AME 485 – Aerospace Structures

Project 2

Henry Glover
10/07/2024

Part 1

1. It is important to identify failure modes early in the design process to mitigate failures down the line. Failures are also promeninet in aerospace structural applications, therefore, they have to be identified as early as possible. It is the goal of the engineer to avoid expensive failures during test programs, production phases, and operational life.

2. Four sources of failures in aerospace design include:
    1. Hardware defects – these can be caused by known or unknown manufacturing issues.
    2. Carelessness – failure to convert units, cutting cost or manufacturing corners, saving time and not balancing judgment, inaccurate cahrateriziations of material properties, dishonesty, etc.
    3. Assembly errors – incorrect assembly of a part or system which can include incorrect torque specs, sequencing, or omitting/adding unspecified components.
    4. Normal wear and tear – creep, fatigue, and fracture are all examples of expected failure modes.
    5. Overload – where the stress exceeds the strength of the material or system.
    6. Excessive deformations – caused by a material to underperform more than expected/tested.

3. Five failure modes specific to metals include:
    1. Creep – where permanent deformation occurs as a result of an exceeding amount of stress
    2. Stress rupture – failure when a component has been statically loaded at a high temperature for a long period of time
    3. Crack propagation life – where an initial crack on a component from an initial flaw size grows to a critical prorogation and failure happens
    4. Ductile fracture – where a meatal undergoes significant plastic deformation before failing.
    5. Corrosion – when metals chemically degrade as a result of the harsh environment.
    6. Hydrogen embrittlement – failure when there is absorption of hydrogen in metals, which leads to a loss of ductility and an increase in brittleness.

Part 1

4. Failure modes specific to composite laminates include:
    1. Matrix cracking/failure – the matrix of the composite material can develop cracks in the resin due to mechanical loads, thermal stresses, or harsh expose to the environment.
    2. Delamination – when layers of the composite laminate begin to separate due to a weak bonding between the layers.
    3. Fiber breakage – when fibers in the composite has an applied load that exceeds the tensile strength of the fibers, causing a breakage.

5. Failure modes specific to composite sandwich structures include:
    1. Core shear failure – when the composite laminates doesn't have enough core strength or panel thickness.
    2. Face fracture – when the composite face sheets have insufficient panel thickness, facing thickness, or facing strength. A fracture can occur in tension when fibers break or in compression due to buckling.
    3. General buckling – when composite sandwich structure has insufficient core shear rigidity or insufficient panel thickness. This is a global structural deformation.
    4. Face wrinkling – when the face sheets of the composite laminates of the sandwich structure wrinkle when subjected to compressive loads. This is a localized buckling of the face sheet.
    5. Shear crimping – when the core material of the sandwich structure fails under shear loading usually caused by a low core shear modulus or a low adhesive shear strength.

Part 1

6. Failure modes of bonded joints include:
    1. Adhesive failure – when the adhesive layer between the bonded surfaces fail.
    2. Cohesive failure – when the adhesive itself breaks down, not the bonded surface causing a failure.
    3. Peeling failure – when the bonded joint is subject to forces that "peel" one adherend away from the other in opposite directions perpendicular to the bond line.
    4. Metal adherend bending – when the metallic adherends undergo a significant amount of bending, causing a break in the bond line.
    5. Interlaminar failure – when the layers of the composite laminate separate between the layers.

7. Failure modes of mechanically fastened joints:
    1. Net section failure – the material between the fastener hole and the hole fails in tension. The material encompassing the fastner hole fails.
    2. Bearing failure – the material around the fastener hole is deformed causing a reduced carrying capacity of the joint and/or a misalignment of the joint. The fastener hole is deformed and potentially destroyed.
    3. Shear-out failure – when the material shears out from the edge of the fastener hole to the edge of the structure.
    4. Cleavage failure - when a significant load is applied on the fastener causing a high stress situation on the fastener or at the edged of the joint leading to a fracture/crack.
    5. Bolt failure – when the bolt in a mechanically fastened joint fails due to excessice stress. There are various causes for bolt failures which include: shear failure, tensile failure, fatigue, and bending failure.

Part 1

8. Three aerospace examples:
   1. Delamination
      1. In 2020, a Boeing 737-8FE departing from Queensland to Melbourne, Victoria was climbing to its cruising altitude and a passenger alerted the crew to a disconnected panel on the aircrafts left wing. The panel was dislodged on the trailing edge of the flap. The crew subsequently requested to land the plane immediately. An investigation was pursued, and it was found that delamination on the flap had occurred due to the moister ingress and the excess amount of heat from the aircraft's engine. Following the investigation Boeing released a modified metallic assembly that was to be retrofitted on aircraft. The operator of the airline conducted a fleet investigation and found 7 other aircrafts had delamination findings.

