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Structural Design and Analysis of a Corrugated Composite Plate

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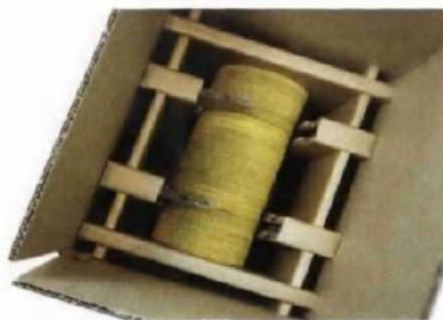
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ABSTRACT: In this study, plates with corrugated and flat geometries were designed with the same composite material and design criteria, and the displacement and stress results under the same loading and boundary conditions were obtained analytically. Furthermore, the effect of plate geometry and loading condition on the results were investigated. The equations were solved by writing codes in MATLAB separately for trapezoidal, sinusoidal and flat plates. The study is performed by using Classical Lamination Theory with Equivalent Orthotropic Flat Plate Model of a Corrugated Plate and Navier Method. In the Navier method, the boundary condition for the plates was determined as simply supported on four sides, and the solution was made under both uniformly distributed load and sinusoidal load. As a result, it has been concluded that the displacement and stress values of the corrugated plates are lower than the flat plate and the corrugation increases the stiffness of the plate against bending.

KEYWORDS: Corrugated plate, Composite materials, Homogenization method, Analytical solution.

I. INTRODUCTION

The term corrugated, describing a series of parallel ridges or furrows [1]. Corrugated structures have been used for many applications in different engineering fields such as, packaging industry, civil structures, marine structures, mechanical engineering structures and aerospace structures [2]. This is because they have more stiffness in the transverse direction and flexible in the corrugation direction. Industrial applications of corrugated structures are as follows.



(a)



(b)



(b)



(d)



(e)



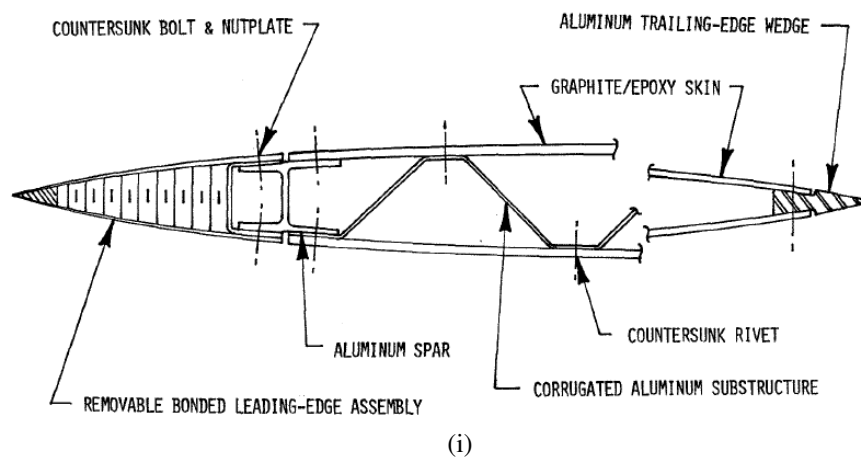
(f)



(g)



(h)



(i)

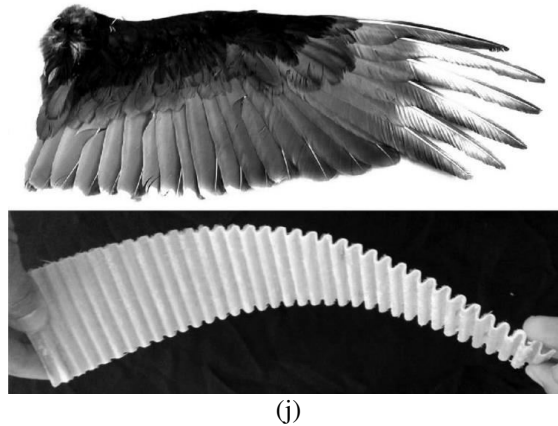


Fig. 1. Some applications of corrugated structures in engineering (a) Packaging [2] (b) Beams with corrugated web [2] (c) Corrugated roof and walls [2] (d) Corrugated tunnel [2] (e) Corrugated pipe [2] (f) Corrugated hose [2] (g) Corrugated bulkheads in ships [2] (h) Corrugated gasket [2] (i) F-16 fighter aircraft horizontal stabilizer with aluminum corrugated substructure [3] (j) Corrugated structures of a wing and a composite sample [4]

