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Article

Static and Dynamic Performance Evaluation of Three-Wheeled Vehicle Frames Based on Aluminum and High-Grade Steel Using Finite Element Simulation

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Abstract

The increasing demand for energy efficiency and lightweight transportation has encouraged the development of three-wheeled vehicles with optimized structural frames. This study evaluates the static and dynamic performance of three-wheeled vehicle frames using three high-performance materials: Aluminum 7075-T6, S690 steel, and ASTM A572 HSLA 60 steel. Finite Element Analysis (FEA) was conducted with Altair HyperWorks to analyze stress distribution, deformation, safety factor, and natural frequency response. Static analysis results indicate that all materials are structurally safe, with S690 steel showing the highest stiffness and safety factor. At the same time, Aluminum 7075-T6 provides the greatest strength-to-weight efficiency despite higher deformation. ASTM A572 HSLA 60 offers moderate performance as a cost-effective alternative. Modal analysis reveals similar natural frequency ranges (1.5–3.2 Hz) across all materials, indicating that geometry influences dynamic behavior more than material properties. The findings highlight the trade-off between strength, stiffness, and weight, suggesting Aluminum 7075-T6 as the optimal choice for lightweight and energy-efficient applications. At the same time, S690 steel is preferable for heavy-duty requirements. Overall, this research emphasizes a holistic approach in material selection for three-wheeled vehicle frames to balance mechanical strength, vibration characteristics, and energy efficiency.

Keywords: Three-wheeled vehicle; Finite element analysis; Static analysis; Dynamic analysis

INTRODUCTION

Rising fuel prices and demands for energy efficiency are driving the development of lightweight vehicles while maintaining adequate structural strength. Three-wheeled vehicles are increasingly being considered as logistics transportation solutions in urban areas with limited road access [1], [2], [3], [4]. The vehicle frame is vital, accounting for approximately 30% of the total mass and serving as the primary load-bearing element. Therefore, the choice of frame material plays a crucial role in determining the vehicle's structural performance and efficiency [5], [6], [7], [8], [9], [10].

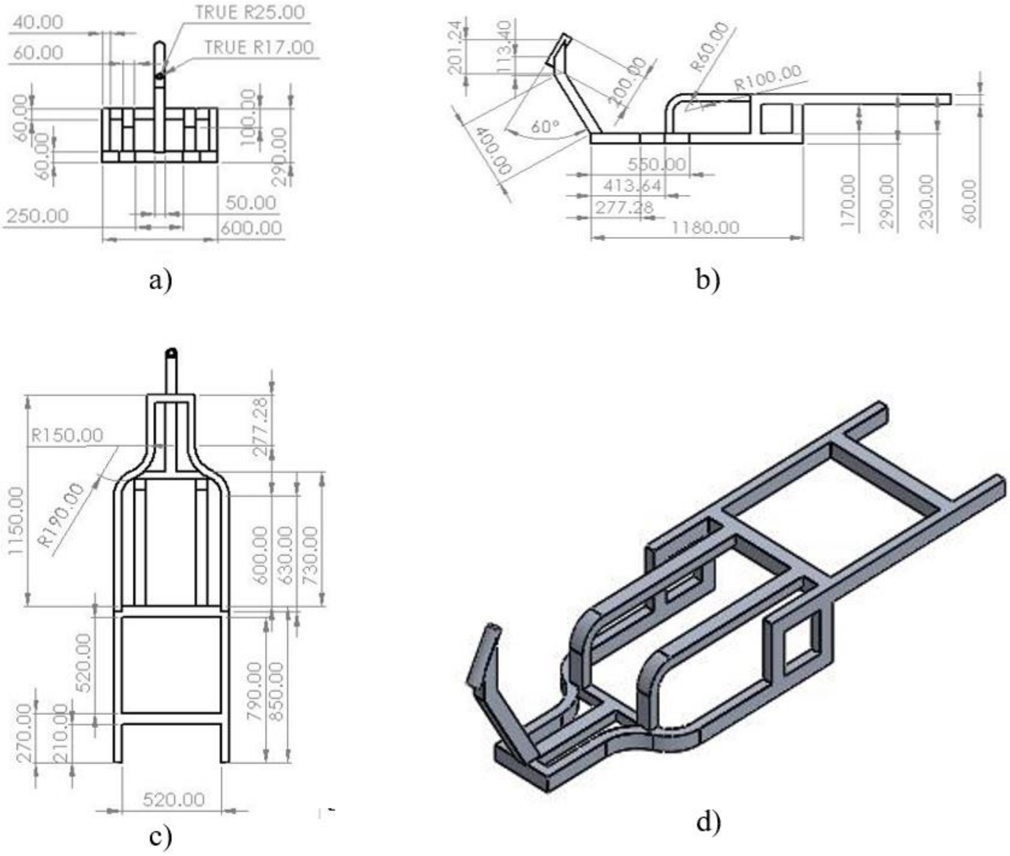
Previous studies have used finite element analysis (FEA) to analyze vehicle frame performance. Rahardian et al. [11] compared aluminum and steel frames in an electric tricycle and found that although aluminum is lighter, its strength is relatively lower than that of steel. However, with certain thickness settings, aluminum can approach steel performance. Pratama et al. [12] reported the results of an analysis of three electric bicycle frame designs for people with disabilities using ANSYS, where the best design showed a maximum Von Mises stress of 62.67 MPa, a maximum deformation of 0.3288 mm, and a safety factor of 6.62 when subjected to a total load of 90 kg. Another study on tricycle chassis in India found Von Mises stress of up to 294.69 MPa with deformation reaching 4.488 mm, demonstrating the importance of design evaluation to avoid exceeding the material's strength limits [13]. A different study on electric tricycle chassis with varying frame thicknesses showed that at a thickness of 2.4 mm (weight 29.6 kg), the maximum stress was recorded at 75.8 MPa with a deformation of 2.567 mm and a safety factor of 3.5. However, when the frame thickness was reduced to 1.6 mm (weight 20.3 kg), the stress increased drastically to 180.9 MPa, the deformation increased to 4,190 mm, and the safety factor decreased significantly, indicating the limitations of thin materials in bearing loads [14].