   2. Fatigue/crack propagation
      2. In 2022 the crew of a Boeing 737-800, registration, VH-YFZ departing from Queensland noticed during climbing that the aircraft tended to roll to the right and trimmed the rudder to keep the wings level. Once the flight reached cruising altitude the issue disappeared only to reappear during the decent when the flaps were actuated again. The aircraft landed safely but, an investigation determined that a fatigue crack progressed through the aft flap's inboard programming roller cartridge. The undetected fatigue crack eventually led to the fracture of the component's surfaces under excessive stress not allowing the flap to function properly.
         2. Boeing has had 10 reports of similar occurrences between 2017 and 2022. Because the failure of this component did not affect the controllability of the aircraft, the safety recommendation given by the investigation team were subpar. The team recommend Boeing adopt a better detection system to point out fatigue cracks in the roller cartridges of the 737-800 before failure occurs.

Sources: ATSB (Australian Transport Safety Bureau)

Part 1

2. Fatigue/crack propagation - Boeing 737-800, April 27, 2022

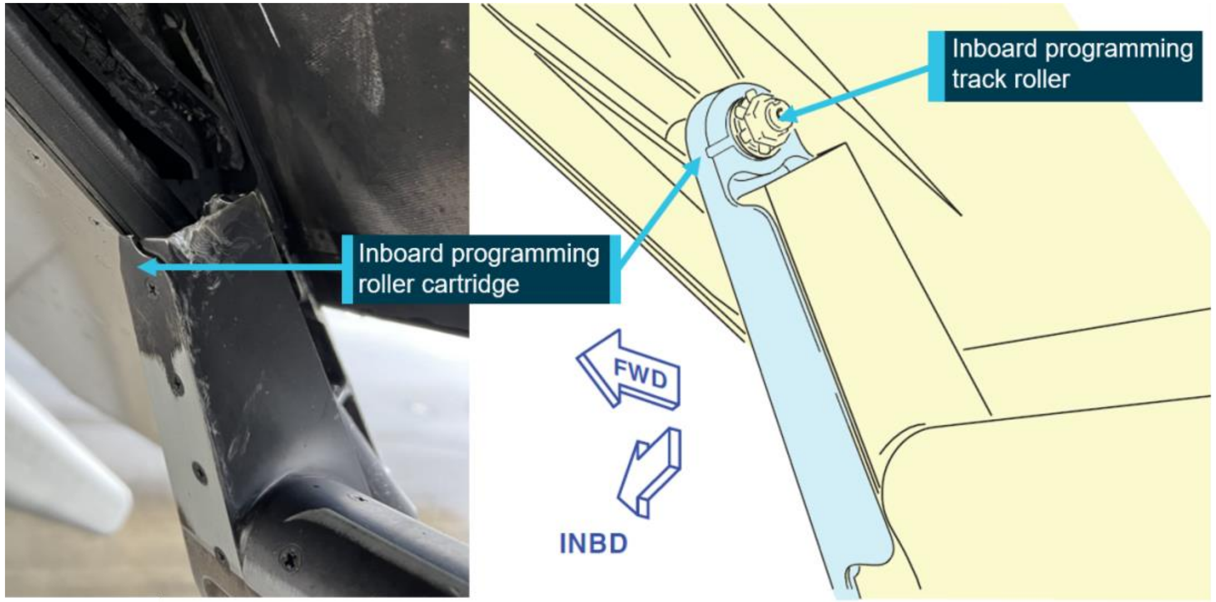

Figure 1 - Image and diagram of the inboard programming roller cartridge.

