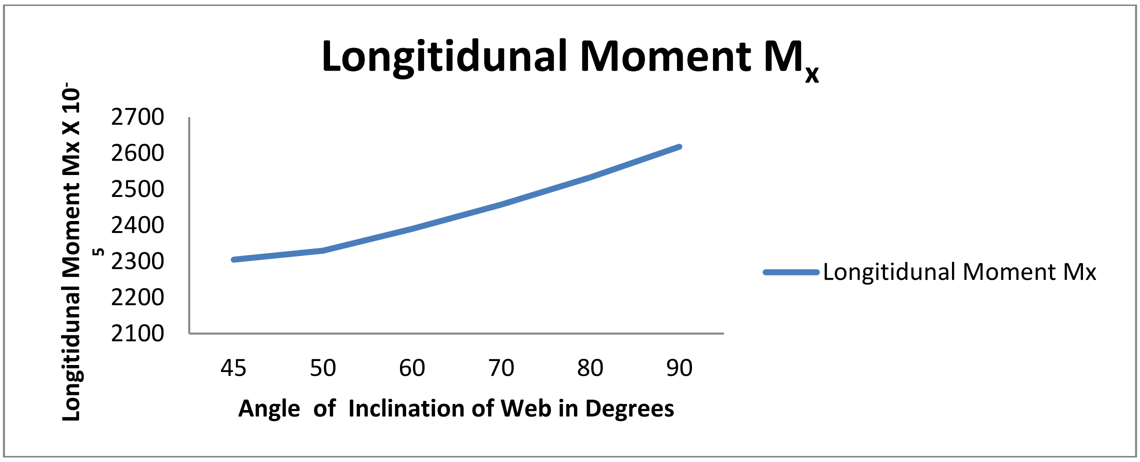

Figure 12: Bending Moment M_x vs Angle of Inclination of Web

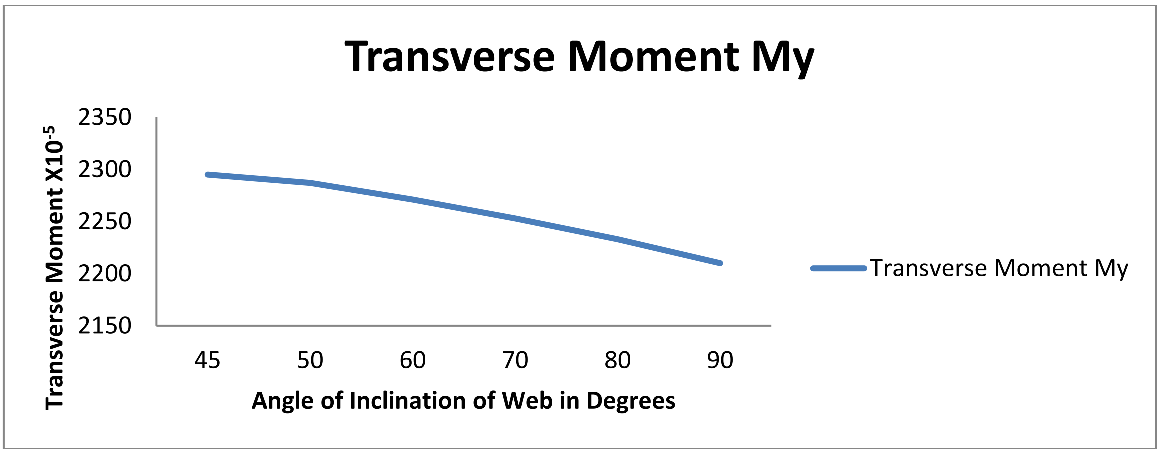

Figure 13: Bending Moment M_y vs Angle of Inclination of Web

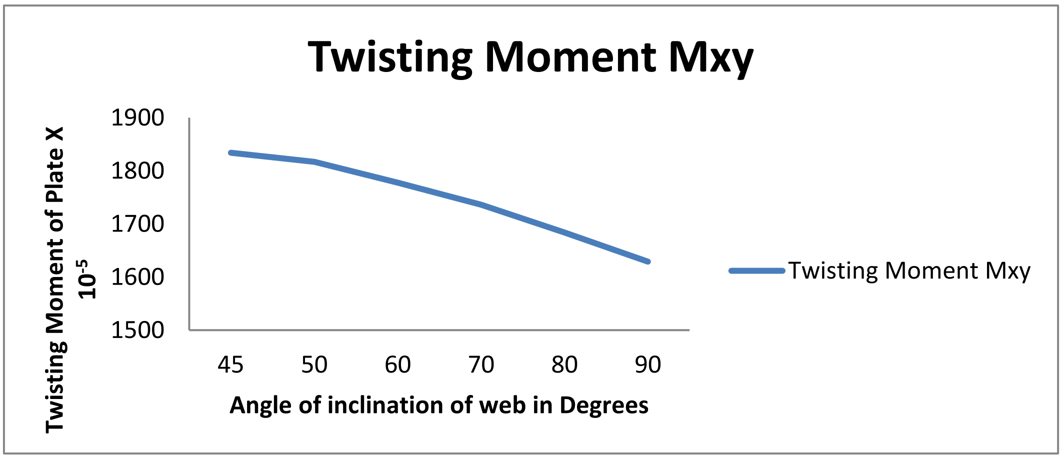

Figure 14: Twisting Moment M_{xy} vs Angle of Inclination of Web

In-Plane Extensional Stiffness

Figures 3 to 4 show that the in-plane extensional stiffness A11 increases with an increase in the angle of inclination of the web. In contrast, the angle of inclination of the web slightly influences the in-plane extensional stiffness A22. Figures 5 and 6 indicate that the in-plane extensional stiffness is not affected by the angle of inclination of the web. The solutions for the stiffness and deflections using the proposed model agree with that of Martinez et al. (2007), who used the finite element method to validate the analytical models.

Bending And Twisting Stiffness

In Figures 7 and 8, it is evident that the Analytical model and Martinez et al.'s (2007) model both show an increase in bending stiffness for D11 and D22 with an increase in the angle inclination of the web. Additionally, these figures indicate that the Sandwich corrugated panel, with the vertical web, offers the highest value for bending stiffness. Meanwhile, Figures 9 and 10 reveal that the angle of inclination of the web has no effect on the bending stiffness of DI2 and D66, as observed in both the analytical model and Martinez's model.

Bending And Twisting Moment

According to Figure 11, an increase in the angle of inclination of the web results in an increase in the bending moment in the x-direction. Conversely, Figure 12 demonstrates that an increase in the angle of inclination of the web in the y-direction leads to a decrease in the bending moment. Finally, Figure 13 reveals that the twisting moment in the twisting direction decreases as the angle of inclination of the web increases.

Minimum Plate Deflection

The deflection of the sandwich construction at a 90-degree angle of web inclination, as depicted in Figure 11, shows a difference in percentage between the Analytical model by Martinez et al 2007 and the Finite Element Model of 4.7% and 7.7%, respectively. Based on the results from both the analytical and Martinez models, the Triangular Truss core may be the preferred choice for this design exploration due to its lower Stiffness to Deflection ratio.

V. Conclusion

The finite element analysis commonly used to analyze sandwich plates can be quite costly when applied to a full 3-dimensional structure. However, by assuming that such panels are thick orthotropic plates, analytical solutions can be utilized. This method seeks to simplify the complexity of solving anisotropic plates, with a particular focus on sandwich plates with corrugated cores. The model, which relies on classical laminates theory, structural smearing parallel axis theorem for axis rotation, and finite series assumptions, has produced results that are consistent with those obtained by other researchers who used the finite element method to validate their findings.

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