II. LITERATURE SURVEY

Various studies were carried out which are related to bending stiffness of corrugated structures. These studies include analytical solutions, finite element analysis and experiments to obtain flexural rigidities of the test elements. Yokozeki et al. [5] studied the corrugated composites manufactured from carbon fiber plain woven fabrics for flexible structural components. In-plane stiffness was evaluated with tensile and bending tests. Analytical model was developed for corrugated structures in stiffness point of view. As a result, corrugated composites have enough strength under bending loads in longitudinal direction.

III. METHODOLOGY

There are three types of plate models which are compared in terms of stress. Plate CAD models and dimensions are as shown below.

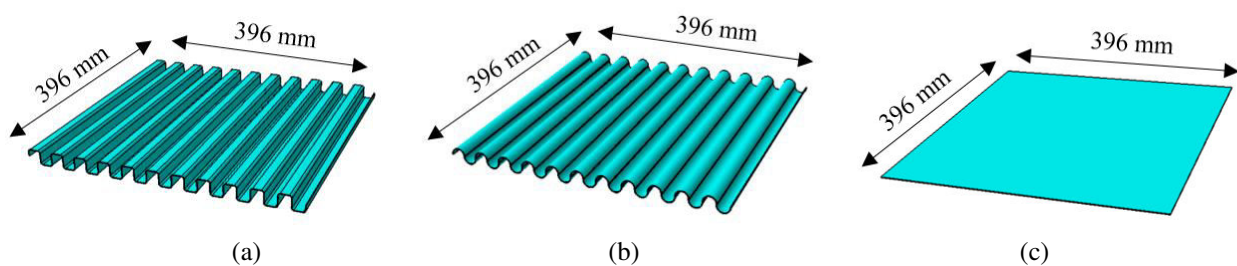


Fig. 2. Corrugated plate CAD models (a) Trapezoidal corrugated plate (b) Round corrugated plate (c) Flat plate

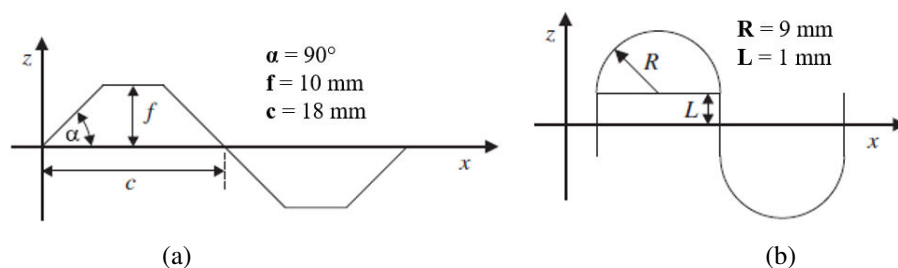


Fig. 3. Corrugation dimensions (a) Trapezoidal corrugated plate (b) Round corrugated plate

All the plates are made of AS4/3501-6 Carbon/Epoxy laminate and have same plies of equal thickness. Lay-up configuration is symmetric and balanced laminate configuration due to structural point of view. Relevant lay-up configuration and material properties are as follows.

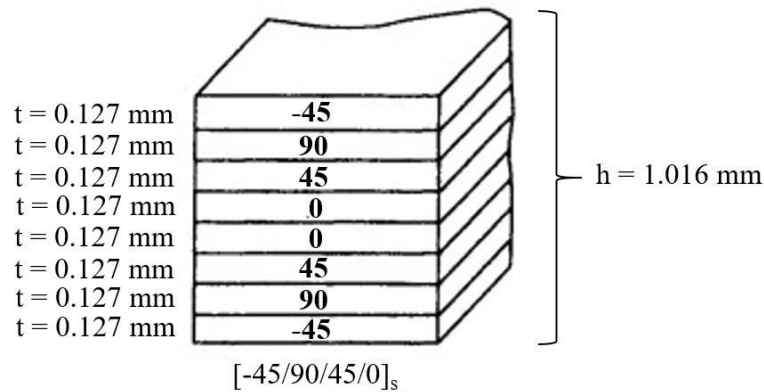


Fig. 4. Lay-up configuration and ply thickness values of the laminate

Axial Modulus, E_1 (GPa)	Transverse Modulus, E_2 (GPa)	Poisson's Ratio, ν_{12}
148	10.5	0.3
Shear Modulus, G_{12} (GPa)	Shear Modulus, G_{23} (GPa)	Poisson's Ratio, ν_{23}
5.61	3.17	0.59