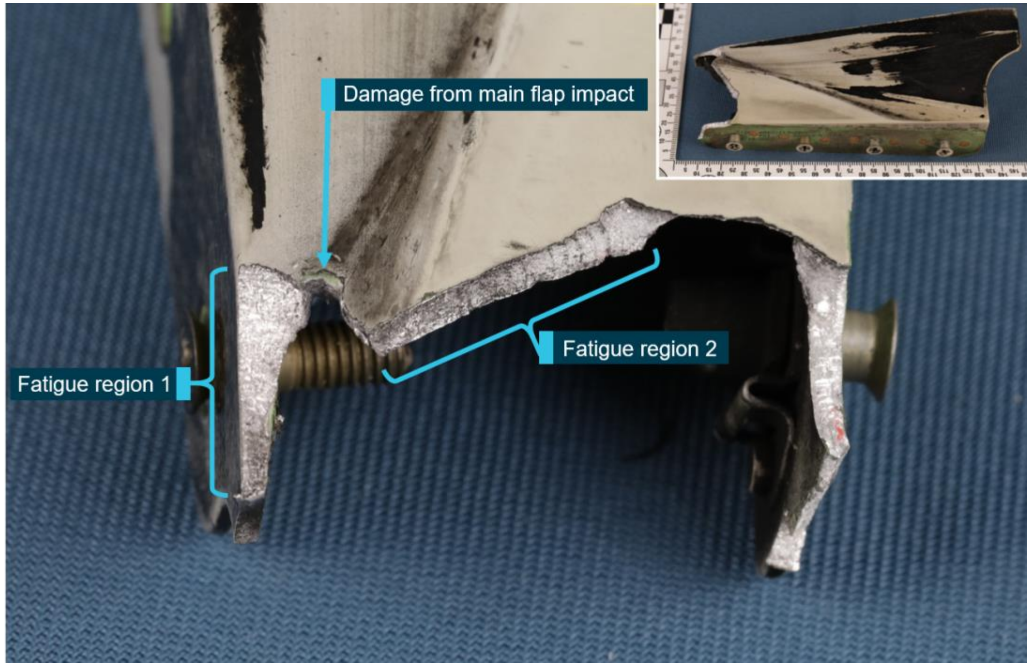

Figure 2 - Actual image of the component fracture.

Sources: ATSB (Australian Transport Safety Bureau)

Part 1

Sources: NTSB, ASN (Aviation Safety Network)
https://asn.flightsafety.org/reports/2016/20161028_DC10_N370FE.pdf

8. Three aerospace examples:
    3. Corrosion
        3. On Friday 28, October 2016 a McDonnel Douglas MD-10-10F converted into a cargo plane owned and operated by FedEx crash landed in Fort Lauderdale International Airport with two occupants inside. Following a successful touchdown on the tarmac, the left main landing gear collapsed after landing on runway 10L. An NTSB investigation found that an overstress fracture emanated from the air filler valve bore. Later findings suggested that the crack initiation was caused by a corrosion pit however, a corrosion repair was completed on the accident cylinder, and it underwent brush cadmium plaiting per the maintenance manual before being sent back into service. Further investigation found that there was no indications of nickel, chrome, or cadmium plating found at the radius or along the sections of the air filler valve bore where the corrosion emanated from. The lack of any protective coating likely, over time, caused the corrosion pitting.

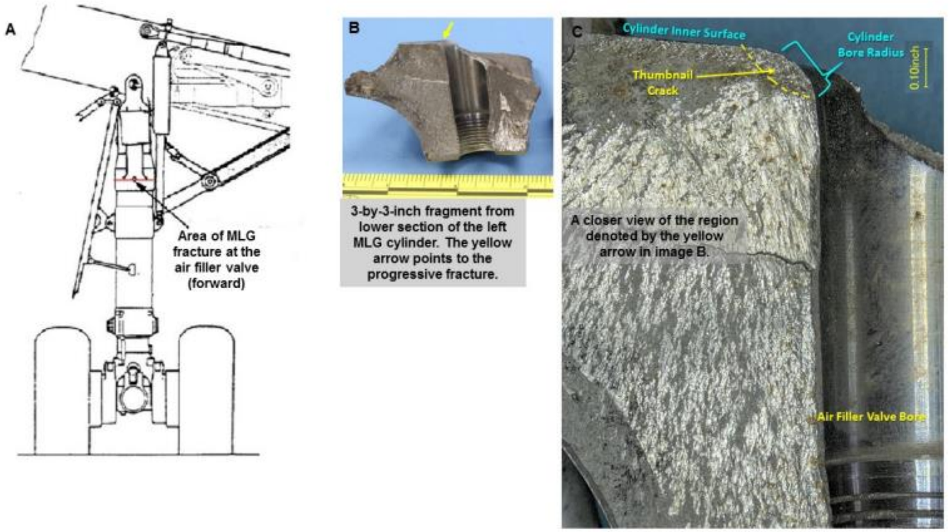

Figure 3 - Image and diagram of the MLG

Figure 4 - Image of the air filler valve bore

Figure 5 - Image of the accident

Part 1

9. Damage Tolerance in aircraft design ensures an aircraft can withstand certain levels of damage without experiencing a cataphoric failure. Southwest airlines has a unique business model. They fly short domestic flight as cheap as possible for as long as possible. Failures occur with Southwest airlines because their flight hours per aircraft are far lower than their flight cycles per aircraft. This introduces Southwest to various incidents related to damage tolerance often occurring with fatigue failures.
    - Southwest Boeing 737-7H4, N772SW had a failure of its Left CFM turbofan engine while climbing to the aircraft cruse altitude. Investigation found that shims for blade number 11, 12, and 13 were cracked. The cause of the cracking was a low-cycle fatigue crack in the dovetail of the fan blade number 13 which resulted in the separation of the engine. The low cycle fatigue initiated because of higher-than-expected dovetail stress under normal operating loads. The plan landed safely and there was one death. Boeing was required to determine the critical fan blade impact locations on the engine fan case and redesign the fan cowl structure on all Boeing 737 to ensure the rigidity of the cowl after a fan blade out event.
    - Southwest Airlines flight 812 had a failure in the fuselage where a hole developed during flight causing a rapid decompression. The investigation found that the failure was due to meatal fatigue caused by inadequate maintenance inspections of previous repairs. Southwest airlines was mandated to inspect all the older 737 aircrafts. They also were made to increase the frequency of inspections and instituted better maintenance protocols.
    - Boeing 737-700 skin cracking was discovered on the fuselage of several Boeing 737-700 aircraft in Southwest's fleet. The investigation revealed fatigue cracks due to the number of flight cycles and the aircraft age which exceeded the manufactures recommendations for inspections. The FAA issued Southwest to inspect all of the 737-700 aircraft and mandated repairs or replacement of affected components.
    - Boeing 727-800 rudder issues were identified during routine inepction rasing concerns about potential failures. Investigation have indicated that wear and tear on critical components such as the rudder system are caused by the aircrafts age and high stress environments. Southwest has been under fire and works closely with Boeing as well as with regulatory aurhtroties like the FAA to address these issues.

