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Optimum Longitudinal and Bending Response Analysis of SS304 Stainless Steel Corrugated Core

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Abstract:* A sandwich Structures with core of corrugated shape offers greater rigidity in the transverse direction and flexibility in the direction of the corrugations. The corrugations' particular shape has an impact on how stiffly they bend in both directions. The usage of corrugated cores is an effective way to increase aerodynamic performance and attain the desired performance because they are more practical for morphing technologies. In general, the utilization of a corrugated core results in a construction that is pliable along the corrugation direction while exhibiting rigid characteristics in the perpendicular direction. In this research, a basic analytical framework was established by utilizing strain energy and applying Castiglione's principle to determine the efficient stiffness, longitudinal and transverse strains of symmetrical and unsymmetrical corrugated core structures for different trapezoidal corrugated core structures. The purpose was to validate the analysis results experimentally and simulate them afterwards. The outcome of the elemental analysis was eventually confirmed. Using the commercial FEM software and compared to analytical models. Finally, the various stages of for analysing the behaviour shown such as loads and their corresponding deformations are shown by curves of load displacement of both the tensile and bending tests are investigated and formulated for the validation. Because of their versatile stiffness and rigid property these sandwich panels may be used for morphing wings of aero plane, marine and other industrial applications.

***Index terms** - Sandwich structure, corrugated core, Face skins, Aerodynamic, Trapezoidal, symmetric. skin with corrugations mechanical behaviour. Geometrical trapezoids.*

I. INTRODUCTION

Different mechanical behaviours are required for the aero plane wing in various directions. The capacity to carry aerodynamic and inertial loads is provided by the stiffness along the span direction (transverse to the corrugation). Changes in shape and increases in surface area are permitted by the obsequiousness in the direction of corrugation [1]. In the same way that many other technologies have their roots in nature, The idea of merging morphing technology with relatively variable behaviour in various directions with corrugated core structure has its roots in nature as well. The significant benefit of adaptable face skins is their ability to undergo substantial deformation while possessing a low modulus of elasticity. When evaluating the efficiency of the actuator that propels the morphing configuration, it is essential for the elastic modulus to be minimal [2].

Adaptable coverings or face skins offer notable benefits such as substantial flexibility and comparably reduced elasticity. Given the actuator's operation in manipulating the morphing configuration, the elasticity ought to be minimized for optimal performance [3]. The evolution of corrugated core structure in aircraft and associated technology has the potential to significantly alter aviation. Additionally, this technology may lead to considerable improvements in aircraft control and performance, as well as reductions in weight and fuel consumption.

Recent years have seen a lot of interest in wind turbines with flexible blades and morphing aero plane wings. Due to their highly severe anisotropic nature, Corrugated sheets may be utilised in morphing constructions and other situations where specific behaviours in various directions are required: 1) Shape alterations and surface area expansion are allowed by compliance and flexibility in the corrugation direction.2) stiffness in the corrugation's transverse direction to withstand aerodynamic and inertial loads [4-6]. Like many other technologies. The idea of fusing morphing technologies with corrugated structures has origins in nature and exhibits highly varied behaviour in various directions. There are many excellent instances of this mechanism in the nature. Naturally occurring examples include the wings of birds and insects.

As a result of their efficient functioning, which involves a low ratio of mass to stiffness in the direction of transverse corrugation, the adaptability of the vehicle is improved, allowing for optimized mechanical behaviour such as resistance to buckling and absorption of energy [7-9], It is not a new concept in engineering or the environment to use corrugated structures with two face skins. Sandwich panels have been utilized for a long time in the military, automotive, and aerospace sectors. by putting the concepts of using morphable materials into practice. The corrugated core laminates used in this research project are bent into curved shapes. For the goal of validating the numerical results, these rounded corrugated laminates were created and put through tension and bending tests along the longitudinal and transverse dimensions of the corrugation direction [10].

By utilizing the finite element methodology and empirical findings, the use of corrugated cores with faceplates demonstrates increased resilience to deformation in comparison to flat foam panels. It is plausible to substitute wing skins with a steel corrugated core [11]. The Bernoulli-Euler beam principle and the first and

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second principles of Castigliano's theorem are applied for the computation of the operational effective tensile and bending resistance of steel panels with trapezoidal-shaped corrugated cores in the longitudinal and transverse directions. The findings of a load- displacement research are presented in a straightforward stiffness model [12-14]. The accuracy of the current model's output is then evaluated by contrasting them with the results of symmetrical and unsymmetrical lay-up obtained using finite elements and experimental data. The ultimate stage involves examining and categorizing the diverse load-deflection curve elements in tests for tension and flexure.

