Oral Presentation

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Structural Wing Sizing in Preliminary Aircraft Design

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Abstract

This paper is focused on sizing the wing structure of a single engine, two-seat kit aircraft. The calculation covers the design process in the following order: the obtaining of aircraft configuration, the calculation of V-n diagram, the calculation of the expected loads on the wing, the lay-out of the arrangement of wing components, the design of the spar and rib dimensions, the estimation of the skin and stiffener dimensions, the calculation to check the stability of each component, and finally the suggestion for the lightening holes. Additionally, figures displaying the arrangement of the sub-structure wing component are illustrated. In this study, the wing structure is fabricated by aluminum sheet. The details of the design are based on the theory of aircraft design in consideration of yield strength of material and buckling stress due to dimensions of the components with a factor of safety of 1.5. The overall weight of a half-wing was 41.62 kg excluding fuel. It is satisfactory to the estimation of aircraft designer. The dimension of each component shows applied stress is lower than both yield strength and buckling stress. Finally, the dimensions of all components are shown and drawn up in a 3D model.

***Keywords**:* Aircraft wing structure, Aircraft design theory, Buckling stress

1. Introduction

This paper provides information obtained on a single engine, two-seat plane type JX-200 RG Sport Thunder of JFox Aircraft Co., Ltd. (Figs. 1-2), in collaboration with Design Clinic Research Unit to analyze aerodynamic characteristics and structural strength of the plane. This type of plane will be available as a KIT. The purpose of this paper is to design the main structure of aircraft wing using the theory of aircraft design and estimate the wing structure weight to compare with the weight estimation, 70 kg per half span, obtained by the company. The dimensions of various wing's components, including spars, ribs, stiffeners, and skin were estimated by using metal in the market to fabricate. It was designed to have enough strength to sustain the loads acting on the wing with a factor of safety of 1.5 and not buckle.

The information about the aircraft specifications consisting of dimensions, weight and flight performance of the airplane is described in Table. 1 [8].

Fig. 1 Aircraft model top view

Fig. 2 Aircraft model 3D view

For preliminary design, the wing planform of the aircraft was set as tapered wing. Location of spars and ribs were arranged as shown in Fig. 3. These information leads to calculate the distributed load along the wing span and estimate size of the wing components.

Table. 1 Aircraft specifications [8]

No.	Parameter	Value	Unit
1	Length	6.4	m
2	Height	2.2	m
3	Wingspan	8.7	m
4	Maximum takeoff weight	750	kg
5	Empty weight	360	kg
6	Useful load	390	kg
7	Takeoff distance	450	m
8	Takeoff over 50 ft object	677	m
9	Climb rate	7.62	m/s
10	Cruise speed	92.6	m/s
11	Maximum range with reserve (55% pwr)	1454	km
12	Landing ground roll	260	m
13	Landing over 50 ft object	803	m

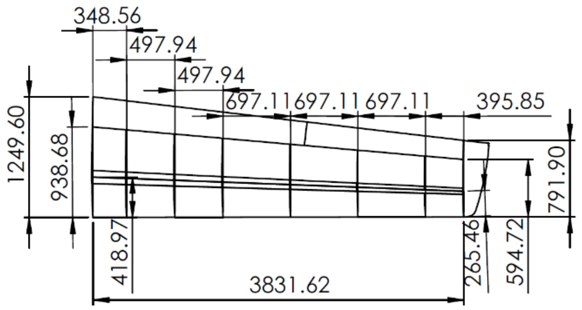

Fig. 3 Dimensions of wing and chord length (in mm)

2. Wing Load

There are two kinds of loads that act in vertical direction of the wing. One is lifting force generated from aerodynamic load acting in an upward direction called “Airload”, another is weight itself acting in a downward direction called “Dead Weight”. Both of them are approximated along the span by wing section theory [1]. The wing span is divided as many small sections then the loads are computed at each small section. After that, load will be integrated in term of shear force, bending moment and torsion.

The obtained load must be multiplied as prescribed by the regulation in FAR23 [7] acrobatic aircraft category that limit the maximum load factor is +6 and minimum load factor is -3. The positive strength of the wing’s structure is required by the combination of airspeed and load factor called “flight envelope” or “V-n diagram”. This flight loading conditions is generated with gust load to define the maximum and minimum load factor that act on the wing in any conditions with the factor of safety of 1.5.

