Lightweight Design and Analysis of Four-Wing UAV Fuselage Structure Based on Topology Optimization

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Keywords: Four-Wing UAV, Fuselage Structure, Lightweight Design, Topological Optimization, Finite Element Analysis.

Abstract: The lightweight fuselage construction of unmanned aerial vehicles (UAVs), which are often utilized in the military, agricultural, and other sectors, is a crucial element in enhancing their durability. First, the fuselage structure of a small four-wing UAV for aerial photography is designed. Then, using the SolidWorks program to create the 3D model of the fuselage structure and the Inspire software to do the variable density topology optimization, the optimized model's mass is reduced by 51.5%. In the end, the static and dynamic properties of the model before and after optimization are compared after being static and dynamically analyzed using the ANSYS finite element analysis software. The results demonstrate that the optimized model's strength and stiffness are within the permissible stress range and that it does not exhibit resonance phenomena in a limited operating condition, proving the viability of optimization.

1 INTRODUCTION

Because of its advantages of low development cost, reusable, safe, and reliable, UAV has seen increased application in recent years in the military, aerospace, agricultural (Li Bo - Dong Xulei), and other areas. A composite UAV wing structure was created by Zhang Qingsong and colleagues employing the continuous topology optimization design approach under the SIMP method (Zhang Qingsong, 2023). The optimum volume is reduced by 35% and the fatigue life of the sensitive area is examined using the wing volume ratio as the limitation condition. The analysis's findings demonstrate that the improved wing structure satisfies the design specifications. By utilizing the variable density topology optimization approach and the OptiStruct structure optimization platform, Liu Wenbin et al. created the topology optimization model for the outer cylinder pillar of the UAV landing gear. The model's static properties were compared before and after optimization, and it was shown that the optimized model could cut weight by 20% while still maintaining design specifications for strength (Liu Wenbin, 2014).

By utilizing topology optimization technology, predecessors have made some advancements in the field of UAV lightweight and have provided a reference scheme for use in this field; however, the majority of research focuses on the structure of UAV landing gear and wings, and there are few studies on the optimization of the fuselage structure. This study optimizes the fuselage structure of a tiny four-wing UAV using the variable density topology optimization method, offering yet another reference approach for the development of lightweight UAVs.

2 FUSELAGE STRUCTURE DESIGN

2.1 Integrated Layout

The four-wing UAV's general fuselage structure is a cross-type arrangement, which is further separated into "ten" layout and "X" configuration (Imang Eko Saputro, 2019), as shown in Figure 1. The cross-over "X" layout method was chosen because it has been demonstrated to offer higher overall performance, a more robust structure, and greater flexibility (Zhong Jianwei, 2018).

The four-wing UAV's minimum wheelbase is a crucial factor in determining its total size. Following selection of the layout strategy, the wheelbase may be established in accordance with the UAV's intended use. The schematic layout of the UAV's wheelbase design is shown in Figure 2, where L is the frame's wheelbase, r_{max} is the rotor's maximum

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radius when the wheelbase is fixed, and r_p is the rotor's operational range. The four-wing UAV's design primarily focuses on achieving airborne shooting tasks; as a result, the weight requirement is low and a two-blade paddle rotor with a 200mm operating range is used.

$$L = 2\sqrt{2} \times r_{\max} \tag{1}$$

$$r_{\max} \geq 1.05 r_p \tag{2}$$

According to formula 1 and 2, the wheelbase is finally determined to be 600mm.

Combined with the working requirements and lightweight criteria of the four-wing UAV, ABS is selected as the material, and its material parameters are shown in Table 1.

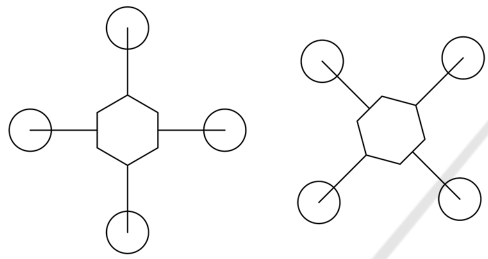


Figure 1: Placement scheme.

