3 Unit Cube-Sat Mass Reduction Using Topology Optimization

Joud A. Alfayez and Sobhi Mejjaouli

***Abstract*—This study aims to Design and perform Finite element Analysis under the static load of a solid 3U cube structure. an evaluation of the critical loads affecting the structure during launching will be conducted to help re-design a topologized structure designed for additive manufacturing. The development of the structure's design was performed using SolidWorks, while the analysis was performed with both SolidWorks simulations and Fusion 360. The study shows the effect on the structure during the launching phase and promising results for the topology optimization approach's effectiveness as it gave an initial mass reduction of 40% that can be archived by focusing on the stress point while generating the new design even though the analysis was done using the same material, it is expected that with the material change the percentage of the original mass will drop by a higher percentage.**

***Index Terms*—Additive manufacturing, cube-Satellites, topology optimization.**

I. Introduction

This section aims to present an overview of the current situation of cub-sat purpose and optimization methodologies used to provide a more efficient, cost-effective approach for small satellites in general and CubeSat in particular.

Since the start of modern innovations and the space-time, the Cube satellite division spoke to the most desired project for unconventional innovations by nations or associations with restricted financial plans and minor involvement with space innovation. When Stanford University and California Polytechnic University in the USA founded the CubeSat in 1999, released the standard specifications for Cube-Sat, low-cost satellites presented itself. [1]

An article in the form of a case study was published to tackle the use of topology optimization and additive manufacturing in the aviation field. The study found that the percentage of the Airbus A320 nacelle hinge bracket has reduced to 64% weight; it was also noted that half of the reduction was due to the change of material used. One of the difficulties that were faced is the amount of time it took to optimize the part was relativity long for such a result. The authors suggested that to avoid the high cost of optimization is to spread the cost upon smaller parts to increase the optional saving by creating families of a similar part that uses variations of the same topology approach. [2]

Rather than evaluating the additive manufacture of CubeSat platforms, a study conducted a wholly unique study of the incorporation of additive manufacture technologies into the CubeSat-based platform itself. They first note that a spacecraft in orbit could encounter a variety of undesirable contingencies, including electronic charges and debris impacts, that are capable of damaging its power sources. In such events, the electrical power system is unable to energize the satellite and keep it operational. The research team at the University of Texas, El Paso, planned the development of a 1U CubeSat that was capable of 3D printing a conductive trace in order to repair such solar cell contingencies. Design parameters imposed upon the 3D printing capability included the damaging effects of the Van Allen radiation belt, as well as reduced gravity, vacuum, and extreme temperatures. The team pioneered a novel space-borne 3D printing environment consisting of three principal subsystems, namely, the material dispenser, the gantry table mechanism, and the motion controller. Their study closely examines the development of that printing environment, to include the selection of conductive ink material, the specific design parameters of the printer mechanism, and the system integration of the indicated components.[3]

Another article began by noting that the successful development of integrated technologies for space-borne platforms has led to the continuous miniaturization of spacecraft subsystems. To this extent, the CubeSat has taken on a prominent role as the chief executor of space missions targeted at scientific exploration. Among the foremost current design challenges is the desire to integrate the CubeSat design with the additive manufacture capabilities of 3D printing. The authors note that 3D printing brings several advantages to bear with respect to traditional manufacture via machining. Specifically, 3D printing offers a shorter manufacturing cycle, high accuracy in the creation of small parts, and reduced cost. The authors specifically considered the design of a low earth orbit CubeSat mission capable of sustaining a maximum acceleration of 5 g during launch, an internal operating temperature range of 0C to 40C, and an external ambient temperature range of –80C to 100C. The CubeSat design and manufacture process took careful note of the variety of environmental factors, relying upon ANSYS software to evaluate the impact load both before and after achieving orbit to verify the feasibility of the design. The authors observe that the critical importance of identifying superior manufacturing techniques for CubeSat is based upon their particular suitability insofar as orbit, payload, thermal balance, subsystem layout, and mission requirements are concerned. The feasibility of relying upon 3D printing for rapid prototyping was evaluated, however, by means of simulation tests rather than via actual manufacture. The overall thrust of the research was to demonstrate the pragmatism of so constructing a CubeSat craft capable of withstanding the indicated launch loads without incurring structural damage while meeting necessary launch stiffness

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specifications.[4]