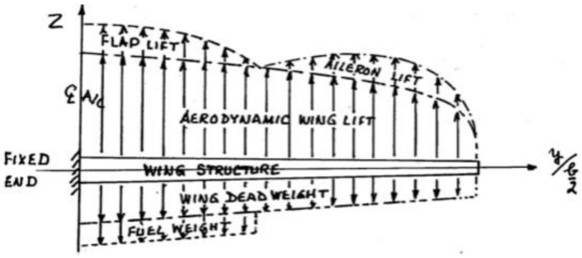

Fig. 4 Aerodynamic lift and wing dead weight [11]

3. Aircraft Design Theory

The design and sizing optimization concept of wing components are considered on three types of stress: yield, buckling, and applied stress. The first is yield stress of material which is aluminum 7075-T6 [5] that was selected for this study. The second is buckling stress that uses for the evaluation of wing structural stability. The third is applied stress that varies with each component. The aircraft wing’s components require minimum mass but the smaller size makes it weaker. So, the dimension of each component must be optimized to obtain the lightest weight but can carry load without any failure. In calculation process, wing will be independently separated to compute its size as a component including front spar, rear spar, skin, rib and any reinforced members in order to make the calculations easier.

3.1 Front spar

In this paper, the first common component to be discussed is front spar. This part is assumed as a beam to support all bending loads that act on a half of the wing in spanwise direction. The apply stress on the front spar is bending stress [2].

$$\sigma_{bending} = \frac{Mc}{I_x} \qquad (1)$$

Eq. (1) is bending stress formula, when M is bending moment of the section; c is half spar height and I_x is section moment of inertia depending on spar flange and spar web.

Generally, the front spar is composed of two flanges and a web. The dimension of flange was selected from aluminum extrude beam list [3] with the condition of maximum moment of inertia (I_x) per cross-section area. This means it can carry maximum load with the lightest weight.

The spar web is a part linking between two flanges. Its dimension is computed to maintain stress under material’s yield strength without buckling.

Buckling stress of the web without stiffener ($F_{S,cr}$) is calculated by graph in Fig. 5. This stress depends on dimension of web, height and thickness, the buckling stress is half of the collapse stress that was read from graph.

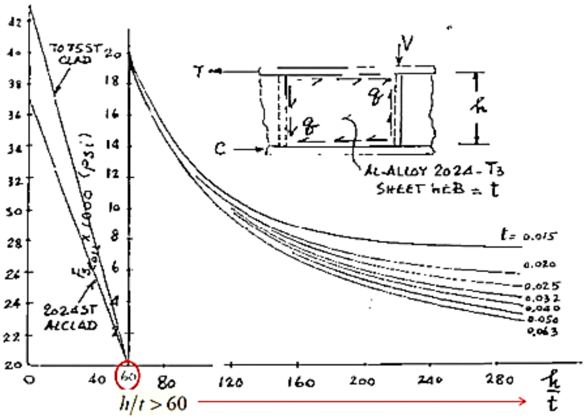

Fig. 5 Collapsing shear stress for webs [3]

If buckling stress of web is more than the apply stress of spar, it must be reinforced by stiffener. The buckling stress of web with stiffener is calculated by the equation as follow

$$F_{S,cr} = K_s E\left(\frac{t}{d}\right)^2 \qquad (2)$$

Where K_s is end condition (using 1.2), E is elastic modulus of material, t is web thickness and d is web height [9].

The minimum sheet thickness is selected as spar web to maintain a balance between the level of apply stress and the magnitude of buckling stress.

3.2 Rear spar

Rear spar is assumed to support only shear load with pinned end at root. The dimension of rear spar can be calculated by using the same method as the front spar, the different is only apply stress that is replaced by shear stress obtained from

$$\sigma_{shear} = \frac{V}{A} \tag{3}$$

in which V is shear force and A is cross-section area.

3.3 Skin thickness

The calculation of skin thickness can be divided into two parts. First, minimum skin thickness to carry shear flow around wing cross section is calculated to be a start value to compute the true skin thickness. Shear flow was calculated by "Idealized Thin-Walled Section" method as shown in Fig. 6 [4].