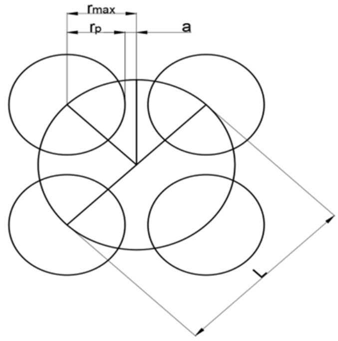


Figure 2: Design philosophy.

Table 1: ABS Material parameter.

Modulus of elasticity	**Poisson ratio**	**Density**	**Yield strength**
2000MPa	0.35	1060kg/m3	45MPa

According to the above parameters, the three-dimensional model was finally established by using SolidWorks 3D modeling software, as shown in Figure 3.

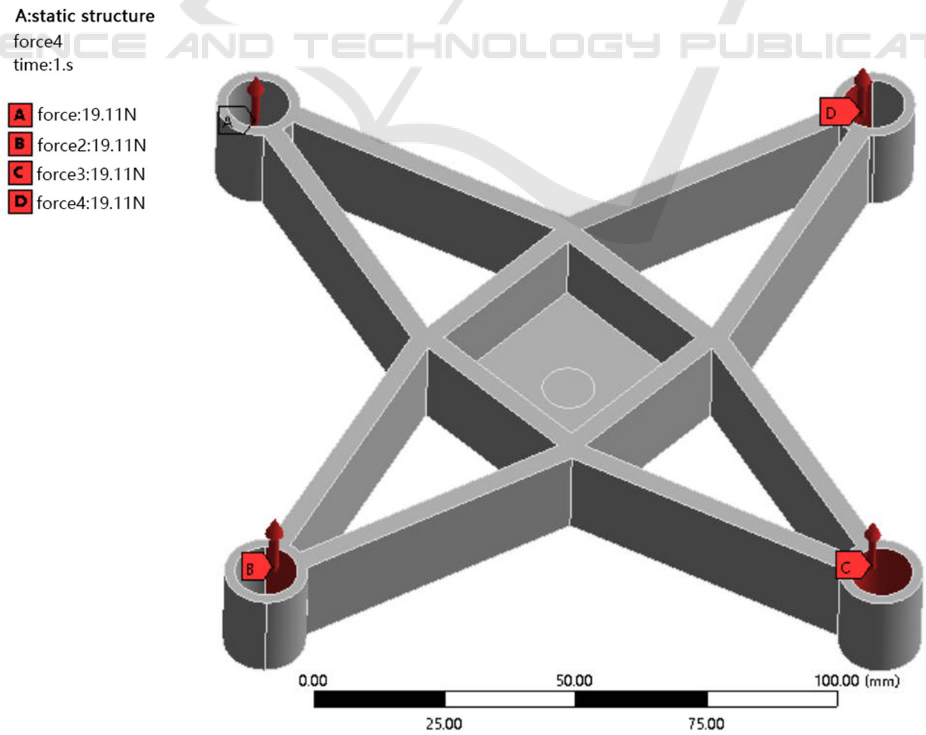


Figure 3: Fuselage 3D model.

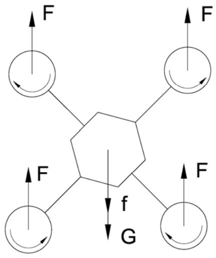


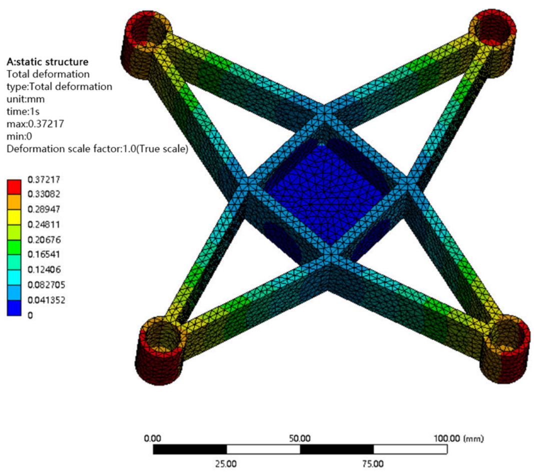
Figure 4: Vertical motion force.

