Design Development And Simulation Of Payload Fairing SLS Cargo Block 2 Spacecraft Using Composite Material To Improve Consistency For Orbital Insertion.

[1]Krish Shah, [2]Parth Atulkumar Shah,

[1]Krish Shah, JG International School, Ahmedabad
[2]Parth Atulkumar Shah, Anant National University, Product design, Ahmedabad

Abstract

The SLS Launch vehicle with Orion spacecraft is going to be used for NASA's Artemis project to send humans back to the moon's first after 1972. It has been observed that during the journey to orbit, the spacecraft undergoes various payload conditions. The outer body of the nose cone and the connecting compartment have to undergo temperature changes with respect to speed, atmospheric, and pressure conditions. Due to such conditions, the spacecraft can have a serious impact on the outer surface of the nose cone. When the system is directly integrated with the Abort origin or payload fairing in both versions of SLS, it is going to have an impact. To avoid the impact and to standardize the deformation on the spacecraft, there have been changes in the design, and a modified design is compared with the current existing SLS models. This paper also reveals the study results of the simulation analysis of the nose cone of the SLS model, which have carried out simulations of the pre-existing materials, such as metals and alloys, and a new composite material is taken as a review for the analysis under the harsh and extreme conditions faced by the spacecraft and launch vehicle during the launch sequence, in space, and atmospheric re-entry. Comparing the results to get an efficient material outcome that makes the design robust, sturdy, and efficient, considering safety parameters.

Keywords: NASA, launch vehicle, Satellite, Rocket Simulation, Payload fairing

I. Introduction

SLS is space launch system divided into 4 stages. The first stage: this stage provides the majority of the thrust required for the ascension of the rocket. Then comes the Inter stage, it connects the first stage and the second stage. After the first stage is jettisoned, the second stage continues to provide thrust so the vehicle reaches orbital velocity which last the payload fairing which protects the payload from extreme conditions during the launch and then separates afterwards to release the payload.
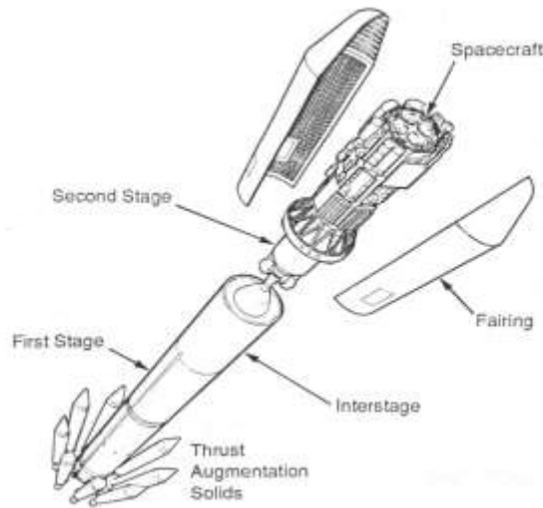
Figure 1:- Expendable Launch vehicle

The SLS currently has three different designs available. Block 1, Block 1B, and Block 2, and each one of them is divided into crew and cargo. All the blocks are of different sizes and have different amounts of payload they can carry. Block 1 is the smallest and can carry the least amount of weight, and Block 2 is the largest and carries the highest amount of mass. [5] Consequently, payload fairing is constructed out of materials that do not deform in extreme environments.
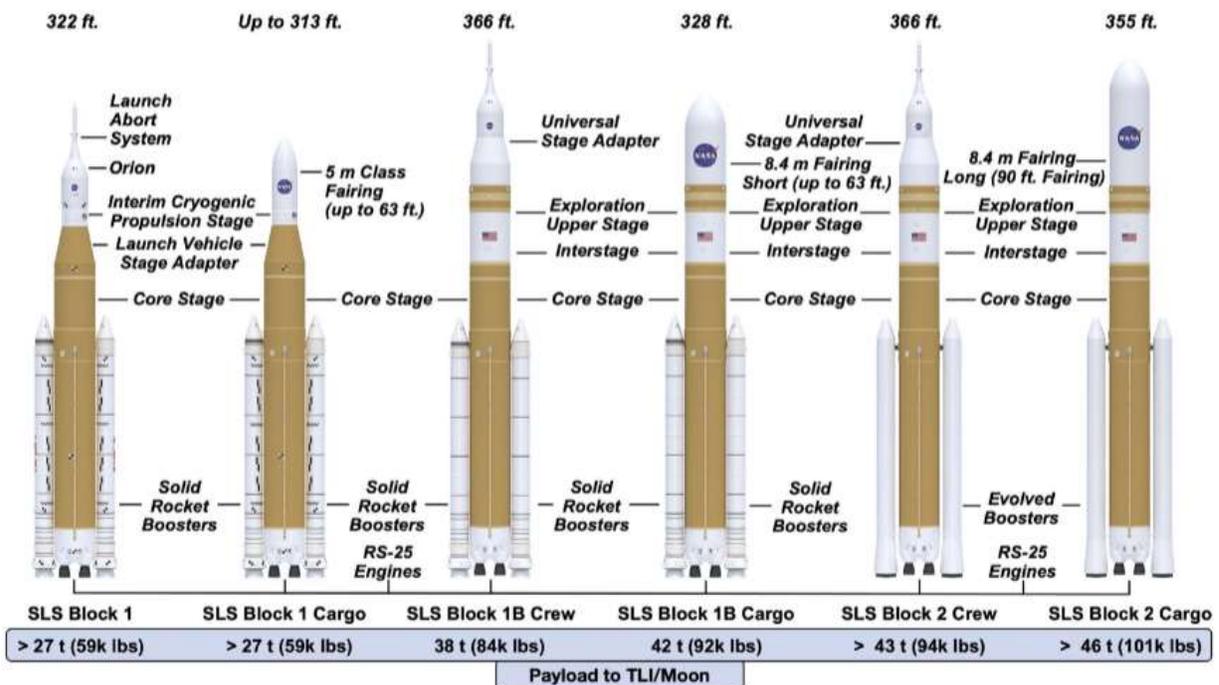

