MECHANICAL DESIGN AND FINITE ELEMENT ANALYSIS OF A 3 UNIT CUBESAT STRUCTURE

BsC. Güvenç, C. C., BsC. Topcu B., and Ph.D. Tola C.
Faculty of Aeronautics and Astronautics – University of Turkish Aeronautical Association, Turkey
guvenccerencansu@gmail.com

Abstract: *The aim of this study is to design a 3 Unit CubeSat structure performing finite element analysis under static, dynamic and thermal loads. The main idea of this process is to construct a 3U CubeSat main frame that can structurally endure launching process and space environment. To accomplish the task, a 3U CubeSat structure is designed and standard loads that a 3 unit CubeSat structure has to endure are obtained. After the selection of a suitable material, modal analysis, quasi-static launch analysis and thermal stress analysis coupled with heat transfer analysis are accomplished in Abaqus environment. Finally, the results are evaluatedand endurance level of the design is determined.*

Keywords *: 3U CUBESAT, STRUCTURAL DESIGN, FINITE ELEMENT ANALYSIS*

1. Introduction

Cubesat is a cubic shaped small satellite which has a dimension of 10x10x10 cm for a 1 Unit. However, some cubesats are in the dimensions of 10x10x20cm which are called 2 Units, 10x10x30 cm are called 3 Units. The difference of its dimensions is related about their specifications according to their missions.

Studies on cubesats started in 2001, but until 2013, most of the universities studied on 1 Unit Cubesats to initiate their subsystem development research on relatively small models. Cihan, et. al. designed an innovative cubesat structure provides flexibility for designers during the design, development and test processes of 1U cubesats at 2011 [1]. Oh, et. al. peformed the structural design and performed modal and quasi-static analysis of a 1U cubesat [2]. Sekerere et. al. examined the structural strength of a 1U cubesat and performed the modal analysis of it [3]. After 2013, along with the increase in the work carried out and change of wishes, multi-unit cube satellites began to be used, especially 3U. As known, the studies of space are costly and the environment of space is risky. As an engineer, the aim should be both reduce of this cost and risk. To do this the choice of small satellites are standing out.

In this study, by considering that the importance of cubesats for space applications and subsystem development, a 3U cubesat structure is designed and analyzed using finite element method to determine its natural frequencies and mode shapes, its stress level during the launch period, its temperature distribution at the space environment and thermal stress distribution of the satellite governing from the temperature distribution.

2. Geometry and Material Properties

A 3U cubesat shown in Fig. 1 is designed in SolidWorks environment. Cubesat panels are designed from Al7075 T651 material having 3mm thickness. Properties of the Al7075 T651 is summarized in Table 1.

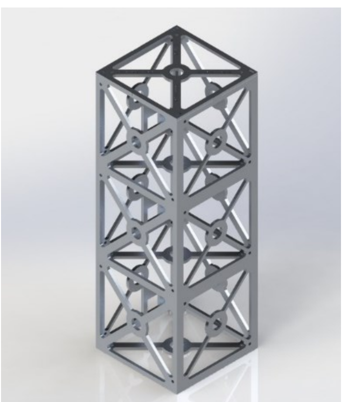

Fig. 1 *Structural Geometry of the 3U cubesat.*

Table 1: *Material Properties of Al7075 T651 [4, 5].*

Symbol	Definition	Value	Unit
E	Young's Modulus	71.7	GPa
v	Poisson's Ratio	0.33	-
ρ	Density	2810	kg/m^3
k	Conductivity	130	W/(m.K)
α	Coefficient of Thermal Expansion	25.2	μm/(m.°C)
c_p	Specific Heat	960	J/(kg. °C)
σ_{yield_std}	Yield Stress at 24 °C	503	MPa
σ_{yield_hot}	Yield Stress at 316 °C	45	MPa
ε	Emissivity	0.81	-

3. Finite Element Model

The finite element model of the cubesat geometry consisting of 226271 nodes and 33764 hexagonal quadratic elements is prepared in Abaqus 6.12 as it is seen from Fig. 2.

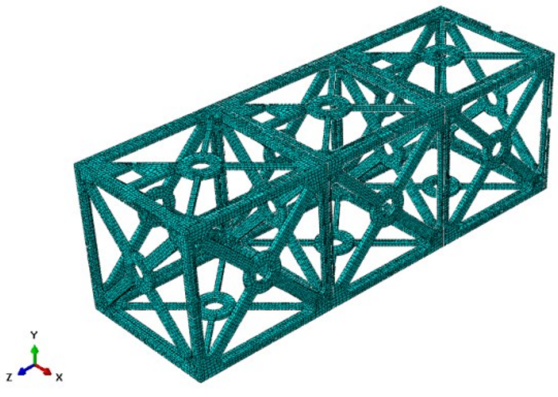

Fig. 2 *Mesh structure of the 3U cubesat.*

The model consists of assembly of the different panels so, they are attached to each other from the certain locations in the finite element model as it is in reality.