2.2 Status Analysis

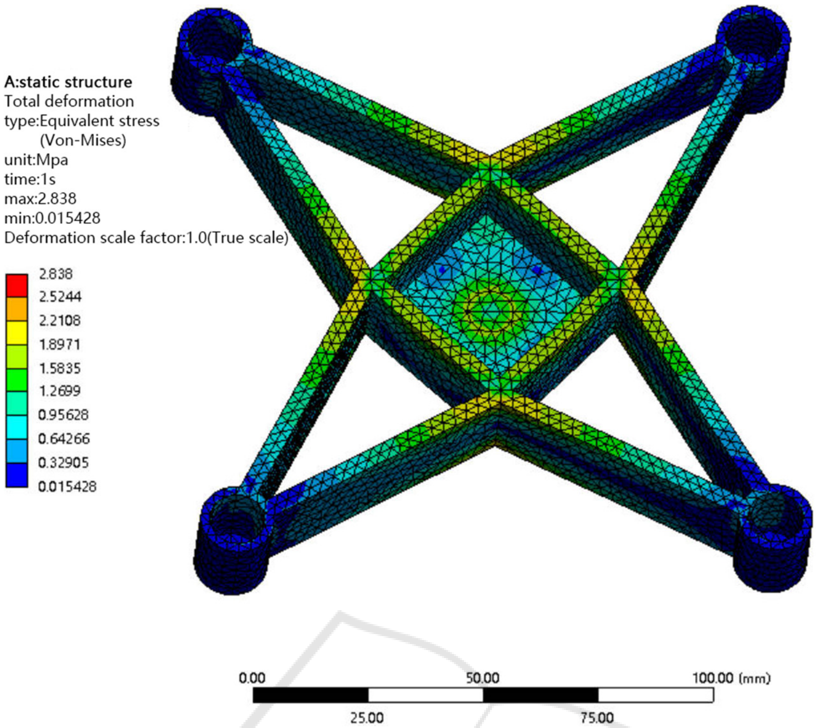
Four-wing UAVs often fly in a condition that involves vertical motion, pitch motion, roll motion, and yaw motion (Song Siqin, 2021). The focus of this research is vertical motion since it places the UAV in the most force on the fuselage. One diagonal rotor rotates clockwise and the second diagonal rotor revolves counterclockwise as the UAV flies upward. The UAV rises when the lift force produced by the whole rotor is higher than the weight of the aircraft. The UAV drops when the lift force produced is less than the weight of the aircraft. The drone hovers in the air when lift equals weight of the aircraft. It is not difficult to draw the conclusion that the spiral wing end perpendicular to the boom and the force of the UAV's own load are the principal forces acting on the fuselage of the four-winged UAV. The drone weighs 1.4 kg by itself and 2.5 kg when loaded. Figure 4 depicts the force situation, where F is the lift force, G is its own gravitational pull, and f is the load. Since 4F=G+f is an obvious conclusion, it follows that M_1=0.975kg is the weight that must be supported by a single cantilever. The load force that a single cantilever must resist during the vertical movement of the UAV is $2M_1$ according to the principle of 2 times thrust weight ratio, hence the traction force that the propeller must generate $F_1=2M_1g$=19.11N (gravitational acceleration g=9.8m/s).

The final three-dimensional model was created using SolidWorks 3D modeling software in accordance with the aforementioned criteria, as shown in Figure 3. In the ANSYS Static Structural Module, the constraint, load, and grid division are applied to the imported 3D model. The static characteristic cloud map is then produced. A vertical lift force of 19.11N was applied to the location where brushless motors were mounted throughout the fuselage, as illustrated in Figure 3, using the whole fuselage as the study object. In order to assure the accuracy of the results, inertial release is introduced to replace the boundary condition since every UAV structure is in a free state when in flight. By using the patch adaptation approach, the 23,592 mesh units and 41,766 mesh nodes of the tetrahedral mesh were identified. After analyzing the static properties, the maximum deformation and equivalent stress nephogram was produced, as shown in Figure 5.

The highest deformation of the fuselage structure occurs around the rotors, as shown in Figure 5(a), and the maximum displacement under difficult operating circumstances is 0.390mm. The four-winged UAV's flight and control are little impacted by this distortion. As noted in Figure 5 (b), the maximum equivalent stress of the fuselage structure is also present around the rotors and is 2.838 MPa, which still leaves a significant gap when compared to the ABS material's 45 MPa yield strength. As a result, there is still room for weight drop and the fuselage structure won't look to be failing from fatigue.