Figure 2:- SLS Evolutionary Path

II. Literature review

Orbital insertion of a satellite or spacecraft is the main objective of a space launch vehicle. Space Launch System (SLS) is being developed by NASA and has been in development since 2011 [7]. SLS is making a big stride in space exploration as it is one of the only launch vehicles available that can carry large cargo to the moon [1]. SLS has a flexible and evolvable design, which will help us take giant leaps in traversing our solar system. This launch vehicle will enable us to carry large and different payload capacities of satellites and rovers, and it can also be used for robotic scientific missions to the Jovian planets [4].

Aluminum-lithium 2195 was used in the construction of the payload fairing for the Atlas V rocket by the United Launch Alliance (ULA) [8]. ULA has also employed Ti-3Al-2.5V in its payload fairing for Ti-3Al-2.5V [9]. Other aluminum alloys, such as AA2014 Aluminum Alloy [10], are also used in the aerospace industry. Many of these aluminum alloys, or aluminum itself, are given configurations such as aluminum honeycomb, aluminum iso-grid, and aluminum ring [3].

This configuration helps with structure integrity and makes the structure strong enough so it does not deform under high conditions. Other alternatives to aluminum are composite materials, as they have potential for design and other calculations as per the outdoor space environmental conditions. Composite materials also have a great advantage compared to metals, like being available as per convenience, which can provide similar benefits to aluminum. In addition, it would be flexible on the assembly line of the plant to get the materials. With that, the manufacturing line will also save time due to predefined materials along with the desired shape of the nose cone.

Composite materials like carbon fiber-reinforced polymer, fiberglass, and other customized materials that have easy access to changes in their properties and behavior can be accepted for a more efficient process. Since payload fairing was being used in the first Atlas Centaur launch, it was made of fiberglass [11]. The payload fairing of Falcon 9 uses Carbon Fiber Reinforced Polymer (CFRP) [12].

