Numerical impact analysis of a suborbital module for transporting CubeSat

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Abstract
The NASA's suborbital balloon program allows scientific experiments in near-space using gondolas for payload transportation. During descent and landing, these structures may experience high loads, especially under parachute failure conditions, which can cause damage to the structure and onboard equipment. This work presents a numerical structural analysis of a suborbital gondola for CubeSat transportation using the Finite Element Method. Three aluminum structural configurations were evaluated under different impact scenarios and fall velocities. The results showed that structural behaviour depends on the impact orientation. Of the evaluated configurations, the extruded-profile design showed the most stable response under different impact conditions, making it a suitable option for future near-space missions.

Introduction
Space exploration has promoted the development of technologies focused on the study of near-space environments. As part of these suborbital programs, such as those developed by NASA, stratospheric balloons are used to perform scientific experiments under conditions similar to space [1]. Experimental modules and instrumentation systems are integrated into high altitude balloon platforms. During the missions, these structures are exposed to different mechanical conditions from launch to the recovery stage [2]. Besides, one of the main challenges occurs during descent and landing. It been reported that even with the use of parachutes, the impact against the ground can cause structural damage and affect the integrity of the internal components, leading to data loss and higher operation costs [2].
In this work, the structural behaviour of a high-altitude balloon platform is analyzed through numerical simulations under different impact conditions and landing orientations, with the objective of optimizing a structural configuration that increases the protection of internal components without significantly increasing the weight.

Statement of the Problem
Due to various atmospheric factors, both the recovery trajectory and the dynamic behaviour of high-altitude balloon payload are inherently unpredictable. While the parachute reduces descent velocity, high-impact ground landings can still cause significant structural failure. Depending on the landing orientation and impact zone, internal components damage, malfunction, and experimental data loss can occur. Some proposed solutions, including damping systems, have been tested. However, these alternatives increase the mass and volume of the platform, reducing the available space for payloads [3]. Therefore, there is a need to develop structural configurations capable of mitigating impact effects without significantly increasing the weigh. A numerical evaluation of a structural configuration under landing and impact orientation conditions is presented.

Material and methods
The methodology used in this study is presented in Fig. 1. Three structural configurations of a suborbital platform were modeled using computational assisted design (see Fig. 2).
For all designs, the same dimensions, mass, and internal component distribution were maintained. The first model proposes a plate-based structure (Fig. 2a), whereas the second structure utilizes extruded profiles in the structural configuration (Fig. 2b). The final configuration employs an L-profile (Fig. 2c).

Fig. 1. Methodology used for the structural evaluation of the suborbital platform

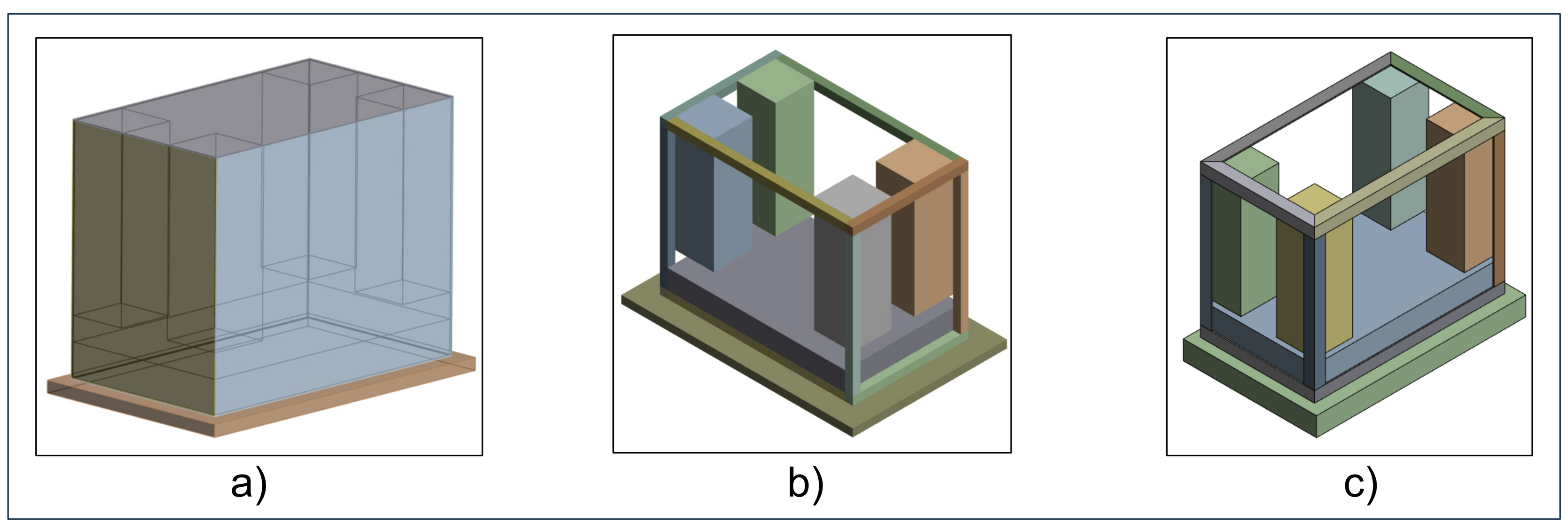


Fig. 2. CAD designs; a) Plate-based structure, b) Extruded profile structure, c) L-profile structure