    Due to southwest airlines business model, adequate inspection and maintenance protocols are overlooked and haven't been adjusted. Recently the FAA has made efforts to enhance its maintenance and inspection protocols to accommodate this model. As more budget airlines adopt similar practices, it is essential for the aviation industry to adapt to the low flight hours and high flight cycles methodology.

Sources: NTSB

1. https://libraryonline.erau.edu/online-full-text/ntsb/aircraft-accident-reports/AAR19-03.pdf
2. https://www.ntsb.gov/investigations/AccidentReports/Reports/AAB1302.pdf
3. https://www.reuters.com/article/us-faa-boeing-southwest/faa-launches-probe-after-in-flight-incident-reveals-12-inch-crack-on-737-jet-idUSKBN21039D/

Part 1

10. CTE mismatch is a problem in spacecraft design because of the extreme temperature conditions spacecraft go through. Coefficient of Thermal Expansion is the amount a material expands or contracts during a change in temperature. A low CTE is good in spacecraft design because it means the material is less sensitive to temperature changes. In space, there is a wide variety of temperature conditions. Large temperature extremes and CTE mismatch of materials can effect a space crafts ability to perform, cause damage, or cause complete failure.

11. These are the ten lessons learned from the paper: *NASA Structural Analysis Report on the American Airlines Flight 587 Accident–Local Analysis of the Right Rear Lug*.
    - It is important when testing to split duties and workloads into separate teams to allow for a more thorough, error free investigation. For instance, a global analysis team and a detailed lug analysis team was created to analyze this incident. The global analysis team envaulted loads on the lugs, out of the 6 lugs holding together the VTP (Vertical Tail Plane) to the fuselage, the right most lug contained the largest loads compared to the allowable loads. The detailed lug analysis team worked on analyzing the failure of the right most composite laminated lug (it was a cleavage type failure)

CONTINUE ON NEXT SLIDE

Part 1

11. These are the ten lessons learned from the paper: *NASA Structural Analysis Report on the American Airlines Flight 587 Accident–Local Analysis of the Right Rear Lug.*
    - It is important when testing to split duties and workloads into separate teams to allow for a more thorough, error free investigation. For instance, a global analysis team and a detailed lug analysis team was created to analyze this incident. The global analysis team envaulted loads on the lugs, out of the 6 lugs holding together the VTP (Vertical Tail Plane) to the fuselage, the right most lug contained the largest loads compared to the allowable loads. The detailed lug analysis team worked on analyzing the failure of the right most composite laminated lug (it was a cleavage type failure)
    - As an engineer there are certain adjustments you have to make when you run into problems especially in progressive failure analysis to be accurate and to produce high quality work. For instance, specific to this analysis, there where software limitations and engineers had to deal with the fact that even though the right rear lug contained multiple plies of T300/913C material in the form of fabric or tape, it was not possible at the time to produce a finite element model that modeled each of the individual plies. This would have required millions of nodes/elements. Furthermore, element extinction was not a thing in ABAQUS and a complete full separation model of the lug was not implemented.
    - Engineers have to adapt to the problem. For instance, A displacement controlled load increment was chosen in PFA because it has fewer convergence difficulties after damage initiates because the load in variable and can decreases as damage occurs and the material has less strength. This was taken over a displacement control method.
    - For failure prediction, load transfer mechanism have to be understood for accurate prediction. For instance, the lug is held in place using a pin held in place only by friction. The pin-lug interface had to be characterized and modeled using advance math (developed a Multi-point constraint equation).
    - Engineers have to apply the proper failure criteria. For this analysis Hashin's criteria was used to characterize the failure modes in the composite material. His criteria assumes that the stress components associated with the plane of fracture control the failure.
    - When modeling it is important to choose modeling approaches that fit the analysis. For this analysis, solid-shell modeling and layered-shell modeling – layered shell means that the lug thickness is made up of several layers rather than a set number of elements in solid-shell – were used.