As seen there are multiple materials available for a rocket's payload fairing but choosing the correct material with correct and uniform properties becomes very important. This can be observed in the failure of NASA's glory spacecraft. The Space failed due its payload fairing not separating on the planned moment (176.98 seconds after the Stage 0 ignition) which caused it to change its trajectory. And one of the potential root causes for the failure was found out to be inconsistency in the material properties at frangibles joints of payload fairing which could have formed during manufacturing and have bypassed the manufacturing process controls.
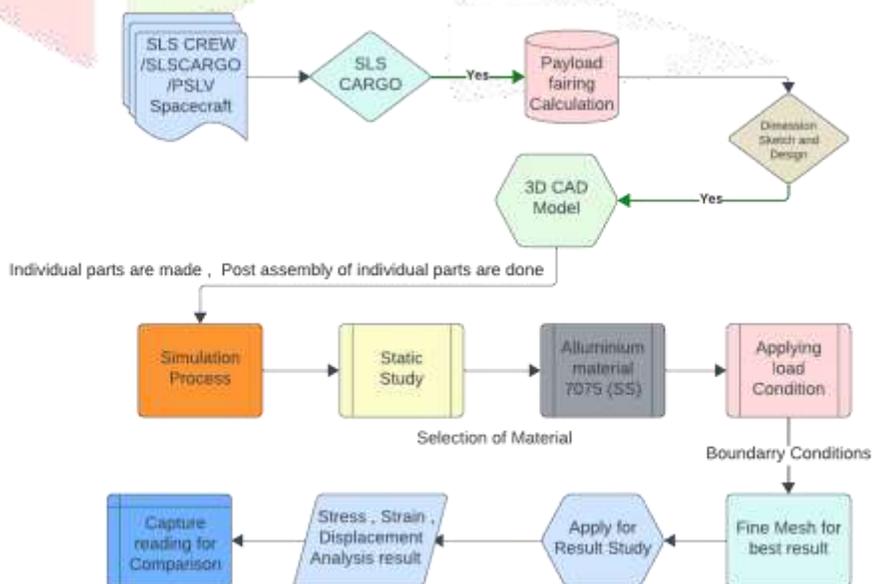
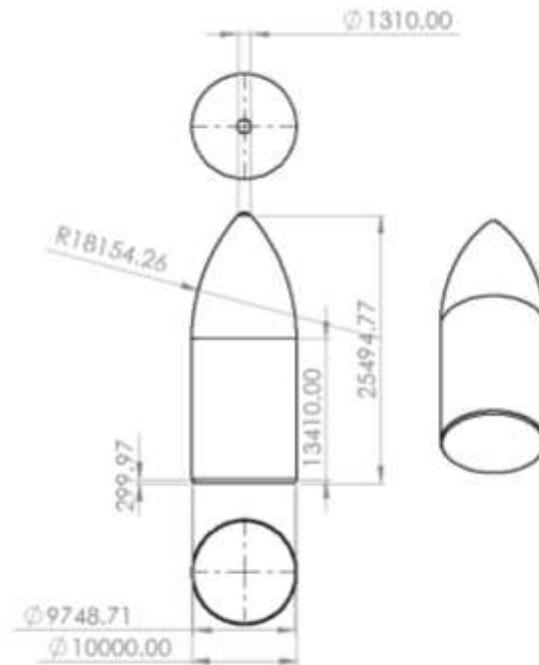Figure 3:- Flow chart of the design process

Figure 4:- SLS Cargo Block 2, 2D drawing with dimensions

Figure 5:- SLS Cargo Block 2, 3D CAD Mode

III. Materials Study

Aluminum Alloy 7075(AA7075) is a high-performance aluminum alloy that is widely used in the aerospace and defense industry. It is a very highly strength material that is used for highly stressed structure parts such as payload fairing. Aluminum 7075 composition includes zinc 5.1-6.1 %, Chromium 0.18 -0.28% Copper 1.2 - 2% Magnesium 2.1 - 2.9 %, Manganese max 0.3%, Iron max 0.5%, Silicon max 0.4%. The high zinc concentration of the material assists with the precipitation hardening. It is also said that the zinc enhances strength by partial dislocation. And the relative high content of chromium helps reduce the crystal growth which increases the material ductility and toughness.

Properties	Value	Unit
Elastic Modulus	7.20×10^{10}	N/m^2
Poisson's Ratio	3.30×10^{-01}	N/A
Shear Modulus	2.69×10^{10}	N/m^2
Mass Density	2.81×10^{03}	kg/m^2
Tensile Strength	2.20×10^{08}	N/m^2
Compressive Strength		N/m^2
Yield Strength	9.50×10^{07}	N/m^2
Thermal Expansion Coefficient	2.40×10^{-05}	/K
Thermal Conductivity	1.73×10^{02}	$W/(m \cdot K)$
Specific Heat	9.60×10^{02}	$J/(kg \cdot K)$
Melting Point	6.35×10^2	°C

Table 2:- Aluminum 7075 Material properties

The AA7075 exhibits a fiber texture with a strong base texture component after extrusion or rolling. This texture is the reason for the anisotropic mechanical behavior of this alloy. The texture of AA7075 evolves during higher temperature compression. The texture of AA7075 can be easily influenced by various factors such as, deformation, recrystallization, alloying elements, and surface modification techniques. Thus controlling the texture of the becomes very crucial while the manufacturing of the payload.

Carbon fiber is a material composed of strong crystalline filaments of carbon. Due to its excellent strength to weight ratio, it becomes an ideal composite material that can be used for payload fairing. So far analysis indicates that it has stronger, lighter and low cost features as compared to other industry standard metals. The properties stated in the table represents the best compatibility for the payload fairing to be lightweight yet rigid and enables it to withstand extreme conditions and aerodynamic force during the launch phase and separation. When used in payload fairing, the carbon fiber exhibits a smooth layered texture which appears to be cubic in shape.