In addition to static analysis, several studies also emphasize the importance of dynamic analysis [15]. Research on aluminum space frames has shown that modal parameters can accurately estimate static stiffness, making dynamic analysis crucial for detecting potential resonance in lightweight vehicle structures [16], [17]. Recent studies on simulated crash tests using 7075-T6 aluminum have also confirmed the superior strength-to-weight ratio of this material, making it worthy of consideration as an alternative to modern vehicle frames [18], [19], [20].

Although numerous studies have been conducted, most still compare conventional steel with standard aluminum and do not investigate high-performance materials that could optimize strength, stiffness, and mass efficiency. These limitations reveal a research gap: the static and dynamic performance of three-wheeled vehicle frames made from advanced materials has not been comprehensively evaluated. This study aims to address this gap by evaluating the frame performance using three selected materials, namely Aluminum 7075-T6, S690 Steel, and ASTM A572 HSLA 60 Steel, through a finite element analysis approach using Altair HyperWorks software. The focus of the analysis includes stress distribution, deformation, natural frequency, and safety factors, so that the results of the study are expected to be able to provide optimal material recommendations for the development of light, strong, and efficient three-wheeled vehicle frames, while also extending previous research that has mainly compared conventional aluminum and mild steel [11], [12], [13]. In contrast, the present study emphasizes evaluating high-grade materials such as Aluminum 7075-T6 and S690 Steel, which have rarely been analyzed in three-wheeled vehicle applications despite their superior mechanical performance [18], [19].

METHODS

This research was conducted through a finite element analysis (FEA) approach using Altair HyperWorks software to evaluate a three-wheeled vehicle frame's static and dynamic performance. A three-dimensional model of the frame was created using SolidWorks software, with dimensions adjusted to the standard design of a light commercial three-wheeled vehicle. The modeled frame includes the main load-bearing components, including longitudinal and transverse members, and structural joints, resulting in a geometric representation that closely approximates the actual conditions. The geometry is presented in Figure 1.



a)

b)

c)

d)

Figure 1. Frame geometry, a) Front view, b) side view, c) bottom view, d) Isometric view