Part 1

11. (Continuation) These are the ten lessons learned from the paper: *NASA Structural Analysis Report on the American Airlines Flight 587 Accident–Local Analysis of the Right Rear Lug.*
    - Validation of experimental results is important. In this case, the progressive failure analysis methodology was validated with older data. The data agreed excellently between predicted and observed failures in both the 1985 certification from airbus and the 2003 subcomponent test. The material past its predicted set failure mode in all tests.
    - Moment played a huge factor in this accident. Higher absolute values of moment from the fuselage significantly reduced the failure loads of the lugs.
    - What is observed from the recovered parts from the accident is crucial in telling the complete story and can help verify isolated tests done on a computer that "mimic" the parameters of the accident. For instance, the cleavage type failure generally agreed with the photos from the recovered, damaged part.
    - Load path analysis is significant to see how the forces were distributed throughout the part that held the lugs. The composite material did its job and performed how it should have according to the data. The NASA analysis confirmed this.

Part 1

12. BVID is barely visible impact damage that is not immediately apparent upon visual inspection. Here are three examples not provided in class.
    1. Notched impact damage – This is damage that occurs when an impact creates a small concentrated stress point that then turns into a notch or small crack. This can be considered BVID of the notch or crack is so small that there are no visible signs but still concentrated stresses.
    2. Blistering – Damage that causses the surface of a composite or a layered laminate to from a small raised deformed area. This could be caused by delamination or separation beneath the surface layer caused by a impact. The void that pushes up the surface layer can be hard to see visible especially in micro conditions.
    3. Pull-out – damage where the fibers or piles in a composite are displaced from the bonding material due to an impact. Fibers in the composite may be pulled out under the surface and the damage may not be visible.

Part 1

13. 10 lessons learned in the report *Guidelines for Analysis, Testing, and Nondestructive Inspection of Impact Damaged Composite Sandwich Structures*:
    1. BVID or nonvisible defects that are not detectable during the manufacturing inspections must endure ultimate loads and not affect the aircraft operation throughout its lifetime, assuming they may never be discover in service inspections. This is important because it is key to damage tolerance and building an aircraft or spacecraft that can withstand certain assumption loads.
    2. Damage that occurs in flight that is immediately obvious should be able to exceed a CDT (Critical Damage Tolerance), requiring the aircraft to maintain limit load capability for a limited maneuver to ensure a safe continuation of flight.
    3. There is a key relationship between planar damage area and impact energy, this highlights that the design and certification efforts typically depend on impact energy and surface visibility for assessing damage tolerance. The investigation in the paper found that the specimens impact diameter significantly influences the resulting damage area. Core thickness is also a contributor to the damage area.
    4. Effective damage detection techniques should focus on quantifying the planer damage to assess residual strength. Data shows that residual strength degradation does not correlate well with the maximum residual indentation, suggesting that the size of planar damage is a more accurate way of finding residual strength in impacted panels.
    5. Core damage in honeycomb core sandwich structures was predominately cell wall bucking, core crushing, and cell wall fracture.
    6. Damage in sandwich panels is confined to the facesheets and core, causing geometric imperfections shown as residual indentations. Thus, the maximum residual indentation depends on the facesheets stiffness and the core's degraded material properties. According to the data, thicker panels show smaller indentations despite having larger damage areas, and fractured cores provide no tensile resistance, making damage harder to detect.
    7. For curved sandwich panels with a smaller internal radii, the core near the impact point experienced higher shear, resulting in lower failure strength and increased damage area from blunt impacts. However, maximum residual indentation depth decrease with larger radii, with curved panels showing minimal permanent indentations. For large impacts, the high restoring force of curved factsheets leads to a lower indentation making it hard to see visually. For smaller impacts there are more noticeable skin fractures on curved sandwich panels.

Part 1

13. 10 lessons learned in the report *Guidelines for Analysis, Testing, and Nondestructive Inspection of Impact Damaged Composite Sandwich Structures*:
    8. The fatigue life and residual strength degradation of honeycomb and foam core sandwich panels depended on the load ration of an impact. Results showed that fatigue life decreased as the load ration increased at certain minimum fatigue loads. Residual strength degradation ranged from 5% to 30% for sandwich specimens that survived the prespecified infinite life of 150,000 cycles.
    9. Stiffness properties of sandwich panels, their energy absorption capabilities, and the support boundary conditions all contribute to the dynamic impact response that results in damage development.
    10. Resonance surface estimates show that residual strength greatly increases when the number of facesheet plies increases.
    11. FEA can offer some estimates of residual strength for impact damaged sandwich structures, provided that the actual initial damage is identified using a standard NDI technique. But the conclusion is that you have to be careful when looking at numerical analysis to estimate residual strength because there is significant variability. The progression of damage and failure may be based on the local damage distribution and residual stress fields both of which are challenging to address using FEA.