Properties	Value	Unit
Elastic Modulus	2.76×10^5	N/mm^2
Poisson's Ratio	3.00×10^{-1}	N/A
Shear Modulus	1.06×10^5	N/mm^2
Mass Density	1.78×10^3	kg/m^3
Tensile Strength	5.65×10^3	N/mm^2
Compressive Strength	1.86×10^3	N/mm^2
Yield Strength	0.00×10^0	N/mm^2
Thermal Expansion Coefficient	-6.40×10^{-1}	/K
Thermal Conductivity	5.40×10^0	W/(m·K)
Specific Heat	8.80×10^2	J/(kg·K)
Material Damping Ratio	1.00×10^{-2}	N/A

Table 3:- Carbon fiber properties

IV. Simulation process

The first step is to look into the industrial design parameters working with the specific industrial standard we carried out the dimensions of the SLS cargo category spacecraft i.e. nose cone were the payload is carried above the second stage of spacecraft in which certain cargo and other satellite are being carried to the space , using the launch abort system the payload fairing will be open are made which is the major element of the simulation on which the entire payload is being decided , to avoid high impact on the outer surface and to improve the result we have considered the +- 0.01 m tolerances included which can control the expansion and contraction while the spacecraft is in the space and having certain environment with variable temperature conditions. Based on the tolerance the cad model is prepared for, post the cad model we have taken the load calculation on the basis of the payload capacity of the cargo space, we selected the material Aluminum 7075 which has a high potential and has a good compatibility. We did the FEM (finite element methods) using the FEM. We created the finite mesh of the 3d part model and then we selected triangular elements then we selected the static analysis in which we are going to get the results on stress, strain & displacement. Additionally the analysis results include the von mises criteria which can be used to compare with all the three principal stresses, later the result of the principle stress can be compared with the yield stress. In the mesh we have also included the factor of safety which will analysis the material in their boundary conditions

a) Fixture and Load applied on the model

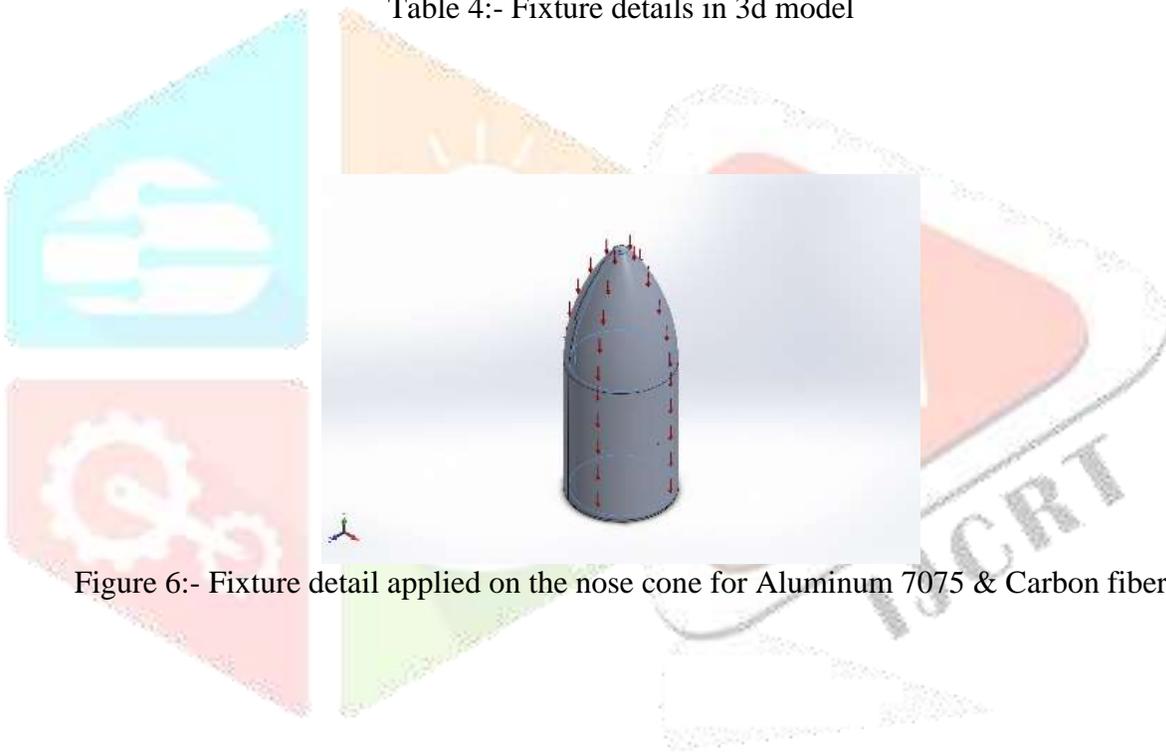| Fixtures	Aluminum				Carbon Fiber			
	Fixture details				Fixture details			
	Entities: 3 face(s) Type; Fixed geometry				Entities: 3 face(s) Type; Fixed geometry			
Components	x	y	z	Resultant	x	y	z	Resultant
Reaction force / N	25.588	3.1748×10^7	-15.7851	3.17484×10^7	-1.27681×10^{-5}	28.2207	1.68337×10^{-6}	28.2207