The models were defined using 6061-T6 aluminum as the main structural material. The platform was designed to accommodate four CubeSat modules and a battery system.
The models were evaluated through structural simulations using the Finite Element Method (FEM) in ANSYS®. A modal analysis was performed to determine the natural frequencies of each design and to evaluate their dynamic behaviour during the mission.
Finally, an impact analysis was performed for various landing orientations, including base, edge, and corner impacts (Fig. 3). Two velocities were analyzed, 11.94 m/s, representing a nominal parachute-assisted condition, and 18 m/s, representing a critical scenario resulting from parachute failure.

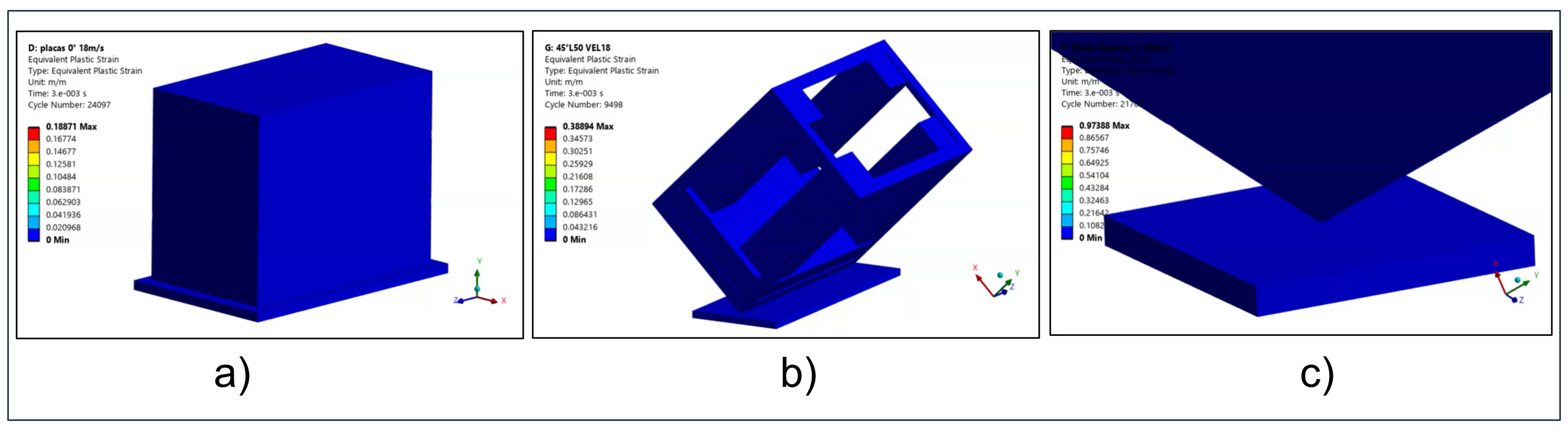


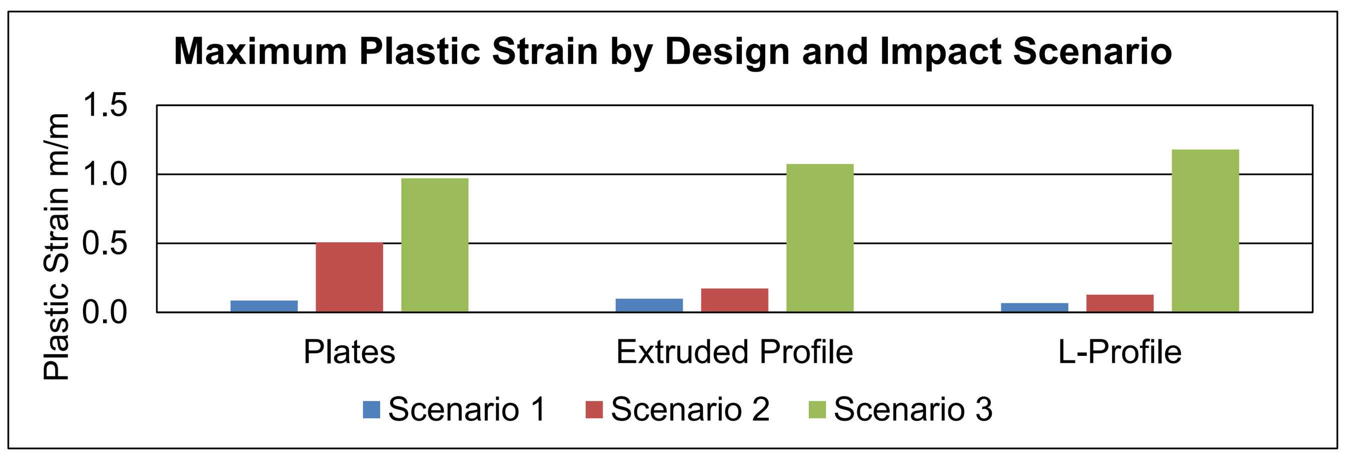
Fig. 3. Impact Scenarios, a) base, b) edge, c) corner

Results
Modal Analysis
Modal analysis was performed for each structural configuration to identify natural frequencies and mode shapes. The results are summarized in Table 1. From the results, it was noted that the first design presented the highest natural frequency indicating greater stiffness, while designs two and three showed a flexible and uniform structural behaviour.