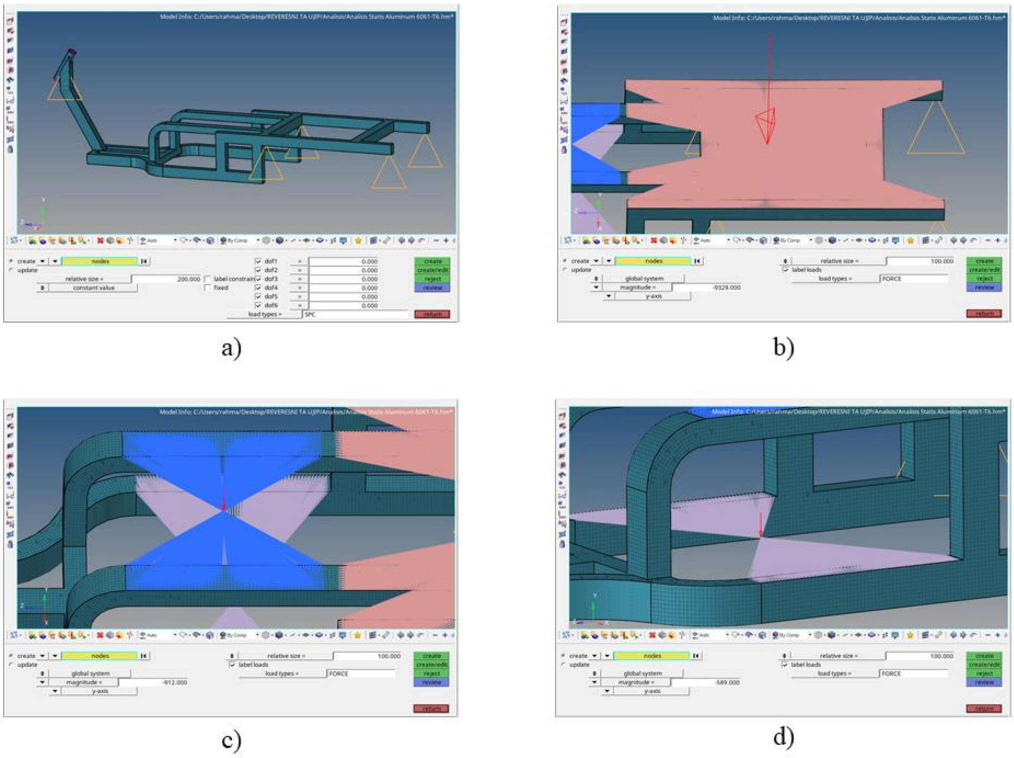
The meshing process employed tetrahedral solid elements because they can conform to complex geometries. To ensure the reliability of the results, a mesh convergence study was conducted with three variations of average element sizes, namely 12 mm (coarse), 8 mm (medium), and 5 mm (fine). The observed parameters were the maximum Von Mises stress and total deformation under static loading conditions in the form of the weight of the driver, engine, and cargo. The calculation results are shown in Table 1.

Table 1. Mesh Convergence Study Results

Element Size (mm)	Number of Elements	Von Mises stress (MPa)	Stress Error (%)	Deformation (mm)	Deformation Error (%)
12 (rough)	58,420	118.2	1.63	3.54	2.02
8 (medium)	132,760	116.8	0.43	3.49	0.58
5 (fine)	298,500	116.3	0.00	3.47	0.00

Based on the study results, the differences between the medium mesh (8 mm) and the fine mesh (5 mm) were <1% for both stress and deformation. These small discrepancies indicate that the 8 mm mesh is mesh-converged (mesh-independent) and was selected for all simulations to balance accuracy and computational efficiency.

Boundary conditions are established by holding the front and rear wheel mountings as the main supports of the vehicle. Load placement is carried out in a distributed manner according to points that represent the vehicle's actual condition. A rider load of 90 kg is applied to the seat mounting area, an engine load of 70 kg is placed at the engine mounting position in the middle of the frame, and a cargo load of 150 kg is given to the rear of the frame, which functions as a cargo space. All loads are converted into static forces using a gravitational acceleration of 9.81 m/s^2. This load distribution represents the real operating conditions of a three-wheeled vehicle, where loading co-occurs at several critical points. The location of the load positions is defined in Figure 2.