Table 4:- Fixture details in 3d model

Figure 6:- Fixture detail applied on the nose cone for Aluminum 7075 & Carbon fiber

We have selected 3 faces in the model the selection of the faces are done with the condition that the spacecraft is flying in the orbit while the forces will be acting on the nose cone surface passing through the entire conical surface and its body the entire model will be acting with the resultant force in all the direction i.e. x, y and z axis considering the payload condition inside the spacecraft, the force acting in the counter direction with the trust impact to the spacecraft flying towards the orbit. While simulation result we have consider two materials on which the analysis have been performed and with the boundary condition we have applied the fixture detail on the model to get the result impact. With the impact there are temperatures which will also play a significant role in giving the analysis result.

The model undergoes the same boundary condition for the loading effect for aluminum and carbon fiber. The applied load for the aluminum is -0.045 Mpa and for the carbon fiber the load applied is $-4*10^{-8}$ MPa

Load	Aluminum	Carbon fiber
Entities	2 face(s), 1 plane(s)	2 face(s), 1 plane(s)
Reference	Top Plane	Top Plane
Type	Normal To Plane	Normal To Plane
Value	-0.045	-4×10^{-8}
Units	N/mm^2 (MPa)	N/mm^2 (MPa)
Phase Angle	0	0
Units	deg	deg

Table 5:- Applied load details on the nose cone

Figure 7:- Load applied on nose cone materials, Aluminum & Carbon fiber

b) Finite Element Analysis

Finite element analysis is used to validate the test result before it goes to floor shops , first steps towards working efficiently is to design and check the various performances prior to manufacturing stage it is common practice to execute the performance of the cad model. The 3D model is developed in the software with the actual dimensions and the material properties. After the 3d model is developed it is taken for the analysis mode where the software will deliver the accurate results by giving the boundary conditions which includes the fixed geometry, force, pressure and other conditions. The FEA breaks the entire 3D model into numbers elements, this process is called meshing. It allows the creation of small elements of a 3D model, these elements are connected by node points so the model will have numbers of nodes. With the coarse mesh the results will be simplified but to obtain the best accurate results this node point is given boundary conditions, later the external load conditions are applied on the elements which will give the result study. This process is called Meshing in the process the 3d model is divided into Solid mesh, with 4 jacobian points. Each element size is 369.42 mm having 49351 total number of elements with tolerance value as 18.471 mm with fine grain size. Total number of nodes 85827.
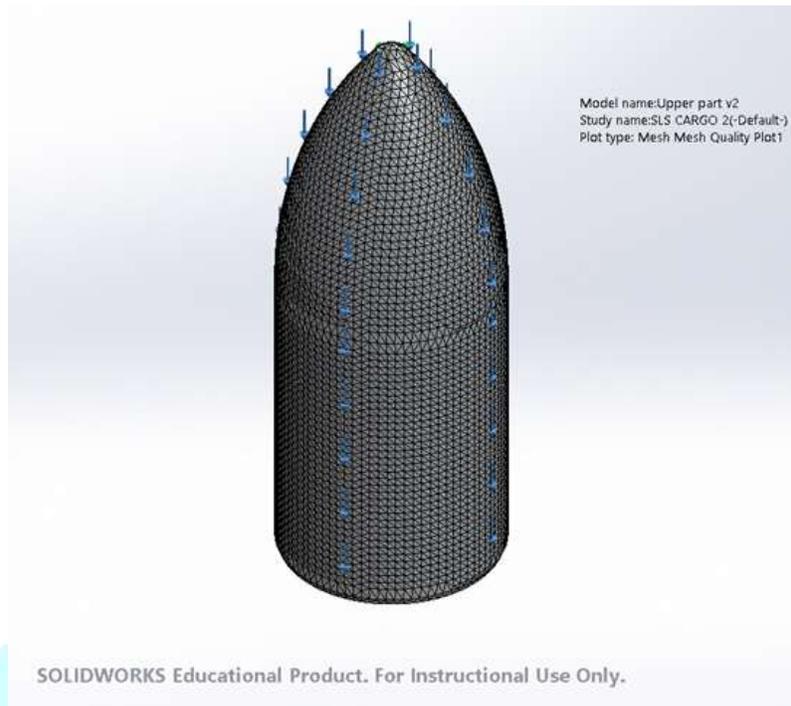
Figure 8:- 3D Mesh Model