4. Modal Analysis

Natural frequencies of the 3 unit cubesat structure is designed considering the excitation frequencies of the Polar Satellite Launch Vehicle (PSLV). According to the vehicle's specifications, natural frequencies of the cubesat should not be less than 35 Hz in longitudinal axis and 20 Hz in lateral axis [1]. At the same time, there will be high amplitude harmonic frequencies are under the 100 Hz during the launching process so, cubesat natural frequencies of the cubesat has to be more than 100 Hz in order to prevent resonance [6].

Modal analysis are performed using empty cubesat structure in order to make a convervative analyse preventing extra stiffness governing from the card structures. Results of the modal analysis excluding the free body motion modes are summarized in Table 2.

Table 2: *Modal Analysis Results.*

Mode	Frequency [Hz]
1	232.13
2	326.54
3	461.72
4	546.04
5	645.17

Accortding to the results, the lowest mode is approximately 232.13 Hz (Fig. 3) and since this value is far beyond the crticial treshold (100 Hz) it is acceptable.

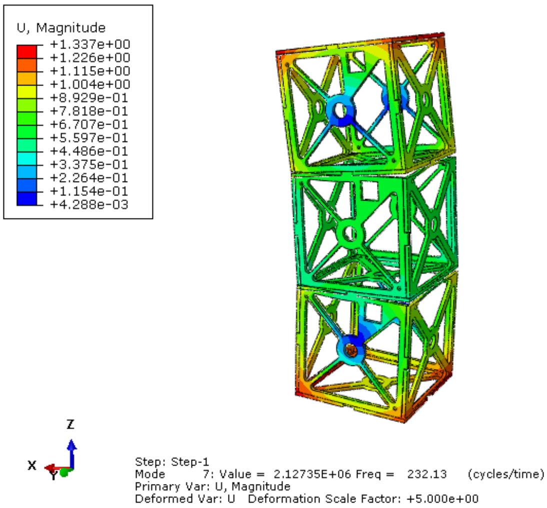

Fig. 3 *Mode-1 (232.13 Hz).*

5. *Quasi-Static Launch Analysis*

During the launch phase, the cubesat has to endure the acceleration loading governing from the launching process. In order to determine the stress level on the cubesat due to these acceleration loads, quasi static launch analysis are performed. Polar Satellite Launch Vehicle, quasi-static launch loads are 11 g in “z” axis and 6 g in both for “x” and “y” axes [7].

Within the content of the quasi-static launch analysis, masses of the cards and the equipments belonging to each unit (1U) of the cubesat are modeled as point mass assuming that the satellite is fully loaded and they are conneted to the related portions of the cubesat frame via couplings as illustrated in Fig. 4.

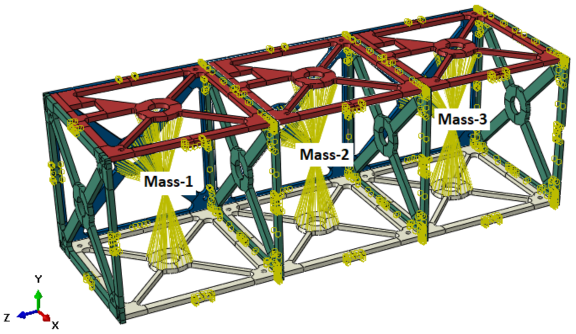

Fig. 4 *Locations of the point masses and connection of them.*

The structure’s top face has been fixed in Z axis to analyze the worst case scenario and quasi static accelerations are applied on the system (Fig. 5).

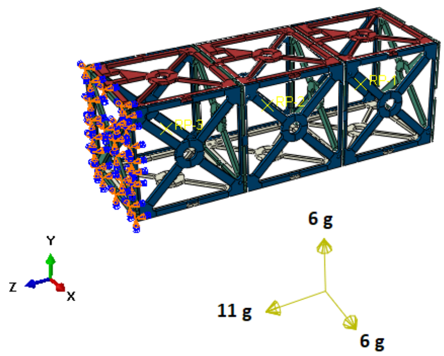

Fig. 5 *Boundary conditions and loads for quasi-static launch analysis.*

According to the finite element analysis results, the highest stress level on the cubesat structure governing from the launching loads is determined as 453.548 MPa (Fig. 6). Detailed results can be further examined from Fig. 7 and Fig. 8.