Model Info: C:/Users/rahma/Desktop/REVERESNI TA UJP/Analisis/Analisis Statis Aluminum 6061-T6.hm*

a)
create: nodes
relative size = 200.000
☐ label constrain
☐ fixed
constant value
☑ dof1 = 0.000
☑ dof2 = 0.000
☑ dof3 = 0.000
☑ dof4 = 0.000
☑ dof5 = 0.000
☑ dof6 = 0.000
load types = SPC

b)
create: nodes
global system
magnitude = -9329.000
y-axis
relative size = 100.000
☑ label loads
load types = FORCE

c)
create: nodes
global system
magnitude = -912.000
y-axis
relative size = 100.000
☑ label loads
load types = FORCE

d)
create: nodes
global system
magnitude = -589.000
y-axis
relative size = 100.000
☑ label loads
load types = FORCE

Figure 2. Location of boundary conditions, a) fixed support, b) location of cargo load, c) location of driver load, d) location of engine load

The materials used in this study focused on three leading candidates, namely Aluminum 7075-T6, S690 Steel, and ASTM A572 HSLA 60 Steel. These three materials were chosen because they have high mechanical strength with a superior strength-to-weight ratio. Data on the mechanical properties of the materials, including elastic modulus, Poisson's ratio, yield stress, and density, were input based on standard literature and material databases available in the software. Table 2 shows the material properties used.

Table 2. Material properties

Parameter	Aluminum 7075-T6	S690 Steel	ASTM A572 HSLA 60
Modulus of Elasticity (GPa)	71.7	210	200
Poisson's ratio	0.33	0.30	0.29
Yield Strength (MPa)	503	690	415
Ultimate Tensile Strength (MPa)	572	770	550
Density (g/cm³)	2.81	7.85	7.85

The analysis consisted of two main stages. First, a linear static analysis was used to obtain the Von Mises stress distribution and total deformation and calculate the safety factor. Second, a modal analysis evaluated the frame's dynamic response by calculating the first ten modes' natural frequencies and mode shapes. This evaluation aimed to ensure that the frame's natural frequencies were not within a range that would cause resonance with the engine's excitation frequency or road conditions.

This research phase is designed to provide a comprehensive overview of the structural performance of three-wheeled vehicle frames. Model validity is ensured through mesh convergence, realistic loading, and methodological comparison with previous studies. Therefore, the results can be a basis for selecting optimal materials for designing lightweight and strong three-wheeled vehicle frames.

RESULT AND DISCUSSION

Numerical analysis using the finite element method has evaluated the static and dynamic performance of three-wheeled vehicle frames with three selected materials: Aluminum 7075-T6, S690 Steel, and ASTM A572 HSLA 60 Steel. The simulation results are presented as Von Mises stress distribution, total deformation, safety factor, and natural frequencies from modal analysis. The data are compared to identify materials that can provide the optimal combination of strength, stiffness, and weight efficiency. This study presents the results in two main parts, namely static analysis and dynamic analysis, which are then discussed to assess the technical implications of selecting three-wheeled vehicle frame materials.

Static Analysis

Static analysis was conducted to evaluate the structural behavior of a three-wheeled vehicle frame when subjected to a combined load of the driver, engine, and cargo. The main focus of this analysis was to obtain the Von Mises stress distribution, total deformation, and safety factor of each material used. Von Mises stress was chosen as the main parameter because it represents the combined stress conditions in structural elements. At the same time, total deformation is used to assess the frame stiffness against static loads. The safety factor is calculated by comparing the yield stress value of the material to the working stress that occurs, thus providing an overview of whether the frame structure is still in a safe condition.

The load combination applied to the model consists of a 90 kg rider load placed on the seat base, a 70 kg engine load on the center of the frame, and a 150 kg cargo load on the frame's rear. All loads are converted into static forces with a gravitational acceleration of 9.81 m/s^2, thus representing the actual operating conditions of the vehicle. The static analysis results compare the strength and stiffness between materials and identify stress concentrations that could become critical points in the frame. Thus, this evaluation provides an initial basis for determining the most suitable material to achieve the optimal combination of strength, stiffness, and weight efficiency in designing a three-wheeled vehicle frame.