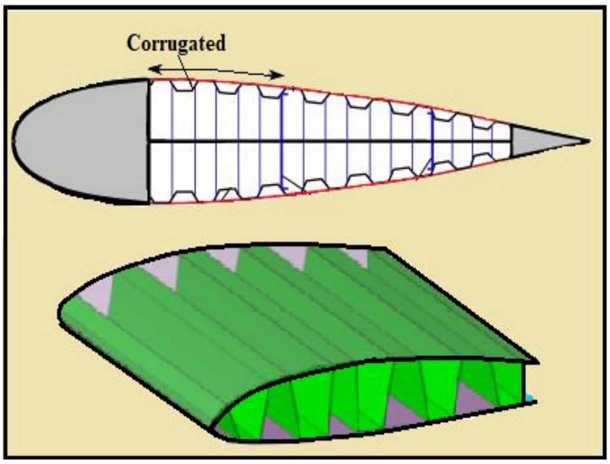

***Figure 1(a)**: wing's corrugated structures and a composite sample*

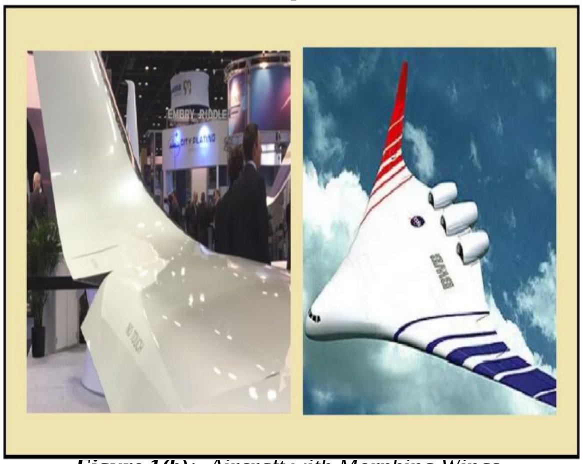

***Figure 1(b)**: Aircraft with Morphing Wings*

II. ANALYTICAL MODEL

The wave amplitude and wave pitch in the corrugated pattern core play a crucial role in the design of steel corrugated cores. An uncomplicated analytical model was formulated for forecasting the performance of the corrugated core, encompassing the efficacious longitudinal and transverse rigidity of the corrugation for.

1) Symmetrical structure.
2) Asymmetric structure.

Equations 1(a), 1(b), and 1c can be used to calculate a laminate's effective stiffness. Additionally, the stiffness of the various fabric laminates' effective flexural (D11 and D22) and extensional (A11 and A22) stiffness could be computed [9]. Take into consideration the *x*-ply laminate in Fig. 2

$$A_{i,j} = \sum_{k=1}^{x} [\overline{\varphi_{ij}}]_k \times (h_k - h_{k-1})\ , i = 1,2,6,\ \ j = 1,2,6 \qquad 1(a)$$

$$B_{i,j} = \frac{1}{2} \sum_{k=1}^{x} [\overline{\varphi_{ij}}]_k \times ({h_k}^2 - h_{k-1}^2)\ , i = 1,2,6, j = 1,2,6 \qquad 1(b)$$

$$D_{i,j} = \frac{1}{3} \sum_{k=1}^{x} [\overline{\varphi_{ij}}]_k \times ({h_k}^3 - h_{k-1}^3)\ , i = 1,2,6,, j = 1,2,6 \qquad 1(c)$$

where [A], [B], and [D] represents the extensional matrix, coupling matrix and bending stiffness matrix. The bending moments that occur are linked to the plate curvatures by the bending stiffness matrix [D], On the other hand, the tensile stiffness matrix [A] relates in-plane force to in-plane stress.