(a) Maximum deformation cloud image



(b) Equivalent stress cloud image

Figure 5: Pre-optimization statics.

2.3 Fuselage Modal Analysis Harmonious Response Analysis

During the actual flight, the four-wing UAV will experience periodic vibration brought on by the brushless motor of the power unit rotating (Ren Shuaiyang, 2021), and this vibration has the most influence on the four-wing UAV's flying process. In order to minimize resonance between the excitation source and the enhanced rotor folding mechanism, which would result in the failure of the UAV mechanical structure, the modal analysis of the fuselage structure and the harmonious response analysis may be used to understand its inherent frequency characteristics. In this step, the dynamic analysis of the fuselage model is performed using ANSYS software to guarantee the logic and dependability of the structural design.

The four-wing UAV's fuselage's chosen brushless motor can run at a maximum speed of 5500 r/min, hence the highest frequency at which it can operate without adversely impacting the fuselage's condition is 92 Hz. Table 3 displays the modal analysis of the UAV fuselage. The harmonic response analysis of the fuselage is conducted to produce the vertical motor direction displacement-frequency curve at various frequencies, as shown in Figure 6. This is predicated on the assumption that the vibration of the fuselage caused by the brushless motor changes in accordance with the simple harmonic law. Combining the aforementioned study, it is determined that the fuselage structure's first order natural frequency is 200.09Hz, which is significantly higher than the brushless motor's working frequency and can successfully prevent the development of resonance phenomena. Figure 6 shows that the four-wing UAV's displacement at its maximum operating frequency is similarly extremely modest, so it won't have an impact on the UAV's flight.

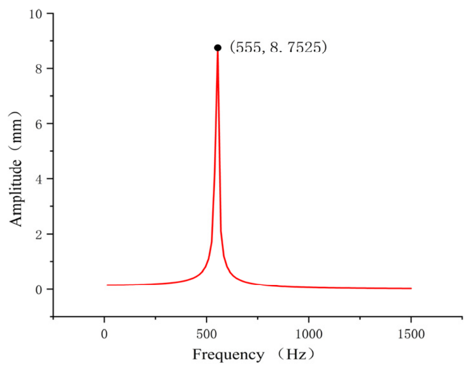


Figure 6: Amplitude diagram.

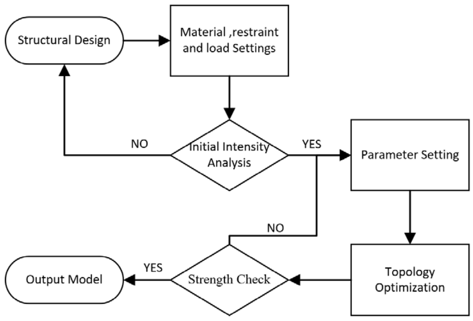


Figure 7: Topology optimization flow chart.

3 TOPOLOGY OPTIMIZATION DESIGN BY VARIABLE DENSITY METHOD

3.1 Topology Optimization Process

To increase the durability of four-wing UAVs, topology optimization aims to provide a lighter fuselage construction. Design engineers and designers can use the Inspire program as an early idea design tool (Carlo Ferro, 2016). The software makes sure that technology supports the development of designs that put a strong emphasis on functionality and producibility. It makes it simple and quick to develop and create conceptual product prototypes that are architecturally flawless.

The program Inspire's Optistruct solver is utilized in this work to optimize the fuselage model. Figure 7 depicts the whole optimization procedure.

3.2 Optimized Result

The 3D model was imported into the Inspire software with the four-wing UAV's fuselage structure as the optimization object. A reasonable optimization area was then designed in accordance with the design requirements and experience, removing as many redundant materials from the model as possible to produce the desired effect. The final optimized fuselage structural model is depicted in Figure 8 with the objective of maximum rigidity.

Before optimization, the fuselage weighed 66.158 grams; after optimization, it weighed 34.08 grams. Topology optimization helped to lower the weight by 51.5%, which increased the four-wing UAV's endurance.

4 PERFORMANCE VERIFICATION

4.1 Static Performance Comparison

The topologically optimized three-dimensional model is imported into the ANSYS Static Structural module for static analysis once again to see whether the model's strength and stiffness criteria for the four-wing UAV are met. Figure 9 displays the deformation cloud picture and corresponding stress cloud image.