With time passing and technology, improving the introduction of additive manufacturing and topology optimization in the aerospace field has been more focused on. A research was conducted using Selective Laser Melting (SLM) and topology optimization to produce a lighter aerospace component. The study showed It was possible to decrease the original component's material volume by 54%, resulting in a 28% weight reduction motivated by the change in material from Aluminum to a titanium alloy. The study also mentioned good approximations of the maximum principal strain in four different points of the component, suggesting a good relationship between the FE model and the produced component. [5]

Another research was conducted to 3D print a frame for the launch of cubes for low earth- orbit missions. This study provided several analyses to assure the accuracy of the results and found that using this method reduced 50% on weight compared to the traditional aluminum frames.[6]

Research in this field started expanding to focus more on space shuttle parts to achieve a more structural way of the design aspect to reduce time and effort. Benefiting from the SLM technique, different researches have looked into the design aspects of brackets and found that Aluminum is the most suitable material to be used in order to go with the harsh requirements that it should stand. Both studies have found that the optimized design was intricate and brought several problems to traditional manufacturing methods; thus, additive manufacturing was introduced.

One study showed that in order to meet the requirements, thermoelastic topology optimization is used to optimize a heavy-loaded aerospace bracket by both topology and size optimization for weight reduction and then manufactured by 3D printing technology.[7]

While in another study, they used the penalization algorithm to change the direction overhang constraint penalty function is looked at, it gave the design more feasible solutions. After different iteration and analysis, the researchers found that magnesium alloy can also be used, but its application is limited due to limiting technologies. Due to the lower Young's modulus, It would require a thicker, but the structural weigh would be similar to the density, and the young's modulus ratio is similar.[8]

After reviewing the literature, it has been found that merging topology optimization and additive manufacturing has been widely researched. Its use in the aerospace field for vehicles circling the orbit is relatively low and still has a massive uncertainty. Even though the literature review showed the most relevant research in the aerospace field and showed promising results in weight and efficiency optimization, none of the articles discussed the cost reduction excepted due to the optimization of design, material change, manufacturing, and testing time. Therefore, the goals of this study are to show an overview of the current design and generate a more optimized design with the use of topology optimalization by doing the following analysis. The rest of the paper will be divided as follows:

- Dimensions and Materials of the current structure
- Finite element model and analysis
- Topology Study to predict the mass decrease of the new model

II. Dimensions and Materials

A. Dimensions

The 3U cube Satellite dimensions where driven from the standard dimensions required from NASA and polytech institute, A Fig of the model is shown in Fig. 1 while the dimensions are summarized in Table I.

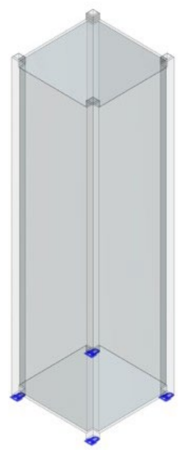

Fig. 1. The model.

TABLE I: DIMENSIONS OF THE OUTER STRUCTURE

Dimension	Value	Unit
Thickness	3	mm
Length	352.5	mm
Width	83	mm

B. Material Properties

The CubeSat panels are designed from Al7075; the material properties are listed and summarized to cover the analysis scope in Table II.

TABLE II: MATERIAL PROPERTIES

Symbol	Definition	Value	Unit
E	Young's Modulus	71.7	GPa
ν	Poisson's Ratio	0.33	…
ρ	Density	2810	kg/m3
σ	Yield Sstrength	145	MPa
ε	Ultimate Tensile Strength	276	MPa

III. Finite Element Model and Analysis

A. Finite Element Model

The finite element model of the CubeSat's designed structure contains 20750 nodes, and 11510 elements are prepared using SolidWorks Simulation is shown in Fig. 2.

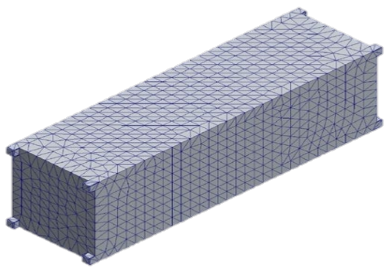

Fig. 2. Finite element model using SolidWorks.

While when prepared using Fusion 360, it contains 15790 nodes and 7875, shown in Fig. 3.