Each kind of finite element will have its own structure with a specific shape which is interconnected with the adjacent element by the nodal point. Each node has its degree of freedom which allows the nodal point to react to the forces acting on the element. Post to the element the resultant forces which have applied will allow the simulation to analysis the load and deformation parameters

V. Result and Analysis

The 3D model is given an external load, in which it faces 0.04MPa of pressure. Under these conditions 4 parameters of the model are recorded and compared: The Von mises stress, the URES: Resultant Displacement, the ESTRN: Equivalent Strain and the factor of safety.
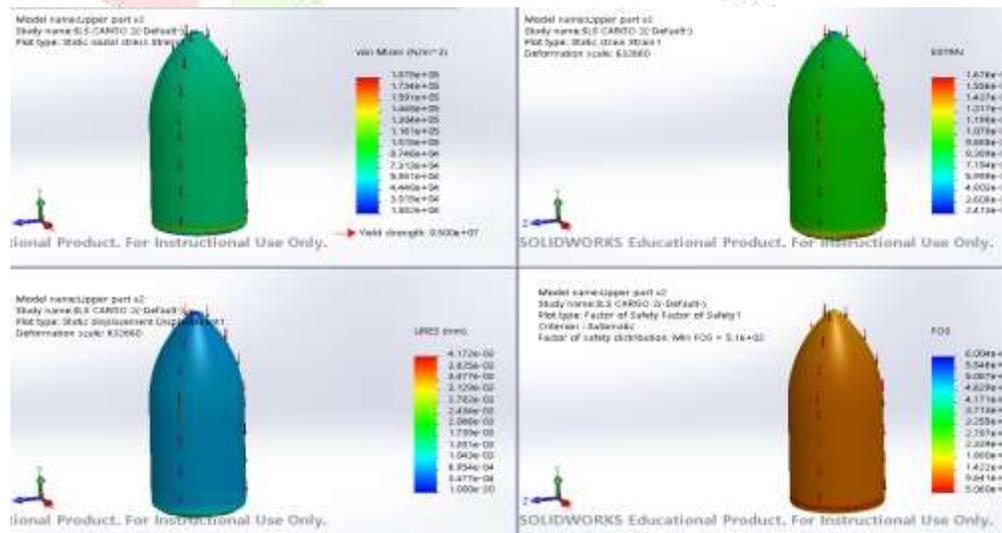

Figure 9:- Stress, Strain, Displacement result on Nose cone for Aluminum 7075
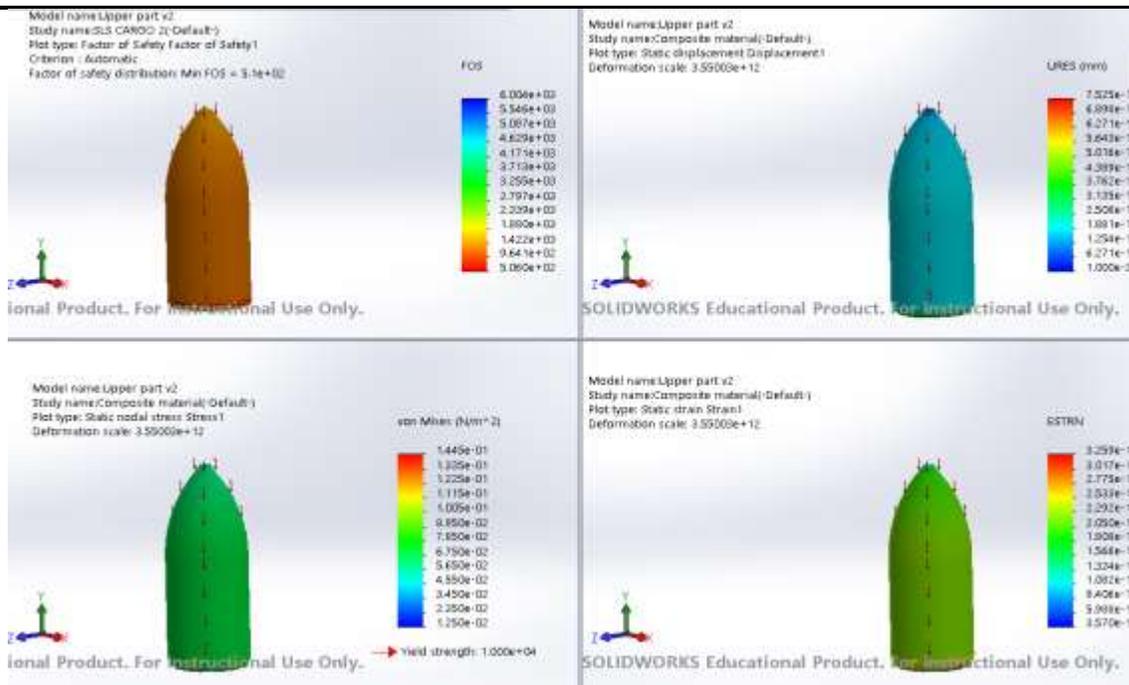
Figure 10:- Stress, Strain, Displacement result on Nose cone for Carbon Fiber