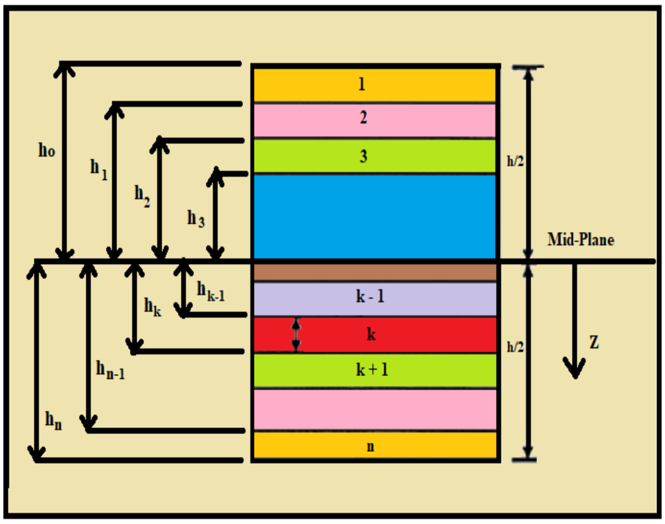

***Figure 2**: Plies locations in a laminate coordinate.*

The force and torque expressions are linked to the midplane strain or deformations and curvatures via the coupling stiffness matrix [B] [9]. The geometrical, dimensional, and effective properties of the laminates are used to deduce and define the trapezoidal corrugated composites' effective mechanical properties The effective stiffness and flexural rigidity of the trapezoidal corrugated core can be determined by analysing a variety of factors. These include the range of analysis for calculating stiffness and bending stiffness, the total or equivalent area of the corrugated sheets, the equivalent cross-sectional area of the corrugated sheets, the amplitude and spacing of the corrugations, and the moment of inertia of the laminates. The strain energy of a curved Bernoulli-Euler beam depicted in Figure 3 can be utilized to ascertain the functional characteristics of the corrugation in the longitudinal orientation.

In this research, the pliant and inflexible orientations (i.e., the orientation parallel to the ridges and the orientation perpendicular to the ridges) are denoted as "lengthwise or " and "crosswise or transverse" orientations [15]. In order to predict the true longitudinal rigidity of the corrugated steel structure, the curved Bernoulli's Euler beam equations theorem is utilized, as depicted in Figure-3. The deformation and angle of rotation to be calculated by using the equation (2). The precise calculation of effective longitudinal rigidity can be achieved by implementing Castigliano`s first and second theorems. Castigliano's first theorem can be used to determine the deflection ‘δ’ at the endpoint caused by load ‘P’ [16]:

$$\delta = \frac{P(a_1+a_2)}{E_1 \cdot b \cdot t} + \frac{8Pa_2h^2}{E_1 \cdot b \cdot t^3} + \frac{12Pa_1h^2}{E_1 \cdot b \cdot t^3} + \frac{2P(sin\varphi)^2 a_2}{E_1 \cdot b \cdot t} \qquad (2)$$

Similarly, by applying Second theorem of Castigliano's, the angle of rotation due to bending moment ‘M’ at the midpoint was determined as follows:

$$\theta = \frac{1}{D_{11}}(a_1 + 2a_2 + a_3) \cdot M \qquad (3)$$

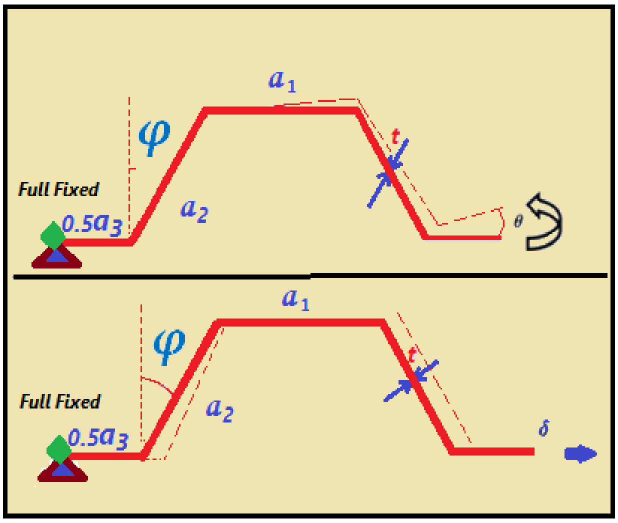

***Figure 3**: Trapezoidal analytical beam element*.

2.1.For Corrugated core Quasi Sinusoidal.