Table 3. Static Analysis Results of Three-Wheeled Vehicle Frames

Material	Maximum Von Mises Stress (MPa)	Total deformation (mm)	Factor of Safety
Aluminum 7075-T6	116	3.47	4.39
S690 Steel	115	1.22	5.94
ASTM A572 HSLA 60	116	1.85	4.05

The Von Mises stress distribution shows the highest stress concentration in the engine mounting area and longitudinal bar joints. The three materials' relatively similar maximum stress values, around 115–116 MPa, indicate that frame geometry factors are more dominant in determining stress distribution than material variations. The main difference lies in the total deformation, where Aluminum 7075-T6 experienced the largest deformation of 3.47 mm, S690 Steel experienced only 1.22 mm, and ASTM A572 HSLA 60 was in between with 1.85 mm. This deformation pattern is consistent with the differences in the elastic modulus of each material, where steel has a higher stiffness than aluminum.

All materials have values above one regarding the safety factor, indicating that the frame is still safe. S690 steel provides the highest safety factor at 5.94, which confirms its superior strength. Aluminum 7075-T6, although showing greater deformation, still has a high safety factor of 4.39, with the advantage of being lighter. ASTM A572 HSLA 60 balances deformation and safety factors, making it a viable alternative, although not superior to the other two materials.

Dynamic Analysis

Dynamic analysis was conducted to evaluate the natural vibration response of the three-wheeled vehicle frame to external excitation. The first ten vibration modes were successfully identified, with the first six modes showing rigid body motion characterized by rigid translational or rotational movements without significant elastic deformation. Hence, their frequencies are very small, approaching zero. From the 7th to the 10th mode, the frame shows elastic body motion characterized by bending and torsional deformation in several parts of the structure. A summary of the natural frequency results for the three selected materials is shown in Table 4.

Table 4. Natural frequency results of the three materials

Mode	Aluminum 7075-T6	S690 Steel	ASTM A572 HSLA 60
1	6.01E-05	7,897E-05	6.12E-05
2	7.10E-05	8.09E-05	6.21E-05
3	7.53E-05	8.68E-05	6.60E-05
4	7.70E-05	9.01E-05	6.77E-05

5	8.05E-05	9.08E-05	6.96E-05
6	8.58E-05	9.43E-05	7.66E-05
7	1.49E+00	1.48E+00	1.46E+00
8	1.66E+00	1.66E+00	1.62E+00
9	2.91E+00	2.90E+00	2.84E+00
10	3.21E+00	3.21E+00	3.14E+00

Based on Table 4, it can be seen that the natural frequency starts to be significant at the 7th mode with a value of around 1.46–1.49 Hz, then increases to reach 3.14–3.21 Hz at the 10th mode. The difference between materials is very small, with Aluminum 7075-T6 and S690 Steel having almost identical values, while ASTM A572 HSLA 60 is slightly lower. These results indicate that the dynamic properties of the frame are more influenced by geometry and boundary conditions than by the material's mechanical properties.

The implication is that using lightweight materials such as Aluminum 7075-T6 does not pose an additional risk of resonance compared to using high-strength steel. However, the natural frequency in the range of 1.5–3.2 Hz requires attention because it can potentially interact with the excitation frequency of the engine or bumpy road conditions. If the values are close, then additional strategies such as stiffness modification, mass redistribution, or the application of vibration dampers need to be considered to avoid resonance. Because the dynamic response between materials is relatively similar, the material selection is more determined by the combination of strength, stiffness, and weight efficiency factors.

Discussion

The static analysis results show that all tested materials, namely Aluminum 7075-T6, S690 Steel, and ASTM A572 HSLA 60, have a safety factor above one, so they can be categorized as safe for use as a three-wheeled vehicle frame. S690 Steel exhibits the highest strength and stiffness, as indicated by the smallest deformation (1.22 mm) and a safety factor of 5.94. Aluminum 7075-T6 displays the largest deformation of 3.47 mm with a safety factor of 4.39. However, its advantage lies in its low density, which can reduce the total weight of the frame significantly. ASTM A572 HSLA 60 is in the middle position, with adequate strength and stiffness and a safety factor of 4.05. These results confirm the trade-off between mechanical strength and weight efficiency, a major issue in modern vehicle design.

On the dynamic side, the modal analysis results show that the three materials have almost identical natural vibration responses, with the first elastic frequency appearing at around 1.5 Hz and the highest frequency in the 10th mode in the range of 3.14–3.21 Hz. These results indicate that the dynamic properties of the frame are more influenced by geometry and boundary conditions than material variations. Therefore, material selection does not have major implications for the potential for resonance, as all materials show similar trends. The main factor that needs to be considered is the compatibility of the natural frequencies with the excitation spectrum of the machine and road, so that design modifications or the addition of dampers are important steps if there is a close value. The calculation of the strength-to-weight ratio (yield strength to density) is performed as a quantitative indicator of material efficiency to strengthen the analysis.