Fig. 5. Material properties of AS4/3501-6 [6]

For the analytical calculations of trapezoidal and round corrugated plate Classical Lamination Theory, Equivalent Orthotropic Flat Plate Model of a Corrugated Plate and Navier Method were used and also for the analytical calculations of flat plate only Classical Lamination Theory and Navier Method were used. Details of procedures can be found in Ref [6], [7] and [8].

The corrugated plate can be approximated by an orthotropic flat plate. In this method, the stiffness terms of the equivalent plate are estimated by applying in-plane and out-of-plane deformations. Detailed procedures of the equivalent orthotropic flat plate model of a corrugated plate are stated well in Ref. [6].

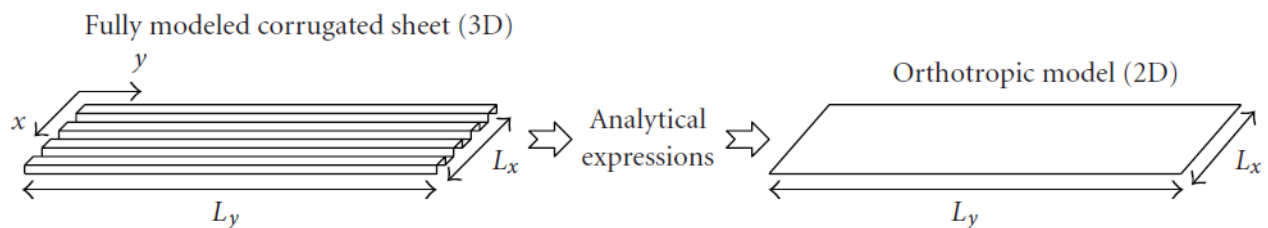
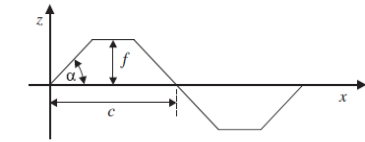


Fig. 6. Trapezoidal or round corrugated plate and equivalent flat plate models [9]

The parameters of the stiffness terms for trapezoidal and round corrugations which are dependent on the corrugation shape are given in Figure 6. The stiffness terms of D matrix were used in Navier Method to calculate transverse deflection and in-plane stress values.

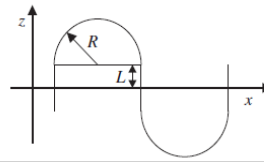
Stiffness properties for a trapezoidal corrugation. Note that the corrugation half length is $l = \frac{2f}{\sin \alpha} + c - \frac{2f}{\tan \alpha}$. The method of Samanta and Mukhopadhyay (1999) assumes an isotropic sheet with thickness t , Young's modulus E , and Poisson's ratio ν .



Stiffness Term	Proposed Method	Samanta and Mukhopadhyay (1999)
$\bar{A}_{11}$	$\frac{2c}{\left[\frac{I_1}{A_{11}} + \frac{I_2}{D_{11}} \right]}$	$\frac{2cEt^3}{I_2 \cdot 12}$
$\bar{A}_{12}$	$\frac{A_{12}}{A_{11}} \bar{A}_{11}$	$\nu \bar{A}_{11}$
$\bar{A}_{22}$	$\frac{A_{12}A_{12}}{A_{11}} + \frac{I_1A_{12}A_{22} - A_{12}^2}{A_{11}}$	$\frac{l}{c} Et$
$\bar{A}_{66}$	$\frac{c}{l} \bar{A}_{66}$	$\frac{c}{l} \frac{Et}{12(1+\nu)}$
$\bar{D}_{11}$	$\frac{c}{l} \bar{D}_{11}$	$\frac{cEt^3}{l \cdot 12}$
$\bar{D}_{12}$	$\frac{D_{12}}{D_{11}} \bar{D}_{11}$	0
$\bar{D}_{22}$	$\frac{1}{2c} [I_2A_{22} + I_1D_{22}]$	$\frac{Et}{2c} I_2$
$\bar{D}_{66}$	$\frac{l}{c} \bar{D}_{66}$	$\frac{l}{c} \frac{Et^3}{6(1+\nu)}$

where $I_1 = \frac{4f \cos \alpha}{3 \sin \alpha} + 2c - \frac{4f}{\tan \alpha}$, and $I_2 = \frac{4f^3}{3 \sin \alpha} + 2f^2 \left(c - \frac{2f}{\tan \alpha} \right)$

Stiffness properties for a round corrugation. Note that the corrugation half length is $l = \pi R + 2L$ and the half period is $c = 2R$. The thickness of the corrugated sheet material is t .