Part 1

14. Pilots avoid lightning and hail damage by utilizing a combination of techniques. First, planning is important for airlines, weather radar systems are used to map out the flight before takeoff to avoid dangerous weather. Radar systems inform pilots of current weather patterns as well as future weather patterns on an upcoming route. Secondly, close flight coordination with air traffic control is crucial for updated weather forecasts and real time storm movements. With clear communication, pilots are allowed to request a maneuver around a storm to avoid where hail and lighting are present. Lastly, if the aircraft is caught in a storm, aircraft manufactures certify the planes and outfit them with lighting and hail protection systems. For lighting, the fuselage of an aircraft has a conductive outer skin and static wicks that can dissipate an electric charge during the even of a strike. For hail, the fuselage is rated for a certain amount of protection in the off chance of a serious hailstorm. That being said, pilots use tactical maneuvering, and real time weather updates to avoid hailstorms at all costs.

Part 1

15. 10 lessons learned after hail impact damage article:
    1. Detectable damage size and damage tolerant designs are interconnected in engineering. A critical failure that weakens a structure should be identifiable with existing NDI methods (non-destructive inspection). If inspection methods can't detect certain flaws, then the design must be able to withstand or accommodate larger defects without any compromise. Essentially, enhance the structures damage tolerance as a safeguard when dealing with critical applications such as transport aircraft.
    2. Methods of inspection are important in fact checking tests. Strain gauges, load cells, optical correlation methods, conventual single element UT inspection (using frequency), phase array UT inspection, LUS techniques (using a laser beam to produce an ultrasound), thermal wave imaging, etc… are all employed to perform analysis and certification.
    3. Ultrasonic Testing (UT) is very effective at assessing lighting strike protection (LSP) and ice protection systems. This is because UT has great depth penetration and can assess multilayer composites. They also have a high sensitivity and are versatile. UT can analyze the conditions of each layer in a composite structure something that is not possible with other methods. For instance, studying hail damage on composite materials is more efficient using this tool to assess the impact damage down to the layer.
    4. Hail damage sometimes leaves little to no surface visual indications of impact or damage. This was simulated in a test where hail was impacted on a carbon fuselage panel at 390 ft per second and little to no damage was visually found.
    5. At UCSD, when testing impact results using a gas gun, a carbon fiber fuselage panel was fabricated. The section described something interesting about the skin layup of the panel. Tapered stringers improve stress distribution at the stringer to skin interface, reducing the risk of disbanding and minimizing the shear stress in the skin near the stringers edge during impact. Furthermore, a pad build up with 12 extra piles under each shear tie provides more material for fastening the shear ties to the skin.
    6. To simulate “tool drop” scenarios or ground-based impact damage (when an aircraft is stationery and hail impacts it on the ground), a drop weight, spear type impact device was design to simulate damage by applying a hard, spherical tipped impacts that included varying levels of damage.

Part 1

15. 10 lessons learned after hail impact damage article:
    7. MIA (Mechanical Impedance Analysis) and LFBT (Low-Frequency Bond Testing) NDI techniques were used to assess the validity of the technologies when conducting hail impact damage tests. MIA compares the stiffness of a structure by sending sonic vibrations through a probe into the material and measuring how it resonates. It was more effective and sensitive to damage in thinner 8-ply panels but struggled with thicker 16 and 24-ply panels. LFBT is a lower frequency bondtester that detects the differences in sound propagation (waves) between damaged and undamaged panels. It is also less effective at deeper penetration, detecting less damage in thicker panels compared to more sensitive ultrasonic testing.
    8. Inspection comparison on a 16-ply panel impacted with a 50.8mm diameter hail ball provide the importance of NDI. To the naked eye it was not visible, and the damage was not detected in the flash thermography scan, in resonance inspection, or by the RDC (Ramp Damage Check). This shows the importance of an impact database to compare sensitivity of different NDI methods.
    9. For hail damage, these are the capabilities of the NDI methods.
        - LFBT (Low Frequency Bond Testing) was not adequate to detect damage in panels
        - MIA (Mechanical Impedance Analysis) detected some level of delamination near the surface but ineffective for small or deep damage in thicker plies.
        - TTU (Through Transmission Ultrasonic) testing was effective in delamination inspection but struggled with microcracking and depth detection on thicker plies.
        - UT (Ultrasonic Testing) worked for detecting low-level hail damage but had a low resolution.
        - Flash thermography detected delimitation but had a hard time detecting light damage in thicker laminates.
        - MAUS (Mobil Automated Scanner) resonance was not as sensitive as PE-UT (Pulse-Echo Ultrasonic Testing).
        - RDC (Ramp Damage Check) worked at detecting delamination in flat panels but struggled with areas where there was only an amplitude decrease.
        - A-Scan analysis helped with delamination depth and verifying intended damage after impacts.