Longitudinal effective tensile stiffness is given by

$$K_{el} = \frac{R_C \cdot D_{11}}{H_C\left\{\frac{I_C^3}{3} + R_C\left[\frac{\pi}{4}\left(2I_C^2 + R_C^2\right) + 2I_C R_C\right]\right\}} \qquad (4)$$

Effective Transverse tensile stiffness is given by

$$K_{et} = \frac{2\pi R_C + 4I_C}{W_C H_C} \cdot A_{22} \qquad (5)$$

Effective longitudinal flexural stiffness is given by

$$S_{el} = \frac{R_C \cdot D_{11}}{\frac{\pi}{2} R_C + I_C} \qquad (6)$$

Effective transverse flexural stiffness is given by

$$S_{et} = \frac{A_{22}[16I_C^3 + 24\pi\, I_C^2\, R_C + 3\,\pi\, R_C(4R_C^2 + t^2) + 8I_C(12R_C^2 + t^2)]}{48R_C} \qquad (7)$$

Total deflection of the core is given by

$$\delta = \frac{1}{D_{11}}\left\{\frac{I_C^3}{3} + R_C\left[\frac{\pi}{4}\left(2I_C^2 + R_C^2\right) 2I_C R_C\right]\right\} P \qquad (8)$$

2.2. For Trapezoidal corrugated structure.

Longitudinal “Effective” tensile stiffness

$$K_{el} = \frac{P\,L}{b \cdot h \cdot \delta} \qquad (9)$$

Effective Transverse tensile stiffness is

$$K_{et} = \frac{(a_1 + 2a_2 + a_3)\,A_{22}}{(a_1 cos\varphi + t)(a_1 + 2a_2 sin\varphi + a_3)} \qquad (10)$$

Effective longitudinal flexural stiffness is

$$S_{el} = \frac{(a_1 + 2a_2\, sin\varphi + a_3)\,D_{11}}{a_1 + 2a_2 + a_3} \qquad (11)$$

Effective transverse flexural stiffness

$$S_{et} = \frac{I \cdot A_{22}}{t(a_1 + 2a_2 sin\varphi + a_3)} \qquad (12)$$

Total Deflection

$$\delta = \frac{P(a_1+a_3)}{a_{11}b} + \frac{2Pa_2h^2}{3D_{11}b} + \frac{Pa_1h^2}{3D_{11}b} + \frac{2P(sin\varphi)^2\, a_2}{a_{11}b} \qquad (13)$$

Where $h = a_2 cos\varphi$

Moment Of inertia of whole corrugated portion

$$I = \frac{a_1 t^3}{12} + a_1\, t\left[\frac{h\,(a_2+a_3)}{a_1+2a_2+a_3}\right]^2 + \frac{a_3 t^3}{12} + a_3 t\left[\frac{h\,(a_1+a_2)}{a_1+2a_2+a_3}\right]^2 + \frac{a_2(sin\varphi)^2 t^3}{6} + \frac{a_2^3(scos\varphi)^2 t^3}{6} \qquad (14)$$

2.3 For a rectangular corrugated structure.

Longitudinal “Effective” tensile stiffness

$$K_{el} = \frac{P\,(a_1+a_2)}{ba_2\delta} \qquad (15)$$

Effective Transverse tensile stiffness

$$K_{et} = \frac{(a_1+2a_2+a_3)A_{22}}{a_2(a_1+a_3)}$$

(16)

Effective longitudinal flexural stiffness

$$S_{el} = \frac{(a_1+a_3)D_{11}}{a_1+2a_2+a_3} \qquad (17)$$

Effective transverse flexural stiffness

$$S_{et} = \frac{I \cdot A_{22}}{t(a_1+a_3)} \qquad (18)$$

Total Deflection

$$\delta = \frac{P((a_1+a_3))}{A_{11} \cdot b} + \frac{2Pa_2^3}{2D_{11} \cdot b} + \frac{Pa_1a_2^2}{D_{11}b}$$

(19)

Where $h = a_2$

Moment Of Inertia

$$I = \frac{a_1t^3}{12} + a_1 t\left[\frac{h\,(a_2+a_3)}{a_1+2a_2+a_3}\right]^2 + \frac{a_3t^3}{12} + a_3 t\left[\frac{h\,(a_1+a_2)}{a_1+2a_2+a_3}\right]^2 + \frac{a_2^3\, t}{6} \qquad (20)$$