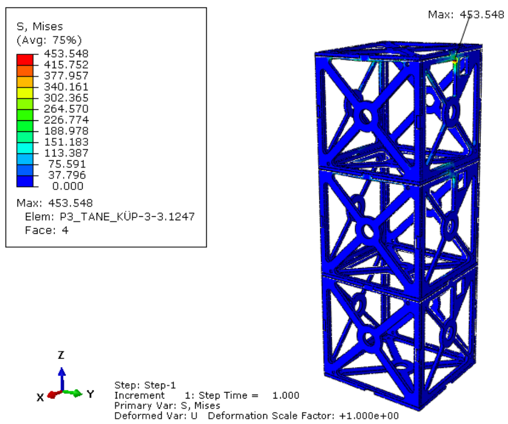

Fig. 6 *Von Misses stress distribution due to launch [MPa].*

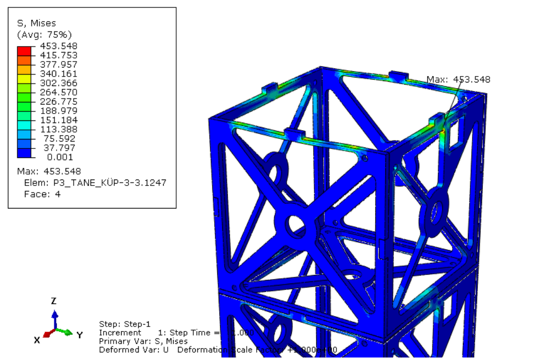

Fig. 7 *Von Misses stress distribution on upper panels due to launch [MPa].*

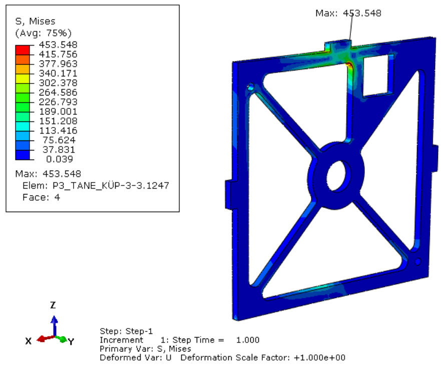

Fig. 8 *Von Misses stress distribution on a panel due to launch [MPa].*

Considering the yield stress of the material is 503 MPa for standard atmospheric conditions, factor of safety value for the quasi-static launch analysis is found as 503/453.548 = 1.1 approximately that is acceptable.

6. Heat Transfer Analysis

Cubesat subsystems and structures have to endure harsh space environment conditions such as radiation incoming from the Sun, albedo reflecting from the Earth, and infrared energy emitting from the Earth (Fig. 9). To determine the temperature distribution of the satellite during its mission it is required to perform a heat transfer analysis considering the worst case scenario.

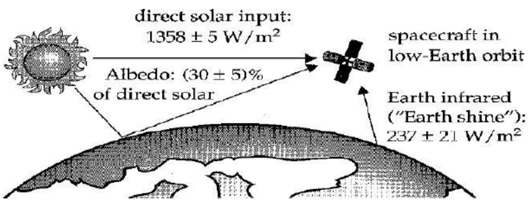

Fig. 9 *Low Earth Orbit (LEO) heat fluxes [8].*

Selecting the orbital altitude of the cubesat as 600 km and referencing the orbital calculations on Ref [8], period of the cubsat is determined as 5801 s and total exposed time for solar radiation coupled with albedo during a period is calculated as 2127 s. Heat fluxes corresponding to the solar radiation, the albedo and the Earth infrared energy are taken into account as 1363 W/m^2, 406 W/m^2 and 237 W/m^2 respectively. Therefore, the heat flux loading illustrated in Fig. 10 is applied to the cubesat.

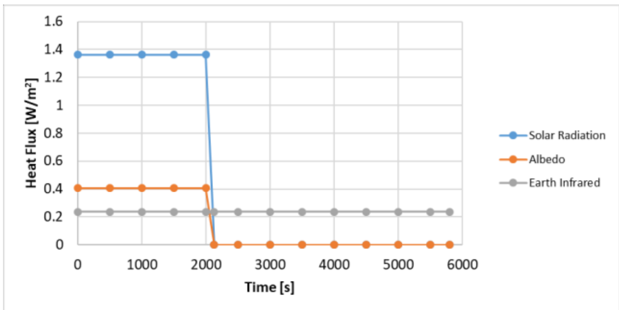

Fig. 10 *Variation of heat fluxes with time.*

Application regions of the heat fluxes are selected as in Fig. 11 to simulate the worst case for the cubesat. In addition to the heat fluxes on the cubesat surfaces, the satellite is emitting radiation as a result of its temperature from its outer surfaces.