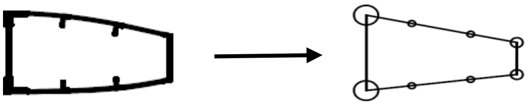

Fig. 6 Idealized wing section

Second, skin deflection is calculated by the method that the wing skin is assumed to support point load that integrated from distributed airload between a pair of rib. Skin deflection (δ) is limited by empirical theory to not exceed 0.002 from graph in Fig. 7. The theory is computed from various parameters: rib spacing (b), skin thickness (t), stiffener spacing (a), modulus of elasticity and Poisson's ratio of material [6].

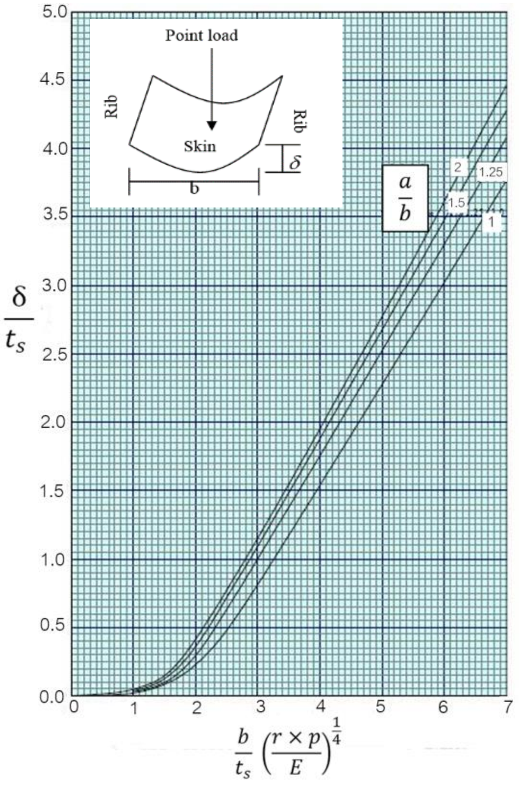

Fig. 7 Skin deflection of plate [6]

3.4 Rib sizing

The lay-out of the arrangement of wing components was assigned by the company. The shape of all ribs is the same as airfoil section. The only thing that this paper can involve is the thickness of the rib. This can be done in order to optimize the rib weight by using minimum rib thickness and lightening hole for the evaluation of strength.

The rib is assumed to support torsion, the optimal thickness can be calculated by

$$t_{rib} = \frac{2AT_p}{\tau_s} \tag{4}$$

in which A is rib area, T_p is torsional force and τ_s is shear strength of rib's material.

So, the apply stress on the rib is a torsional stress ($\sigma_{Torsion}$) calculated by

$$\sigma_{Torsion} = \frac{T_p}{2At} \tag{5}$$

After all calculation, rib dimension (height, width, and thickness) is determined. The buckling stress of rib can be computed in the same manner as the calculation of the web buckling without stiffener.

Then, the lightening hole in circular form is introduced to reduce weight without reducing the strength. The diameter of lightening hole is estimated then calculated to balance between apply stress and buckling stress as shown in Fig. 8. The graph shows when the rib hole size is increased, the buckling stress will decrease while the apply stress will increase. The study must assume the arbitrary size of the hole to check the balance of both stresses. The optimal hole size is the one making apply stress slightly less than buckling stress in each rib. The calculation method was written as a computational code in MATLAB program.

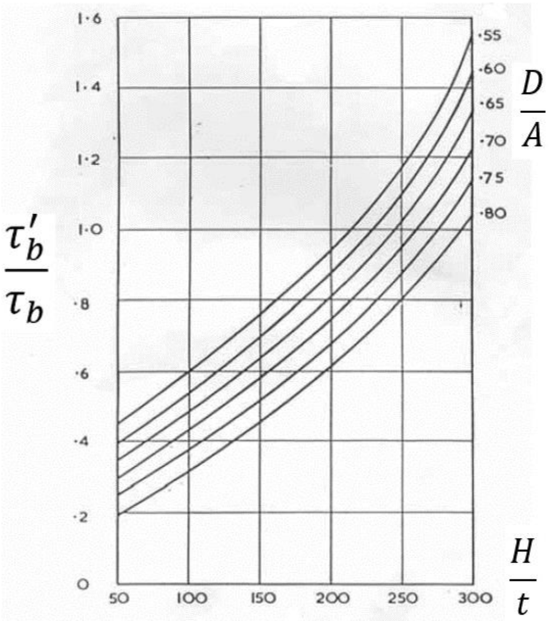

Fig. 8 Rib buckling with hole [10]

The variables included in Fig. 8 are as follows: τ_b is buckling stress without lightening hole, τ_b' is buckling stress with lightening hole, D is hole diameter, A is hole pitch that refers number of hole in a rib, H is rib height and t is rib thickness.