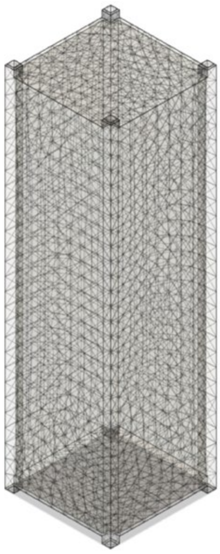

Fig. 3. Finite element model using Fusion360.

B. *Model Analysis*

The modal analysis is performed using an empty CubeSat structure to evaluate the unnecessary material in the structure. The structure study was done to evaluate the launching phase's performance as the acceleration loads it creates is the highest load the structure goes through.

The loads the have been set for the analysis other than the gravity effect were all subjected to 50 g.

Table III provides the loads the cube-sat structure was simulated to withstand in both SolidWorks and fusion 360. In order for the structure to valid the yield strength derived from the simulations should be higher than the martials yield strength.

TABLE III: SIMULATED LOADS

Type	Magnitude	X-Value	Y-Value	Z-Value
Gravity	9.807 m / s^2	0 N	0 N	-9.807 m / s^2
Force	398.9 N	0 N	0 N	-398.9 N
Remote Force	398.9 N	0 N	-398.9 N	0 N

Fig. 4 shows the location of the applied forces in SolidWorks, while Fig. 5 shows the fusion 360 analysis.

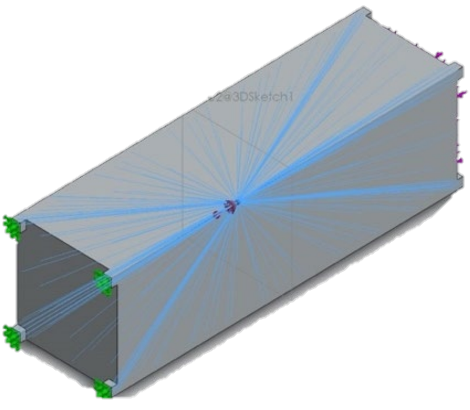

Fig. 4. Location of the applied forces in SolidWorks.

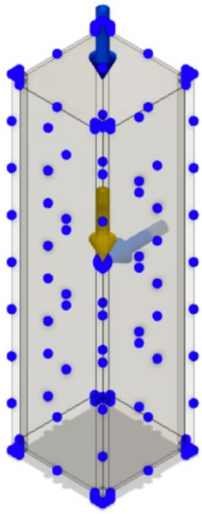

Fig. 5. Location of the applied forces in Fusion 360.

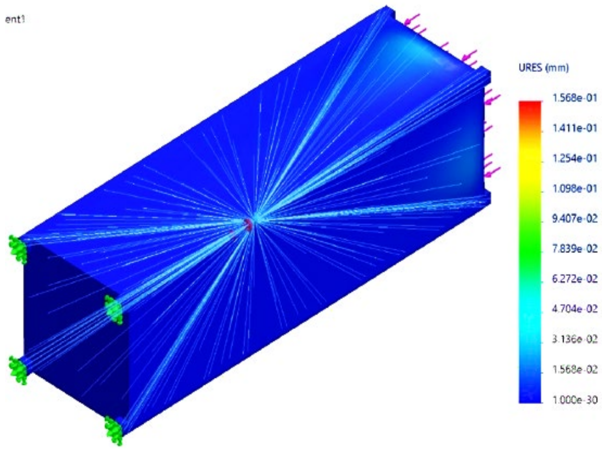

Fig. 6. Static displacement in SolidWorks.

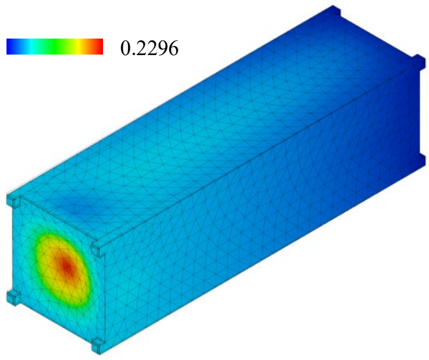

Fig. 7. Static displacement in Fusion 360.