2.4 For a triangular corrugated structure.

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The effective longitudinal tensile stiffness of a triangularly corrugated composite [2] is

$$K_{el} = \frac{2Pa_2 sin\varphi}{bh\delta} \quad (21)$$

Effective Transverse tensile stiffness

$$K_{et} = \frac{2a_2 A_{22}}{(a_2 cos\varphi + t)2a_2 sin\varphi} \quad (22)$$

Effective longitudinal flexural stiffness is

$$S_{el} = \frac{D_{11} 2a_2 sin\varphi}{2a_2} \quad (23)$$

Effective "Flexural transverse" stiffness is

$$S_{et} = \frac{IA_{22}}{t \cdot 2a_2 sin\varphi} \quad (24)$$

Total Deflection

$$\delta = \frac{2Pa_2 h^2}{3D_{11} \cdot b} + \frac{2P(sin\varphi)^2}{A_{11} \cdot b} \quad (25)$$

Where $h = a_2 cos\varphi$

Moment of Inertia

$$I = \frac{a_2 (sin\varphi)^2 t^3}{6} + \frac{a_2^3 (cos\varphi)^2 \cdot t}{6} \quad (26)$$

III. MATERIAL SELECTION FOR MAKING CORRUGATED CORES

The material selection for making core is SS304 because it is an austenitic stainless steel from the T 300 Series is type SS304. It has a minimum of 18% chromium, 8% Ni(Nickel), and a maximum of 0.08% C (Carbon), [17-19]. It is classified as an alloy of austenitic chromium(chr) and nickel(Ni). SS304 material has the following Properties

a. Good Formability and weldability
b. Excellent deep drawing qualities
c. Outstanding toughness, especially at cryogenic temperatures, which are extremely low temperatures
d. Low temperature properties reacting well to cold working for hardening
e. Ease of manufacture, ease of cleaning, and beauty
f. Because of great improved weldability It is utilized in heavy gauge components.
g. Used for Chemical containers, including for transport

The additional physical characteristics of SS304 substance are delineated in table-1. The size-related aspects of structured specimen-1, structured specimen-2 & structured specimen-3 are presented in table-2 & table-3.

Table 1 : Mechanical and geometric properties of SS304 stainless steel

SL No	Description	Dimensions
1	Length of the panel (L)	200 mm
2	Width of the panel (b)	40mm
3	Corrugation angle (ɵ)	60 Degrees
4	Material for making Core	Stainless steel SS304
5	Young's Modulus (E)	$210X10^3$ N/mm^2
6	Poisson's ratio (μ)	0.3
7	Yield Strength (σ yp)	240N/mm^2
8	Shear Strength (G)	$80X10^3$N/mm^2

Table 2: Specimens dimensions

SL No	Length of panel L (mm)	Breadth of panel B or W (mm)	Thickness of face plate & core t (mm)
Tension along Longitudinal direction	200 (20cm)	25 (2.5cm)	0.7
Tension along Transverse direction	250 (25cm)	25 (2.5cm)	0.7
Longitudinal bending	200	30	0.7
Transverse bending	250	40	0.7

Table 3: Experimental samples adopted dimensional parameters

Corrugation	a_1 (mm)	a_2 (mm)	a_3 (mm)	R_C (mm)	I_C (mm^4)	φ (Degrees)
Sample-1	5	8	5	-	-	60
Sample-2	7.5	7.5	7.5	-	-	60
Sample-1	8	8.5	8	-	-	60

IV. MANUFACTURING TECHNIQUE OF CORRUGATED CORE

Acquiring top-notch, precise specimens that adhere to acceptable geometric and dimensional criteria, while limiting casting inaccuracies, is a significant obstacle in the production of corrugated core samples. Additionally, the dimensions of the utilized specimen hold crucial importance. The samples were produced using a creative and simple way. The stages we provide below are as follows:

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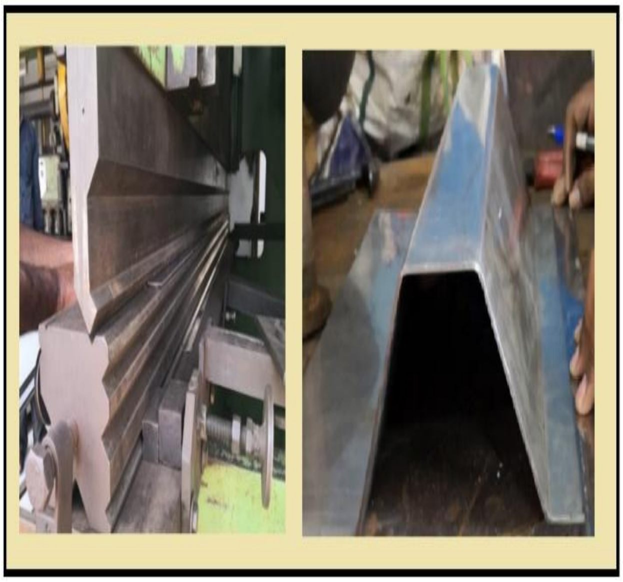

Figure 4: Fabrication Technique of Corrugated Core

1) SS304 stainless steel or other robust corrugated core sheets can be fabricated with the desired geometry by using hydraulic cutting and punching dies.
2) Materials with thicknesses ranging from 2mm to 6mm were employed, including mild steel and SS304 stainless steel.

V. FINITE ELEMENT APPROACHES FOR ANALYTICAL MODEL VALIDATION

The research's findings for the unidirectional properties of chosen trapezoidal corrugated SS304 stainless steel core in terms of longitudinal effective transverse, effective tensile and flexural stiffness are shown in Table-1. The corrugated sheet is 200 mm long, 40 mm wide, and the face plates range in thickness from 2 to 5 mm. The steel made corrugated core's tensile and flexural stiffness were computed by applying the effective properties of SS304 along unidirectional system. Through the use of commercial FEM software, Figure 5(a) shows deflection along Longitudinal direction for model-1, Figure-5(b) shows deflection along transverse direction of model-1, 5(c) shows the deflection along longitudinal direction of model-2,and 5(d) shows deflection along transverse direction of model-2.the numerical analysis of corrugated core in both the longitudinal and transverse directions for the purpose of validation of finite element results with analytical results. Modifications in the mechanical characteristics of corrugated cores with varying thicknesses can be effortlessly computed by utilizing the present analytical techniques expounded earlier. The graphs illustrated on the right-hand side of Figure 7 depict the percentage disparity between the finite element analysis findings and the analytical model methodology.