4. Load Conditions

4.1 V-n diagram

Flight altitude and airfoil shape were selected by the company. The airfoil characteristics were calculated. All significant parameters had been used to construct the V-n diagram for the aircraft (Table. 2).

Table. 2 Aircraft configurations and flight conditions

No.	Parameter	Value	Unit
1	Wing area (S)	8.8	m^2
2	Avg. chord length ($\bar{c}$)	1.07	m
3	$C^{+}_{L,max}$	1.04	
4	$C^{-}_{L,max}$	-0.513	
5	Lift curve slope (C_{l_α})	6.159	1/rad
6	Cruise altitude	15000	ft

The V-n diagram was constructed to determine the flight envelope of the plane as prescribed in airworthiness standards for the issue of airplane in acrobatic categories as shown in Fig. 9. The positive maneuvering load factor (n^{+}_{max}) is +6 and the negative maneuvering load factor (n^{-}_{max}) is -3.45. The wing structure must be designed to have enough strength to withstand ultimate load by a factor of safety of 1.5,

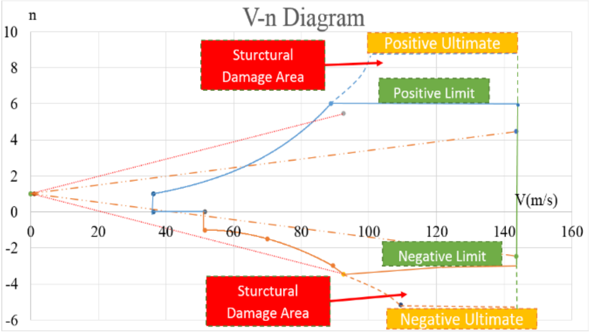

Fig. 9 V-n diagram of the plane

4.2 Load acting on wing

In this study, the airplane is in symmetrical flight condition to limit the out-of-control parameters. The wing structure is considered by assuming all major loads acting on the front spar. The major aerodynamic force component is lift force acting upward. Then the lift can be deducted from the weight of the structure itself acting in the opposite direction. The wing is divided into strips along spanwise direction to be determined the load action on front spar. Loads of each strip was calculated to find shear force (Fig. 10). In addition, bending moment and torsion were calculated and plot in Fig. 11.

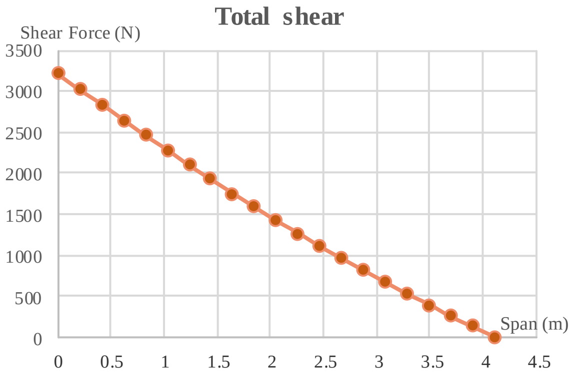

Fig. 10 Shear force along half wing span

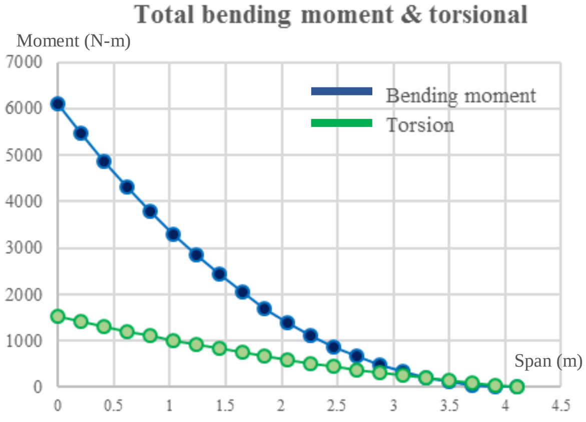

Fig. 11 Bending and torsion along half wing span

5. Wing Component Design

The wing components were arranged by the lay-out obtained from the company. There are eight ribs sketched on the drawing along the span. The dimension of each component was calculated from aircraft design theory by ultimate load acting on wing structure. All components were separately considered for computing the optimal size.