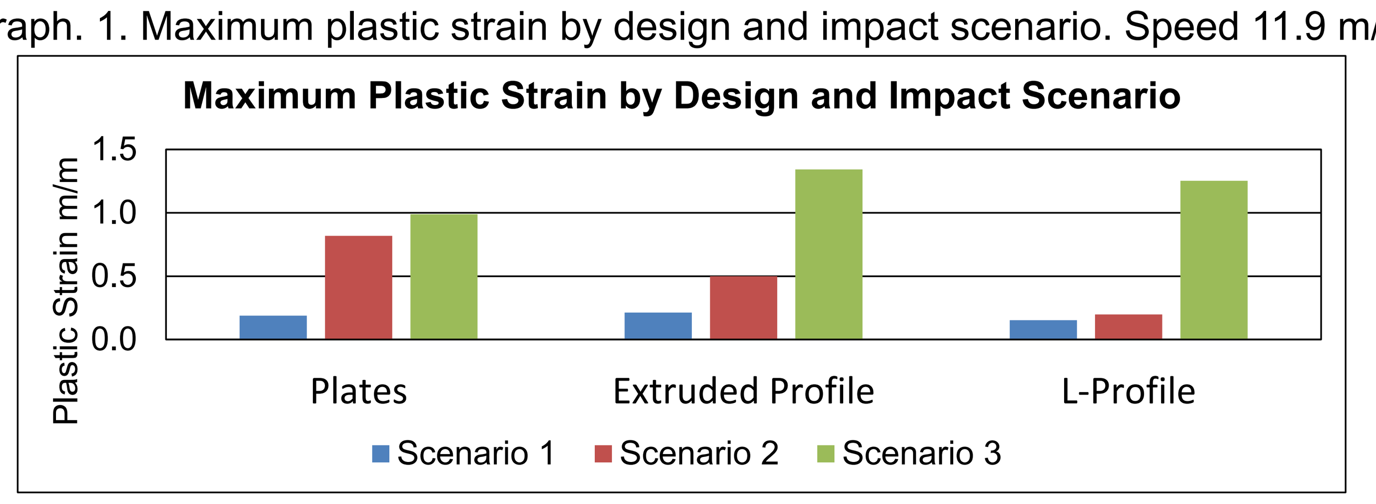
Table 1. Natural Frequencies

	Mode 1 [Hz]	Mode 2 [Hz]	Mode 3 [Hz]	Mode 4 [Hz]
Plates	157.86	167.49	182.08	291.38
Extruded Profile	65.199	104.28	140.72	153.97
L-Profile	74.618	120.51	128.62	130.89

Impact Analysis
The impact simulations enable the evaluation of plastic strain and stress distribution across various landing orientations. The maximum plastic strain results obtained for both velocities are presented in Graphs 1 and 2.
The results showed that the structural response is strongly dependent on both impact orientation and structural geometry. Design 1 exhibited significant plastic deformation, particularly under edge-impact conditions. Design 2 showed an intermediate response, with lower deformation levels in certain scenarios.
The extruded-profile configuration demonstrated a more uniform structural behaviour across several impact conditions; however, higher plastic strain values were observed during corner-impact scenarios due to load concentration effects.
A similar structural behaviour trend was observed for both velocities, increasing the velocity resulted in higher stress and plastic strain levels across all evaluated configurations.



Graph. 1. Maximum plastic strain by design and impact scenario. Speed 11.9 m/s



Graph. 2. Maximum plastic strain by design and impact scenario. Speed 18 m/s

Conclusions
Numerical analysis enabled an assessment of the structural behaviour of three high-altitude balloon platform configurations under different impact conditions.
Modal analysis revealed differences in the natural frequencies of the designs, which were related to the structural stiffness of each configuration. Impact simulations at velocities of 11.94 m/s and 18 m/s demonstrated that the structural response is dependent on both the impact orientation and the geometry of the structure. Results showed different deformation patterns for each structural configuration. The extruded-profile design presented a more uniform stress distribution in several scenarios, while edge and corner impacts induced higher plastic strain levels in all designs. Furthermore, higher impact velocities increased the stress and plastic strain values in every evaluated configuration. Overall, the results indicated that structural geometry significantly influences impact resistance and on the protection of internal components.

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