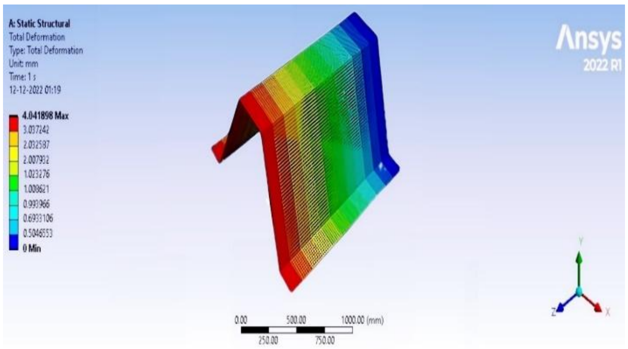

***Figure 5(a):** Deflection along Longitudinal direction of Model-1*

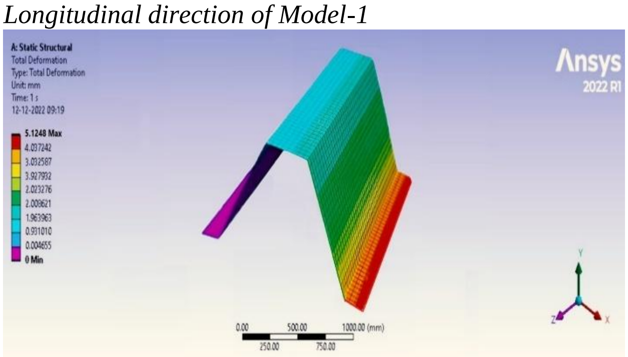

***Figure 5(b):** Deflection along Transverse Direction of Model-1*

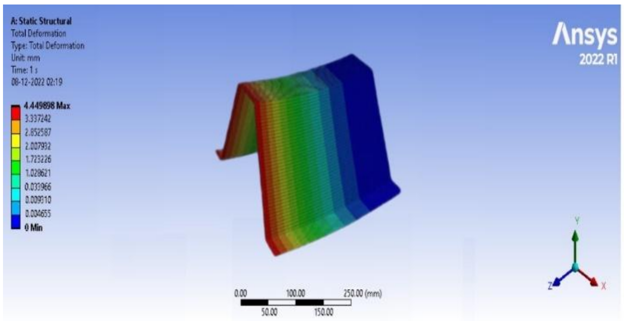

***Figure 5(c):** Deflection along Longitudinal Direction of Model-2*

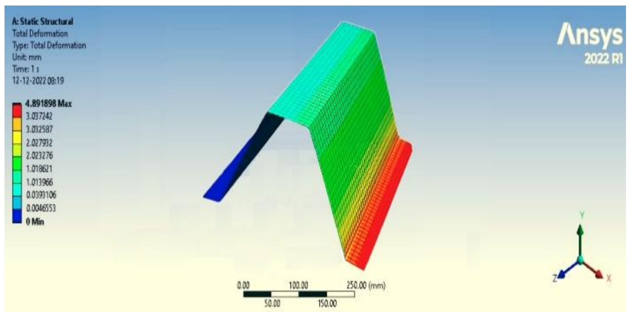

***Figure 5(d):** Deflection along Transverse Direction of Model-2*

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VI. Experimentation

Tensile and bending (flexural) tests were performed on a trapezoidal corrugated core in both the longitudinal and transverse directions to validate the effective stiffness the core material. Testing results in the transverse direction exhibit linear behavior as a result of its symmetrical design. The samples were subjected to a three-point bending stress during the transverse bending test. The corrugated samples have a width of 40 mm and a span length of 200 mm. Figure-6 illustrates the utilization of the Instron 5500R apparatus to evaluate the mechanical properties of the corrugated core in the longitudinal and transverse orientations. The maximum load capacity of the specimen will be limited to 20kN throughout the testing procedure.

Figure 6: *Instron 5500R*

In order to validate the analytical and FEM results. Tensile testing for flat samples and corrugated samples were conducted in accordance with ASTM D3039 test specifications, and the results are described in Table-2 . The level and corrugated samples were subjected to displacement regulation at velocities of 0.5 and 1 milli meters per minute, correspondingly. The INSTRON 5500 apparatus's internal sensors for displacement and force conveyed the experimental measurements to the computer, which enabled the documentation of the elongation versus tensile load relationship curve. The findings of the experiment are displayed in table-4.

Table -4: Experimental results of stiffness.

Sample	Effective Stiffness	Experimental Results
Sample-1	K_{el} (MPa)	0.6471
	K_{et} (MPa)	399.421
	S_{el}(N-m)	0.0538
	S_{et}(N-m)	10.1482
Sample-2	K_{el} (MPa)	0.7186
	K_{et} (MPa)	364.228
	S_{el}(N-m)	0.0638
	S_{et}(N-m)	12.845
Sample-3	K_{el} (MPa)	1.556
	K_{et} (MPa)	397.228

VII. ANALYTICAL MODEL VALIDATIONS USING EXPERIMENTAL & FINITE ELEMENT DATA

A fundamental analytical structure is utilized to assess the efficient rigidity of both symmetrical and unsymmetrical trapezoidal corrugated centers. The proficient rigidity and extension in both longitudinal and transverse directions are assessed for diverse trapezoidal corrugated exteriors and level composites by utilizing Castiglione's principle and strain energy. Using the commercial FEM software Ansys, trapezoidal corrugated composites were simulated and compared to analytical models. Experimental findings from bending and tensile testing are used to validate the analytical and the numerical model as shown in table-5.

Table 5: Results of theoretical and experimental investigation

Sample	Effective Stiffness	Theoretical Results	Experimental Results	FEM Results
Sample-1	K_{el} (MPa)	0.8471	0.6471	0.7239
	K_{et} (MPa)	403.21	399.421	379.839
	S_{el} (N-m)	0.0578	0.0538	0.04892
	S_{et} (N-m)	10.8286	10.1482	9.8891
Sample-2	K_{el} (MPa)	0.7522	0.7186	0.8129
	K_{et} (MPa)	366.442	364.228	354.899
	S_{el} (N-m)	0.0624	0.0638	0.0221
	S_{et} (N-m)	13.128	12.845	11.546
Sample-3	K_{el} (MPa)	1.362	1.556	1.0123
	K_{et} (MPa)	400.862	397.228	359.899
	S_{el} (N-m)	0.0665	0.0714	0.0552
	S_{et} (N-m)	8.443	8.172	7.881

Mechanical Behaviour

Figure 7 shows the load vs displacement curve for a longitudinal extensional test for a SS304 trapezoidal corrugated core sheet. There are three sections to it.