5.1 Front spar

The optimal size of front spar web was calculated by separating into two sections by station 2.118 meters (Fig. 13): closing to and far from the fuselage. The load acting at the first section must be higher than the second one. That means the web of the first section must be thicker to be capable to carry higher load and also being reinforced with stiffener. The farther section carries lower load, so the web thickness is thinner.

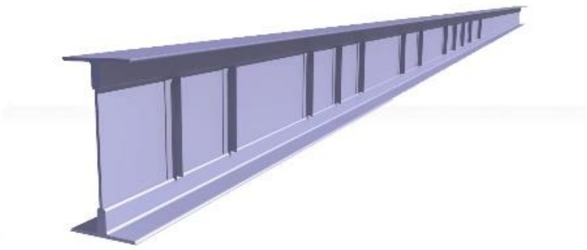

Fig. 12 Front spar assembly

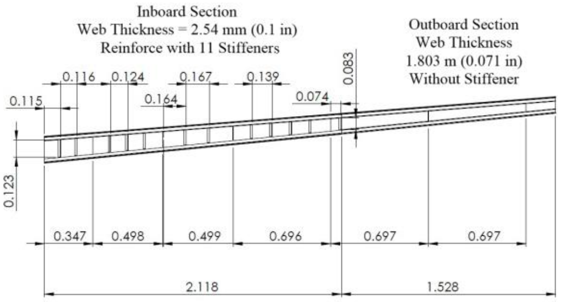

Fig. 13 Front spar dimensions

5.2 Rear spar

The dimension of rear spar can be determined by the same method as front spar. Since the forces acting on the rear spar is less than the front spar, it is the web that play important role to support loads and the flange could be ignored. In this case, the rear spar was designed to be a folded sheet metal forming of C-channel.

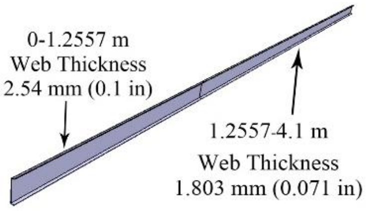

Fig. 14 Rear spar dimensions

5.3 Skin thickness

The minimum skin thickness that can carry shear flow is about 0.4 mm that is minimum aluminum sheet in the market. The minimum skin thickness that can withstand the ultimate load without excessive deflection for each section was calculated by written code in MATLAB program following in Fig. 7. The results of skin thickness at each station are described in Fig. 15 with the reinforcement by aluminum extrude beam.

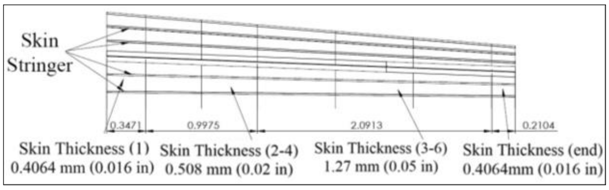

Fig. 15 Skin thickness

5.4 Rib sizing

Ribs were placed at eight stations throughout the span. That means the dimension of the rib at each station is an airfoil at those locations. The only dimension that can be designed is the thickness. Moreover, the most appropriate dimension in less weight comes from minimum thickness and lightening hole which is the diameter and number of holes. The ribs located near the wing tip carry lower loads than the wing root. Thus, it is possible to make a bigger hole to reduce weight of the rib at tip but there are some limitations from the airfoil size itself. This condition was obtained to the rib at station No. 7 and 8. Thickness and hole characteristic of all ribs designed to withstand torsion without failure and buckling including the suggestion of lightening hole (Table. 3). It shows that the performance of the drilled holes in weight reduction mostly is at the wing tip.