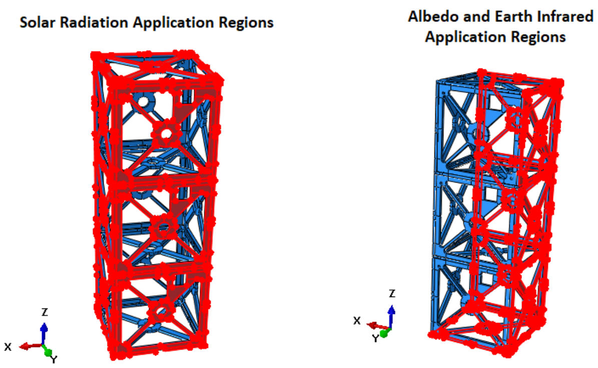

Fig. 10 *Heat flux application surfaces on the cubesat.*

Assuming that the initial temperature of the cubesat is 25 ºC, a transient heat transfer analyse having a resolution of 60 seconds is performed to find out the highest temperature that may be encountered during a period considering the worst case scenario.

According to analysis results, highest temperature distribution on the cubesat is encountered at t=2040s as it is illustrated in Fig. 11.

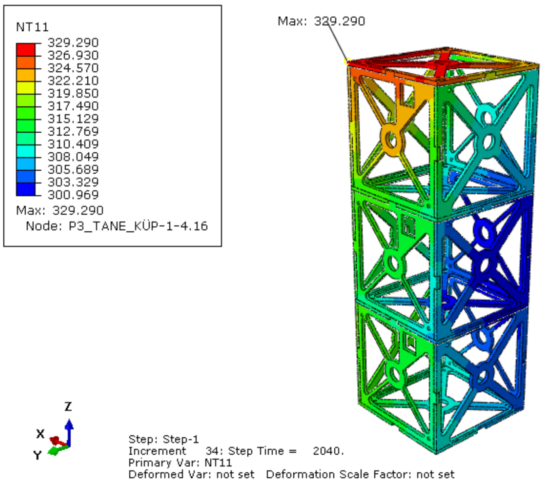

Fig. 11 *Temperature distribution on the cubesat at t=2040s [ºC].*

Tempterature variation of the hottest node during an orbital period can be examined from Fig. 12.

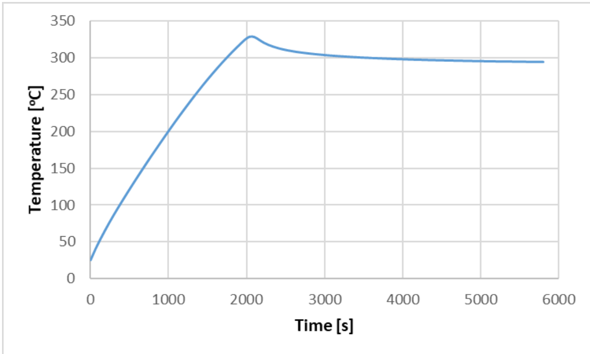

Fig. 12 *Temperature variation of the hottest node.*

7. Thermal Stress Analysis

Thermal stress analyses are performed using the outputs of the heat transfer analysis in order to find out the stress levels on the cubesat frame governing from the thermal loads. Quasi-static thermal stress analyse is performed within the content of this work assuming that the cubesat temperature is increased from 25 ºC to the temperature distribution was shown in Fig. 11.

According the analyse results, thermal stresses govering from the temperature variation is shown in Fig. 13.

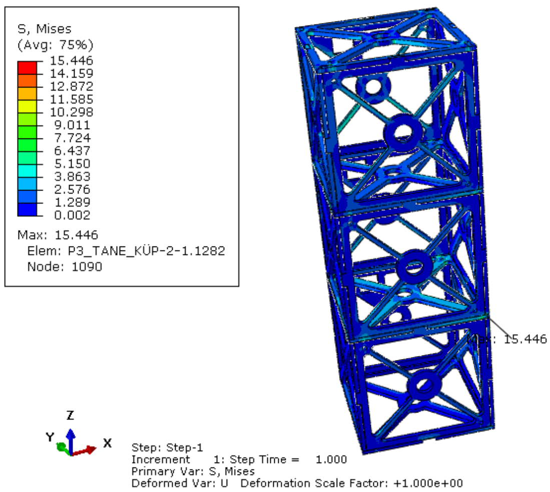

Fig. 13 *Von Misses stress distribution due to temperature load [MPa].*

Detailed results can be further examined from Fig. 14 and Fig. 15.