Table 5. Strength-to-Weight Ratio (Yield Strength / Density)

Material	Yield Strength (MPa)	Density (g/cm^3)	Strength-to-Weight ($MPa \cdot cm^3/g$)
Aluminum 7075-T6	503	2.81	179.0
S690 Steel	690	7.85	87.9
ASTM A572 HSLA 60	415	7.85	52.9

The results in Table 5 show that Aluminum 7075-T6 has the highest strength-to-weight ratio, which is 179 $MPa \cdot cm^3/g$, almost double that of S690 Steel (87.9 $MPa \cdot cm^3/g$) and more than three times that of ASTM A572 HSLA 60 (52.9 $MPa \cdot cm^3/g$). This fact confirms that for each unit mass, Aluminum 7075-T6 can withstand much greater loads than steel, making it very advantageous in the design of lightweight and energy-efficient vehicles. However, the lower elastic modulus of aluminum still results in greater deformation, so its selection must be adjusted to the application needs.

Overall, the integration of static, dynamic, and strength-to-weight ratio results confirms that material selection should be based on the application's specific needs. For commercial tricycles that prioritize energy efficiency and maneuverability, Aluminum 7075-T6 is a more appropriate choice. Conversely, if the main priority is heavy load carrying capacity and a high safety margin, S690 Steel is more recommended. ASTM A572 HSLA 60 can be considered if cost is a primary concern, although its performance is not as optimal as the other two materials. In practical terms, these findings directly affect the transportation sector, particularly in developing urban logistics tricycles and lightweight delivery vehicles where maneuverability and energy efficiency are critical [3], [4]. Aluminum 7075-T6 can be prioritized for applications that demand reduced weight and enhanced fuel economy, whereas S690 Steel is more suitable for heavy-duty operations requiring high load-bearing capacity and structural reliability [5], [6].

CONCLUSION

Numerical analysis based on the finite element method on a three-wheeled vehicle frame with three selected materials, namely Aluminum 7075-

T6, S690 Steel, and ASTM A572 HSLA 60, produced several important findings. First, all materials have a safety factor above one so that it can be ensured safe for use in supporting the combined load of the rider, engine, and cargo. S690 Steel proved superior in strength and stiffness, indicated by the smallest deformation and the highest safety factor. Aluminum 7075-T6, although showing greater deformation, still has an adequate safety factor and a significant advantage in low density. ASTM A572 HSLA 60 is in a compromise position with fairly good mechanical performance, but not as superior as the other two materials.

Second, the dynamic analysis results show that the three materials have nearly identical natural frequency responses, with the principal elastic frequency values in the 1.5–3.2 Hz range. This finding suggests that the dynamic properties of the frame are more influenced by geometry and boundary conditions than by material variations. Therefore, material selection does not significantly impact the resonance risk, and the decision is driven more by strength, stiffness, and weight considerations.

Third, strength-to-weight ratio calculations confirm that Aluminum 7075-T6 has the highest strength-to-mass efficiency, which is 179 MPa·cm^3/g, far exceeding S690 Steel (87.9 MPa·cm^3/g) and ASTM A572 HSLA 60 (52.9 MPa·cm^3/g). Accordingly, makes Aluminum 7075-T6 the most suitable candidate for three-wheeled vehicle applications emphasizing energy efficiency and weight reduction. Conversely, S690 Steel is more suitable for applications that require high load-bearing capacity with maximum safety margin, while ASTM A572 HSLA 60 can be considered when cost is a top priority.

Overall, the results of this study emphasize the importance of a holistic approach in selecting three-wheeled vehicle frame materials, where aspects of strength, stiffness, weight, vibration dynamics, and energy efficiency must be considered simultaneously to produce an optimal design. Nevertheless, this study is limited to finite element simulations and does not yet incorporate experimental validation. Future research should therefore include prototype fabrication, fatigue testing, and crash analysis to verify the numerical predictions and enhance the robustness of the design framework [16], [18], [19].

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