Part 1

15. 10 lessons learned after hail impact damage article:
    10. Inspections of SHI (Static Hail Impact) revealed that interplay delamination's in the skin and stringer flange delamination's were the most common damage modes. This was observed using C-scan imaging to illustrate the differences. Also, it was found that hail impacts caused damage further away from the impact site than originally anticipated, leading to some damage far from the initial impact area being undetected during the initial A-scan inspection.
    11. Ice impact damage located at the edge of a stringer flange caused a complete dis-bond of the stringer flange even though the built-up pad sections of the shear ties helped prevent further dis-bonding. This is interesting because a 721-joule impact at the mid-bay skin not next to a stringer creates no visible damage and slight delamination but a 261-joule impact in the edge of the stringer can create a complete stringer dis-bonding.
    12. Three main type of damage were identified from hail impacts. Interply delamination in the 16-ply skin, dis-bonding at the skin-to-stringer flange interface, and shear tie cracking. Interply skin and substructure delamination were detectable using NDI techniques, shear tie cracking was only visible form the underside of the panel.

Part 2

1.

Components	Function	Potential Failure Modes
Liquid rocket engine	Provides thrust for the stages	Cracking of rotor blades, temperature-induced fatigue, strength failure, seal leakage, plumbing failures, valve failures, combustion instability, buckling, etc…
Liquid booster tanks	Provide storage for fuel and LOX to boost second stage	Weld lands can buckle, welds can fracture, skin and seam welds can fail, stringers carry line loads
Payload fairing	Nose cone that protects the payload in launch conditions	Stability, separation joint strength, contamination of spacecraft during separation, composite and sandwich failure modes, buckling
Upper stage	The last stage that provides thrust to place spacecraft into orbit	Skin rupture, buckling critical, fracture critical
Pressure vessels	Stores liquid or solid fuel and oxidizer	Fiber failure, metal liner buckling, metal fracture, weld fracture, metal fatigue
Intertanks	Interstage transition provides the transition from the separate stages from fuel to oxidizer tanks	Shells critical in compression, joints critical in tension, metallic/composite sandwich failure modes, buckling, bolted joint failure, strength failure modes
Valves	Used for various control and regulation of fuel, vacuum, pressure, and latches.	Leakage, Structural fatigue, Material compatibility, Contamination, vibration failure, stiction, impact stress failure

Part 2

1. (Continuation) For the SpaceX Falcon 1

Components	Function	Potential Failure Modes
Merlin engine	Liquid Engine that provides thrust using LOX and RP-1	Turbopump failure, combustion instability, pump failure, ignition system failure, vibration fatigue, thrust control, temperature control
Kestrel engine	Provides the second stage with thrust	Combustion chamber pressure failures, cooling failures, pump failure, thrust decay, structural strength and yield failures
Fuel tank	Stores the LOX and RP-1	Tank rupture, fiber failure, metal liner buckling, metal fracture, weld fracture, metal fatigue
Interstage	Falcon 1 is a two-stage rocket, the interstage connects the stages	Aerodynamic stress, fatigue, vibration fatigue, thermal damage, structural failure, separation failure, contamination and debris failure, overpressure
Payload fairing	Protects the payload	Stability, separation joint strength, contamination of spacecraft during separation, composite and sandwich failure modes, buckling
Stage separation	Detaches the first stage from the second stage	Separation timing, mechanical, connection failure, pyrotechnic device failure, debris obstruction, structural damage, aerodynamic locking, control system failure, electronic failure

Part 2

2. The components of a rocket engine consist of the following: This is a generalized list, there are several forms of rocket engines, that include closed, open, and full flow combustion cycles.
   - Fuel turbopump – delivers RP-1 rocket fuel to the combustion chamber at an increased Psi from the storage tanks.
   - Oxidizer turbopump – Delivers the oxidizer (oxygen) to the combustion chamber at an increased Psi from the storage tanks.
   - Turbine - Powers the fuel and oxidizer turbopump by generating an amount of horsepower into a rotational motion used in the turbopump.
   - Pre-burner- Burns a small amount of oxidizer and fuel to generate hot gases that supply the turbine with power (can be called a gas generator).
   - Control valves – limit, manage, or regulate the flow of fuel and oxidizer to make sure the combustion reacts properly.
   - Igniter – How the combustion is initially ignited (think spark plug)
   - Combustion chamber – where the fuel and oxidizer mix and react with each other to produce a combustion.
   - Heat exchanger – Used to regulate heat from the engine to another system, this includes warming up fuel and oxidizer to be ready for combustion.
   - Nozzle – Where the hot combustion gasses and thrust accelerates to generate a thrust that is outputted.
   - SpaceX uses the merlin engine where two propellant tanks roughly at 50 psi each of LOX (liquid oxygen) and RP-1 (rocket propellant) are fed to the combustion chamber using a turbopump to increase its pressure at about 1400 psi. The turbopump is constructed of two back-to-back impellers on a single shaft that intakes low pressure LOX and outputs high pressure LOX through a control valve. The control valves monitor the pressure that goes into the injector. The RP-1 tank is also fed to the turbopump where it gets outputted into another control valve at 1500 psi and into the combustion chamber where the fuel flows up the channels of the chamber to keep it cool. A turbine and combustor, made up of a gas generator, are used to generate horsepower and drive the two turbopumps. The gas generator uses a little of LOX and RP-1 and burns the gasses fuel rich at around 1400 F. Temperature control is key to not burn the blades of the turbine. Lastly, the nozzle is where the hot gases and thrust are made and outputted. The nozzle produces around 110,000 lbF of thrust in altitude. The merlin engine has a mass flow rate of roughly 350 lb/m per second and requires lots of fuel.