Properties	Material Name			
	Aluminum7075		Carbon fiber	
	Minimum Value	Maximum Value	Minimum Value	Maximum Value
Von mises stress N/m^2	1.58×10^4 (Node: 60505)	1.88×10^5 (Node: 7686)	1.25×10^{-2} (Node: 9678)	1.45×10^{-01} (Node: 13203)
URES: Resultant Displacement /mm	0.00×10^0 (Node: 1)	4.17×10^{-3} (Node: 3259)	0.00×10^0 (Node:1)	7.53×10^{-10} (Node:884)
ESTRN: Equivalent Strain	2.41×10^{-7} (Element:15531)	1.68×10^6 (Element: 15832)	3.75×10^{-14} (Element: 5468)	3.26×10^{-13} (Element: 5066)
Factor of Safety	5.060×10^2 (Node: 7868)	6.004×10^3 (Node: 60505)	6.920×10^{04} (Node: 13203)	7.999×10^{05} (Node: 9678)

Table 6:- Compare result of Aluminum 7075 and Carbon fiber

VI. Conclusion

The comparison has been done on the basis of four criteria which includes the von mises stress which determine the value of the yield point were the material start deforming it can see from the Table 6 that the max value of the carbon fiber material resist the impact load and less deformation can be seen in the carbon fiber. The node of the minimum factor of safety matches with the node of the maximum stress and the load of the maximum factor of safety matches with the node of minimum stress. This demonstrates the fact that as the stress increases on the node the factor of safety decreases.

VII. Acknowledgement

Citations

1. *A Peek inside SLS: Fuel Tank for World's Largest Rocket Nears Completion - NASA*. www.nasa.gov/image-article/peek-inside-sls-fuel-tank-worlds-largest-rocket-nears-completion/.

2. *Approved for Public Release; Distribution Is Unlimited.*

3. *Approved for Public Release; Distribution Is Unlimited SLS-SPEC-159 REVISION G CROSS-PROGRAM DESIGN SPECIFICATION for NATURAL ENVIRONMENTS (DSNE).*

4. Askins, Bruce. 2024.

5. ASM. "ASM Material Data Sheet." *Asm.matweb.com*, asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA7075T6.

6. Baggerman, Clint, et al. "Avionics System Architecture for the NASA Orion Vehicle." *SAE Technical Papers on CD-ROM/SAE Technical Paper Series*, 10 Nov. 2009, https://doi.org/10.4271/2009-01-3276. Accessed 22 July 2024.

7. *Block 2 130t Cargo Expanded View - NASA*. www.nasa.gov/image-article/block-2-130t-cargo-expanded-view/.

8. "Carbon Fiber | Hexcel." *Www.hexcel.com*, www.hexcel.com/Products/Carbon-Fiber/.

9. "Delta IV." *Www.ulalaunch.com*, www.ulalaunch.com/rockets/delta-iv.

10. Do, Sydney, and Olivier de Weck. "A Personal Airbag System for the Orion Crew Exploration Vehicle." *Acta Astronautica*, vol. 81, no. 1, Dec. 2012, pp. 239–255, https://doi.org/10.1016/j.actaastro.2012.06.022. Accessed 5 Nov. 2021.

11. Hao, Peng, et al. "A Novel Framework for Reliability Assessment of Payload Fairing Separation Considering Multi-Source Uncertainties and Multiple Failure Modes." *Thin-Walled Structures*, vol. 160, 1 Mar. 2021, pp. 107327–107327, https://doi.org/10.1016/j.tws.2020.107327. Accessed 22 July 2024.

12. Haws, Terry D, and Michael E Fuller. *SLS Block 1B and Block 2 with Kick Stages for Outer Planet Missions and Beyond*. 1 Mar. 2020, https://doi.org/10.1109/aero47225.2020.9172649. Accessed 22 July 2024.

13. Haws, Terry, and Michael Fuller. "SLS with Kick Stages for Science Missions to the Outer Planets and Beyond." *ASCEND 2020*, 2 Nov. 2020, https://doi.org/10.2514/6.2020-4071. Accessed 22 July 2024.