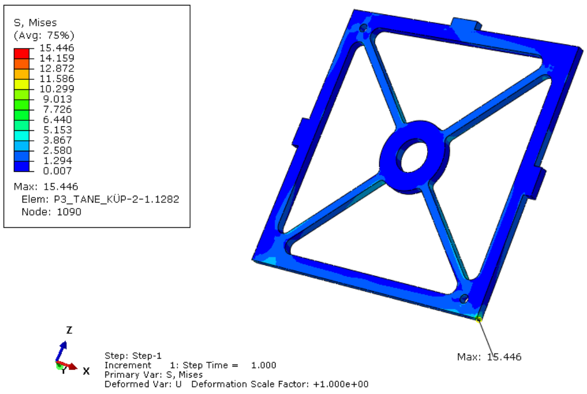

Fig. 14 *Von Misses stress distribution on a due to temperature load [MPa].*

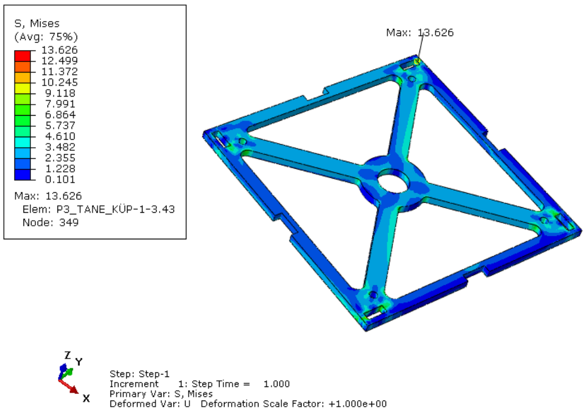

Fig. 15 *Von Misses stress distribution on another due to temperature load [MPa].*

Temperature variation of the node having the highest thermal stress is also illustrated in Fig 16 to make an evaluation considering the endurance limit of the material at high temperatures.

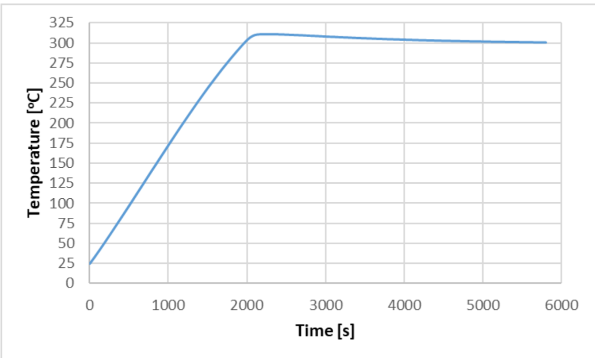

Fig. 16 *Temperature variation of the node having the highest thermal stress.*

According to the material properties, yield stress of the Al-7075 T651 material is 45 MPa at 316 ^{o}C. Considering the highest thermal stress value on the cubesat frame is 15.446 MPa, the factor of safety for the thermal stress analysis is calculated as 2.91 that is also acceptable.

8. Conclusion

Within the content of this work, structural frame for a 3U cubesat is designed and analyzed using finite element method via Abaqus commercial software. Modal analysis, quasi-static launch analysis, heat transfer analysis and thermal stress analyses are performed and evaluation methodology of the results are explained.

According to the results, cubesat's modal frequency values are sufficiently higher than the excitation frequency values of the launch vehicle (PSLV) and factor of safety value of the cubesat structure governing from launching process is approximately 1.1 that is acceptable. According to the heat transfer analysis results that are determined considering the worst case scenario, the highest temperature value on the cubesat frame will be at most approximately 329 ^{o}C. The temperature distribution values may change and probably decrease according to the orbital position and also according to the axial rotation motion of the satellite itself. On the other hand, the structural factor of safety value of the cubesat is calculated as 2.91 according to the thermal stress analysis results that are conducted using the temperature distribution results of the heat transfer analysis. Under these circumstances it can be stated that analysis results of the preliminary design of the 3U cubesat structure is satisfactory and detail design process can be initiated.

As a future work, it is planned to add further details such as card structures, connection parts and other kinds of subsystem elements to the finite element model to perform a detailed analysis for both quasi-static launch and heat transfer analysis. It will be better to use an orbital simation software to increase the accuracy of the heat transfer and thermal stress analysis for the future work.

9. References

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