Stiffness Term	Proposed Method	Yokozeki et al. (2006)
$\bar{A}_{11}$	$\frac{2c}{\left[\frac{I_1}{A_{11}} + \frac{I_2}{D_{11}} \right]}$	$\frac{4RD_{11}}{I_2}$
$\bar{A}_{12}$	$\frac{A_{12}}{A_{11}} \bar{A}_{11}$	
$\bar{A}_{22}$	$\frac{A_{12}A_{12}}{A_{11}} + \frac{A_{11}A_{22} - A_{12}^2}{A_{11}} \frac{l}{2R}$	$\frac{l}{2R} A_{22}$
$\bar{A}_{66}$	$\frac{2R}{l} \bar{A}_{66}$	
$\bar{D}_{11}$	$\frac{2R}{l} \bar{D}_{11}$	$\frac{2R}{l} D_{11}$
$\bar{D}_{12}$	$\frac{D_{12}}{D_{11}} \bar{D}_{11}$	
$\bar{D}_{22}$	$\frac{1}{2c} [I_2A_{22} + I_1D_{22}]$	$\left[I_2 + \frac{(3\pi R + 8L)}{12} t^2 \right] \frac{A_{22}}{4R}$
$\bar{D}_{66}$	$\frac{l}{2R} \bar{D}_{66}$	

where $I_1 = \pi R$, and $I_2 = \frac{4L^3}{3} + 2\pi L^2 R + 8LR^2 + \pi R^3$

Fig. 7. Stiffness properties of trapezoidal and round corrugated plate [6]

IV.RESULTS OF ANALYTICAL CALCULATIONS

Transverse deflections and in-plane stress values according to analytical calculation are as shown below. In the tables, $\bar{w}$ is maximum transverse deflection, $\bar{\sigma}_x$ and $\bar{\sigma}_y$ are maximum in-plane normal stresses, $\bar{\sigma}_{xy}$ is maximum in-plane shear stress.

Sinusoidal Load (SSL)			
$\bar{w}$	$\bar{\sigma}_x$	$\bar{\sigma}_y$	$\bar{\sigma}_{xy}$
0.00128	0.00050	0.00050	0.00046
Uniformly Distributed Load (UDL)			
$\bar{w}$	$\bar{\sigma}_x$	$\bar{\sigma}_y$	$\bar{\sigma}_{xy}$
0.00162	0.00013	0.00024	0.00345

Table 1. Nondimensionalized transverse deflection and in-plane stress results of trapezoidal corrugated plate

Sinusoidal Load (SSL)			
$\bar{w}$	$\bar{\sigma}_x$	$\bar{\sigma}_y$	$\bar{\sigma}_{xy}$
0.00210	0.00082	0.00082	0.00076
Uniformly Distributed Load (UDL)			
$\bar{w}$	$\bar{\sigma}_x$	$\bar{\sigma}_y$	$\bar{\sigma}_{xy}$
0.00267	0.00034	0.00050	0.00481

Table 2. Nondimensionalized transverse deflection and in-plane stress results of round corrugated plate

Sinusoidal Load (SSL)			
$\bar{w}$	$\bar{\sigma}_x$	$\bar{\sigma}_y$	$\bar{\sigma}_{xy}$
0.46499	0.18123	0.18123	0.16737
Uniformly Distributed Load (UDL)			
$\bar{w}$	$\bar{\sigma}_x$	$\bar{\sigma}_y$	$\bar{\sigma}_{xy}$
0.73233	0.25637	0.25833	0.31249

Table 3. Nondimensionalized transverse deflection and in-plane stress results of flat plate

V. CONCLUSIONS

As a result, stress and transverse deflection values of the corrugated plates are lower than flat plate in terms of plate section geometry. Because corrugation gives to the plate extra stiffness as expected. Moreover, the best plate model under both UDL and SSL is trapezoidal one.

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