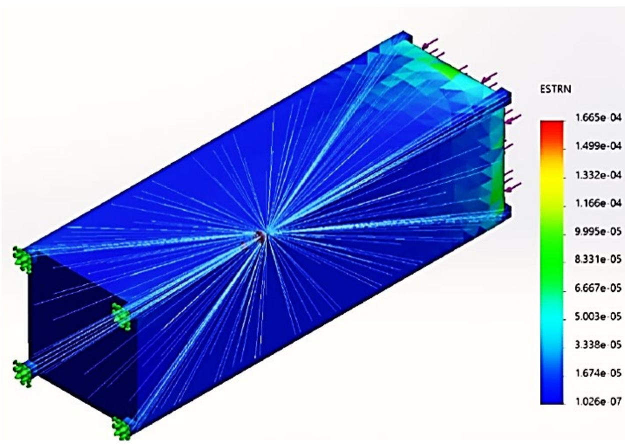

Fig. 8. Static strain in SolidWorks.

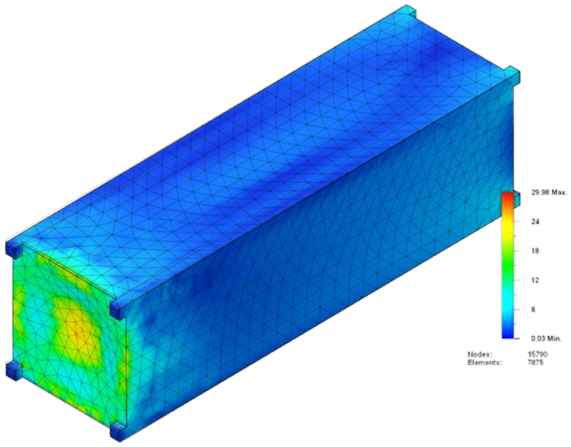

Fig. 9. Static strain in Fusion360.

In Fig. 8 and Fig. 9 the static strain is shown.

The simulation showed that in fact the structure can survive the applied load and meets the criteria as the yield strength is constrains is meet. The simulation also showed that the main stress is located on the upper panel and hence the possibility of the structure to be more optimal is presented.

IV. Topology Study

The Topology study was conducted using Fusion 360 for the structure under the same material specifications and loads.

The Rails of the model have been preserved to fit into the launching vehicle. Fig. 10 shows a topologized compression model concerning the preserved regions, and the loads applied. Table IV shows a summary of the optimization results in the mass reduction aspect.

TABLE IV: Optimization Summary

Mass before	Mass after	Mass Ratio
0.813 kg	0.488 kg	60.01 %

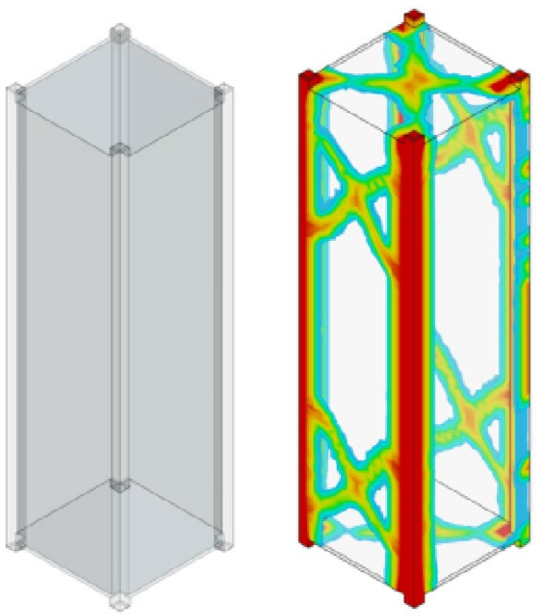

Fig. 10. Compression of the topologized model and the current one.

V. Results and Conclusions

The study of a CubeSat structure is performed by designing a 3U CubeSat using aluminum, 7075, and FEA to determine the critical stress points and evaluate the structure optimization areas to ensure it withstands the same loads while decreasing its total mass.

A Topologized study was performed that showed a reduction of 40% in mass is possible. Even though the new structure does not meet the model's symmetric requirements, a modification of the panels to ensure this requirement is meet t will still provide a high mass reduction.

The cube's structure's investigation revealed that the primary stress and deformation are placed on the upper panel while the rest of the body remains unaffected; hence, developing a topologized 3U CubeSat will reduce the cost of materials is possible. Several factors To find the actual effect will need to be considered later on, as listed below.

- The material selected for the additives manufacturing.
- The cost of adopting the new technologies.
- The printed structure evaluation.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Joud A. Alfayez conducted the research, analyzed the data and wrote the paper; Sobhi Mejjaouli is the primary supervisor of the paper and reviewed all of the work performed; all authors had approved the final version.

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