Table 2 displays the static analysis outcomes for the fuselage structure both before and after optimization. The maximum deformation and stress after optimization are 1.127mm and 11.793MPa, respectively, and the rise is within the controlled range, satisfying the design criteria of the four-wing UAV statically.

Table 2: Comparison of results of static analysis.

	Max Deformation/mm	Maximum Stress/MPa	Quality/g
Primitive	0.390	2.838	66.158
Optimize	1.127	11.793	32.078

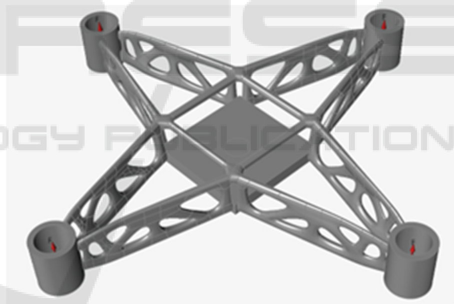
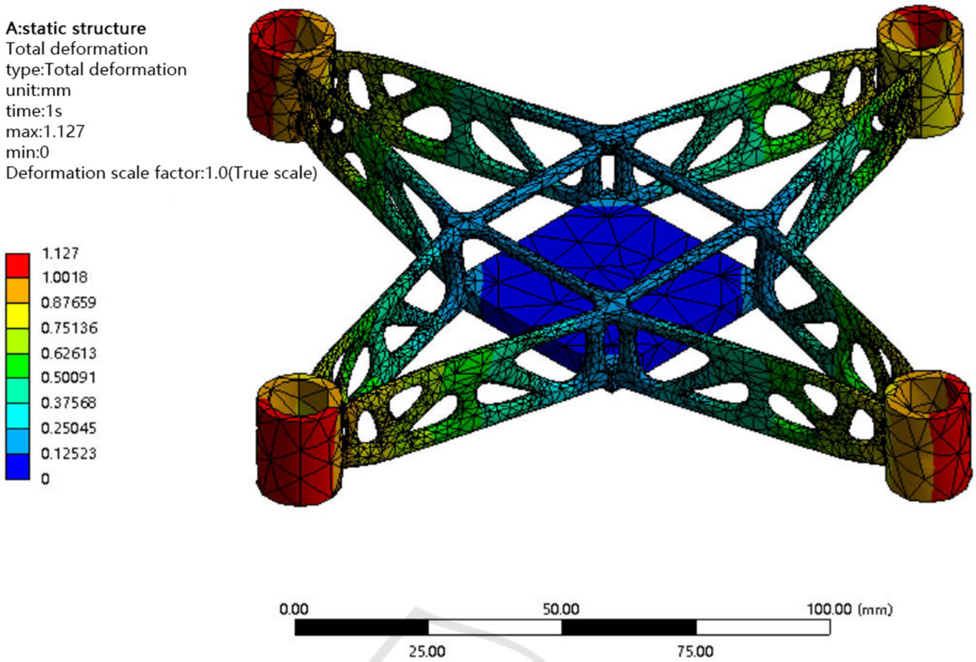