14. Henson, Grant. *Materials for Launch Vehicle Structures*.

15. *HexTow ® IM7 Carbon Fiber*.

16. Honeycutt, John H., et al. "NASA's Space Launch System: Progress toward Launch." *ASCEND 2020*, 2 Nov. 2020, https://doi.org/10.2514/6.2020-4037.

17. Honeycutt, John, and Garry Lyles. *NASA's SPACE LAUNCH SYSTEM: Development and Progress*. 2016.

18. Jacobsen, Guenther. *MECHANICAL CHARACTERIZATION of STRETCH BROKEN CARBON FIBER MATERIALS -IM7 FIBER in 8552 RESIN*.

19. "Launch Vehicle Fairings: Protecting Precious Payloads." *New Space Economy*, 6 May 2024, newspaceeconomy.ca/2024/05/06/launch-vehicle-fairings-protecting-precious-payloads/. Accessed 22 July 2024.

20. "Light Carbon-Fiber Structure Protects Heavy Space Cargo." *Air Force Materiel Command*, 23 Feb. 2007, www.afmc.af.mil/News/Article-Display/Article/155158/light-carbon-fiber-structure-protects-heavy-space-cargo. Accessed 22 July 2024.

21. Litty Molly Mathew, et al. "Design and Analysis of a Metallic Ogive Payload Fairing for a New Generation Launch Vehicle." *IOSR Journal of Mechanical and Civil Engineering*, vol. 13, no. 05, 1 May 2016, pp. 99–103, https://doi.org/10.9790/1684-13050199103. Accessed 22 July 2024.

22. May, Todd. *Space Launch System Space Launch System (SLS) Safety, Mission Assurance, and Risk Mitigation*. 2013.

23. Murugesan, V., et al. "Failure Analysis of a Launch Vehicle Umbilical Shutter Mechanism during Vibration Qualification." *Journal of Failure Analysis and Prevention*, vol. 18, no. 3, 9 Mar. 2018, pp. 457–464, https://doi.org/10.1007/s11668-018-0442-4. Accessed 13 Apr. 2023.

24. *NASAfacts*.

25. *NASA'S SPACE L AUNCH SYSTEM REFERENCE GUIDE*.

26. *Orion Components - NASA*. www.nasa.gov/reference/orion-components/.

27. *Overvi SUMMA*.

28. Patrick, Sean, et al. *ASSESSMENT and VERIFICATION of SLS BLOCK 1-B EXPLORATION UPPER STAGE and STAGE DISPOSAL PERFORMANCE*.

29. "Polar Satellite Launch Vehicle." *Wikipedia*, 28 Feb. 2021, en.wikipedia.org/wiki/Polar_Satellite_Launch_Vehicle.

30. Scarritt, Sara, et al. *(Preprint) AAS 15-096 ADVANCES in ORION'S ON-ORBIT GUIDANCE and TARGETING SYSTEM ARCHITECTURE*.

31. Schorr, Andrew, et al. *Space Launch System Spacecraft and Payload Elements: Progress toward Crewed Launch and Beyond*.

32. Shen, Frank, and Dennis Pope. "Design and Development of Composite Fairing Structures for Space Launch Vehicles." *SAE Transactions*, vol. 99, 1990, pp. 1447–1455, www.jstor.org/stable/44473117. Accessed 22 July 2024.

33. "Space Launch System." *Wikipedia*, 9 July 2024, en.wikipedia.org/wiki/Space_Launch_System#:~:text=The%20first%20SLS%20launch%20was. Accessed 22 July 2024.

34. *Space Launch System (SLS) Block 1B Secondary Payloads: ESPA-Type and 27U Cubesat Potential Accommodations WHITEPAPER*. 2019.

35. *Space Launch System Block 1B Cargo Expanded View - NASA*. www.nasa.gov/image-article/space-launch-system-block-1b-cargo-expanded-view/. Accessed 22 July 2024.

36. Sreenivasula Reddy, M, and N Keerthi. "Design and Structural Analysis of Missile Nose Cone." *Australian Journal of Basic and Applied Sciences*, vol. 11, no. 11, 2017, pp. 30–40, www.ajbasweb.com/old/ajbas/2017/August/30-40.pdf. Accessed 22 July 2024.

37. Von Der Porten, Paul, et al. *POWERED EXPLICIT GUIDANCE MODIFICATIONS & ENHANCEMENTS for SPACE LAUNCH SYSTEM BLOCK-1 and BLOCK-1B VEHICLES*.

38. Wikipedia Contributors. "Falcon 9." *Wikipedia*, Wikimedia Foundation, 14 Oct. 2019, en.wikipedia.org/wiki/Falcon_9.