Table. 3 Rib thickness and lightening hole

Rib no.	Rib location	Web thick (mm)	Num. of hole	Hole pitch (m)	Hole dia. (m)	% Weight reduce
1	Front	2.032	1	0.45	0.06	4.1%
	Rear	2.032	1	0.38	0.078	7.5%
2	Front	2.032	1	0.43	0.08	7.8%
	Rear	2.032	1	0.37	0.051	3.4%
3	Front	1.8034	1	0.37	0.061	5.0%
	Rear	1.8034	1	0.35	0.033	1.6%
4	Front	1.8034	1	0.41	0.067	6.7%
	Rear	1.8034	1	0.33	0.064	6.8%
5	Front	1.4224	1	0.36	0.04	2.8%
	Rear	1.4224	1	0.3	0.033	2.2%
6	Front	1.27	2	0.17	0.056	12.8%
	Rear	1.27	1	0.27	0.078	15.2%
7	Front	1.27	3	0.1	0.055	22.3%
	Rear	1.27	2	0.12	0.078	37.8%
8	Front	0.4064	3	0.1	0.06	28.5%
	Rear	0.4064	3	0.08	0.053	28.9%

5.5 Wing assembly

The main components of the wing have been calculated by the method mentioned above and have been assembled together and drawing up into three-dimensional model (Figs. 16 – 17). The total weight of the main wing structure composed of front spar, rear spar, skin, ribs and stiffeners, is estimated at about 41.62 kg which is 59% of the acceptable weight of the company (70 kg). However, this estimation does not include the weight of joints such as rivets and fuel tank. The weight breakdown and dimension from the calculation of wing structure has been summarized in the Table. 4.

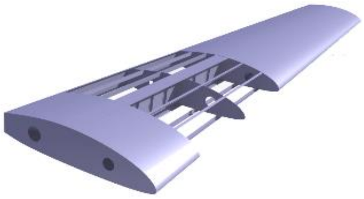

Fig. 16 3D wing assembly with wing skin

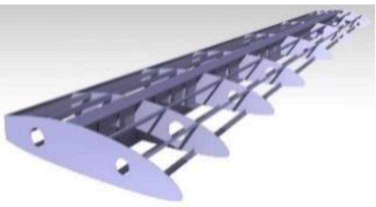

Fig. 17 3D wing assembly without skin

Table. 4 Wing structure weight breakdowns

Component			Area (m^2)	Thickness/ Length (m)	No.	Mass (kg)
Front spar (I-beam)		Web	0.41374	0.004064	1	4.72
			0.14877	0.003175	1	1.33
		Flange	0.00031	3.65994	4	12.69
		Stiffener	0.00003	0.1031925	12	0.12
Rear spar (C-channel)		Web	0.16379	0.00254	1	1.17
			0.26751	0.001803	1	1.36
Skin		1	0.61230	0.0004064	1	0.70
		2--3	1.63144	0.000508	1	2.33
		4--5--6	2.85992	0.00127	1	10.21
		7	0.24550	0.0004064	1	0.28
Stringer			0.00004	3.65834	8	3.61
Rib	1	Front	0.06591	0.002032	1	0.38
		Rear	0.05875	0.002032	1	0.34
	2	Front	0.05932	0.002032	1	0.34
		Rear	0.05754	0.002032	1	0.33
	3	Front	0.05536	0.0018034	1	0.28
		Rear	0.05227	0.0018034	1	0.26
	4	Front	0.04897	0.0018034	1	0.25
		Rear	0.04378	0.0018034	1	0.22
	5	Front	0.04427	0.0014224	1	0.18
		Rear	0.03764	0.0014224	1	0.15
	6	Front	0.03356	0.00127	1	0.12
		Rear	0.02658	0.00127	1	0.09
	7	Front	0.02352	0.00127	1	0.08
		Rear	0.01553	0.00127	1	0.06
	8	Front	0.02131	0.0004064	1	0.02
		Rear	0.01648	0.0004064	1	0.02
				Total mass (kg)		41.62

6. Conclusion

Dimension of each component of the wing structure is determined from the aircraft configuration described above. Major loads are applied on the front spar to find the optimal size of its upper and lower flange including the web. The other components such as rear spar, skin, rib thickness and stiffener are designed to have enough strength to support the predicted loads as prescribed by the aircraft regulation. The lightening holes on the ribs are suggested. The wing model is derived to predict weight within the preliminary aircraft design phase. The performance of the model will be studied in the near future for more detailed structural analysis.

7. Acknowledgement

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