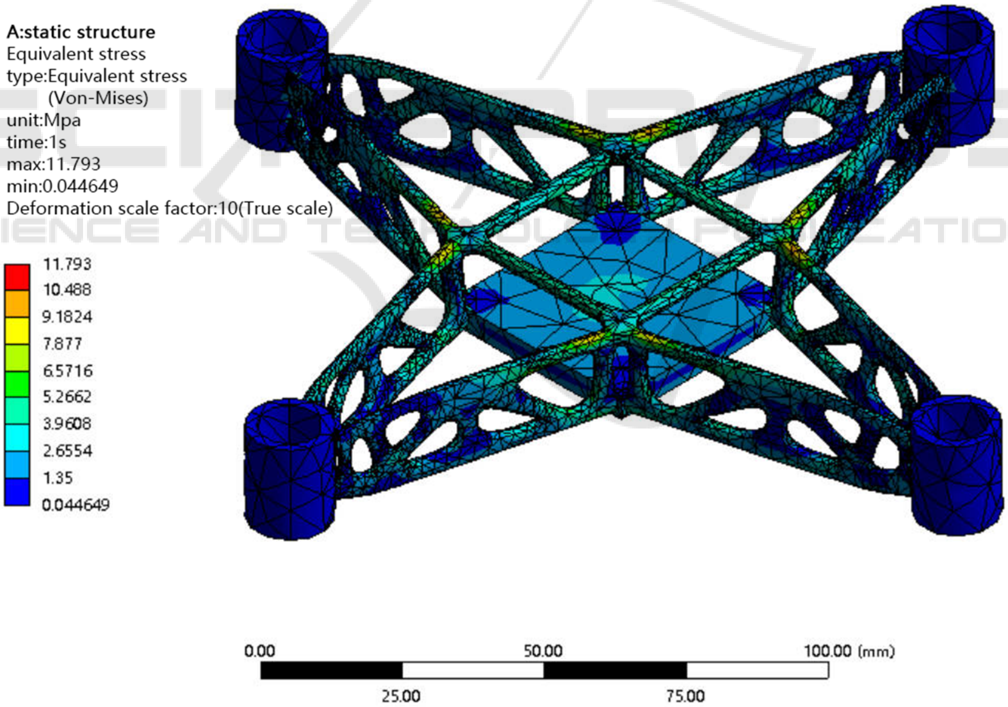
Figure 8 Optimized model.

4.2 Dynamic Performance Comparison

The dynamic properties of the optimized model can be determined through modal analysis of the optimized fuselage structure and harmonious response analysis. The analysis can then be used to determine whether the altered size and shape following topology optimization has an effect on the strength and stiffness of the UAV during normal operation. The harmonic response curve of the improved model is shown in Figure 10. The optimized fuselage will exhibit reasonably noticeable vibration at 165Hz and 285Hz, as can be shown in the picture, however these two frequencies are far higher than the maximum operating frequency of 92Hz.



(a) Maximum deformation cloud image



(b) Equivalent stress cloud image

Figure 9 Static analysis results of optimized fuselage mechanism.

The second frequency, which lowers by 45.86Hz after optimization, has the largest change out of the first six frequencies, as demonstrated in Table 3's findings of the modal study performed before and after the optimization of the fuselage structure. The optimal frequency, which may successfully prevent the occurrence of resonance phenomena, is nevertheless much higher than the UAV's maximum operating frequency of 92Hz. The study shown above demonstrates that the UAV fuselage can also fully assure that the structural dynamic characteristics after topology optimization fulfill the design criteria, therefore this topology optimization technique is applicable.

Table 3: Comparison of modal analysis results.

Frequency/Hz	Primitive	Optimize
first-stage	200.90	156.66
Second stage	202.59	156.73
Third stage	239.64	221.90
Fourth stage	489.72	469.32
Fifth stage	550.15	530.26
Sixth stage	646.43	630.73

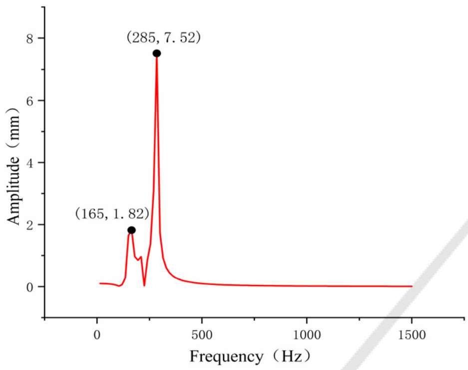


Figure 10: Amplitude diagram.

5 CONCLUSION

1)Design and analysis are done on the fuselage of a tiny, four-wing UAV that is primarily employed for high-altitude shooting. The "X" layout concept is used, and ABS is chosen as the material, taking into account features like dependable construction, fluid movement, and lightweight.

2)SolidWorks was used to model the fuselage structure in three dimensions, and the Inspire software's Optistruct structure optimization platform was used to perform topological optimization on the original fuselage mechanism. The weight of the fuselage construction was ultimately decreased by 51.5% with the purpose of maximum rigidity, which is significant for enhancing the UAV's endurance.

3)The static and dynamic properties of the fuselage structure before and after topology optimization were examined using ANSYS finite element software. The static and dynamic properties of the optimized model satisfied the design criteria under the actual operating circumstances when the static and dynamic parameters of the model were compared between before and after optimization. This optimization plan offers another theoretical point of reference for structural lightweight design.

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