1. In load Vs displacement curve the portion-1 has a constant gradient. Effective tensile stiffness is calculated by substituting this gradient ‘δ ‘in Equation-13. The corrugated shaped sheet behaves in this portion entirely elastic [23].

$$k_{el} = \frac{k \times L}{A} \quad (27)$$

The gradient of k is observed in the curve depicting the relationship between load and displacement, wherein 'L' signifies the length of the core, 'A' signifies the cross-sectional area of the corrugated sheet, and either sheet width B or W. The trapezium-shaped metal panel depicted in Section 2, Load vs. Deflection, attains its utmost length and transforms into a level panel. The gradient in this area is gentler than the gradient of the load-deformation graph for a level panel (without any fundamental corrugation).

2. In comparison to a flat sheet, a folded core sheet with corrugations in section-2 leads to cracking and separation of layers (excluding the primary corrugation). The sheet fails at position three. From Figure 7 and Equation 14, it is apparent that the corrugated sheet has a strain of 2.5%, whereas the flat sheet has a strain of 2.6%. Corrugated composite sheets are a better alternative in cases where considerable strain and displacement are necessary, such as in morphing applications [24].

$$Strain = \frac{\delta}{L} = \frac{5}{200} = 2.5\% \quad (28)$$

Figure 9 displays the load-deflection graph of a trapezoidal corrugated sheet during a flexural test. The transverse flexural stiffness of the corrugation can be determined by modifying the Equation that defines the load-deflection curve [25-26]

$$S_{et} = \frac{mL^3}{48\,b}$$

where m and L, respectively, represent the flexural test curve's gradient and the span's length.

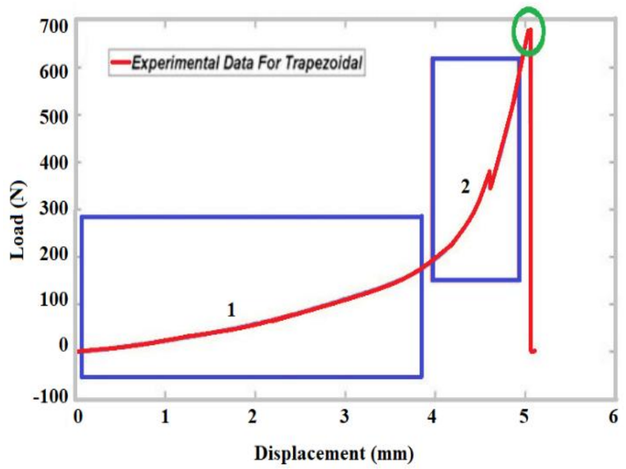

Figure 7: Load Vs displacement diagram for a corrugated sheet along the longitudinal direction

VIII. CONCLUSION

The utilization of trapezoidal corrugated specimens exhibiting highly anisotropic characteristics can enhance the functioning of morphing aircraft applications and other applications that demand distinct qualities in various directions. The effective mechanical characteristics of trapezoidal corrugated steel core were evaluated by conducting tensile and flexural examinations in both longitudinal and transverse orientations of the corrugation. While the transverse direction exhibits only linear behaviour, the longitudinal tensile test demonstrates a three-stage activity for the corrugated skins. In various mechanical tests carried out in the longitudinal direction of the corrugation, a strain exceeding 40% was achieved. This property can be advantageously utilized in the trailing edge of the wing. An uncomplicated analytical model was created to ascertain the efficient rigidity of trapezoidal corrugated composites in symmetrical lay-up, and its accuracy was verified using experimental and FEM findings. Several mechanical experiments conducted along the lengthwise orientation of the corrugation resulted in a deformation that surpassed 40%. This characteristic can be beneficially employed in the rear edge of the aircraft wing. A simple analytical framework was formulated to determine the optimal stiffness of trapezoidal corrugated composites with symmetrical arrangement, and its precision was authenticated through empirical and FEM data.

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