Part 2

3. *Design of Liquid Propellant Rocket Engines* – Components and Failure modes
    - Thrust chamber – contains the combustion of the propellants – Failure modes: Combustion instability, abrupt pressure surges, erosion from wall temperatures exceeding the values assumed during design.
    - Injector – injects the mixture of fuel and oxidizer into the combustion chamber - Failure modes: injector can burn through, melt, leak, blockage, erosion.
    - Propellant EVAP system – liquid propellant is evaporated for injection into the combustion chamber, limited use - Failure modes: pressure loss and thermal degradation, it is noted that this device is used for low pressure applications and has to be used with cryogenics (low temperature propellant)
    - Turbopump – Propellant feed system that increases the pressure of the propellant to feed into the combustion chamber - Failure modes: bearing failure, seal leakage, blade erosion, pressure loss, contact fatigue.
    - Centrifugal pumps – Moves propellant using rotational energy - Failure modes: cavitation, impeller failure, ball bearing failure, leakage
    - Axial flow pumps – Moves propellant using a linear flow direction (inducer – increase the static pressure to permit normal operation of the main propeller) - Failure modes: pressure failure, fatigue on vanes, cavitation (can't starve).
    - Turbines – powers the turbopumps using gas energy - Failure modes: vibration failure, fatigue, thermal failure, seal failure, blade cracking.
    - Thrust level control – Adjusts the engine thrust during operation - Failure modes: control system failure, sensor failure, actuation mechanism failure, vacuum, temperature, and radiation effects on exposed high-speed bearing and dynamic seals, micrometeorite penetration of fluid passages.
    - Thrust vector control – Altitude control of the thrust vector by gimbaling the entire engine - Failure modes: hydraulic or pneumatic actuator failure, control logic failure, mechanical binding.
    - Propellant Valves – Regulates the flow of propellant into the combustion chamber - Failure modes: leakage, sticking, proper actuating time, pressure drop, fatigue.
    - Gas pressure Regulators – Maintains gas pressure for the engine component - Failure modes: blockage, valve failure, actutation failure, leakage, pressure oscitations.

Part 2

3. *Design of Liquid Propellant Rocket Engines* - Components and Failure modes
    - Pressure relief valves – Relive valve to rid the extra pressure - Failure modes: valve sticking, flow capacity failure, environmental conditions (temp, gravity, vibration), partial opening position failure.
    - Tubing – Transfer liquid (oil, gas, propellant, etc..) between components - Failure modes: pressure drops, cracking, contamination, leakage, erosion.
    - Flange joints – Joint that connects parts of the engine (tubing, engine components, etc..) - Failure modes: overstress, thermal consideration for large temperature drops and steep temperature increases, fatigue.
    - Brazed joints – Metal joining process using heat to melt a filler metal to create a joint - Failure modes: weld failure, corrosion, fatigue, thermal cycling.
    - Electrical system – Powers the structure and engine - Failure modes: wiring damage, circuit failure (short circuits), timing failure, high power draw.
    - Engine instrumentation – Reports the values of the engine to the crew - Failure modes: improper execution of command signals, calibration issues, sensor failure.
    - Engine to vehicle interface – Connects the engine to the rest of the spacecraft - Failure modes: vibration failure, misalignment, heat protection (thermal failure), mechanical failure of fasteners, bolts, joints, and welds.
    - Propellant tanks – stores the propellants
        - Cryogenic liquid tanks – Stores cryogenic propellants at extremely low temperatures - Failure modes: thermal issues (boil off), tan rupture, insulation failure, weld and joint failure.
        - Fiber glass filament tanks – Lightweight propellant storage tanks - Failure modes: delamination of composite material, pressure loss, fatigue, cracking.

Part 2

4. The components of a solid rocket motor include,
   - Propellant grain – The solid material that burns to produce thrust. This is the rockets fuel.
   - Thrust skirt – This is a support component that helps stabilize the motor when thrust is being produced.
   - Forward end ignitor – This initiates the combustion of the propellant grain.
   - Motor case – This is the structural shell that encapsules the fuel and the other components.
   - Protective coating – A coating to protect the system from heat, corrosion, and other environmental factors.
   - Thrust termination port – The port/opening where a pressure relief valve is located to stop the engine incase of a catastrophic failure.
   - Insulation – The material lining between the grain and the motor case that minimizes heat transfer to prevent structural failure.
   - Propellant release boot – A component to manage the flow of combustion gases and propellant during the ignition and combustion.
   - Nozzle assembly – Where the exhaust gases that produce the thrust come out of.
   - Nozzle throat diameter – This area of the nozzle controls the flow (speed) of the exhaust gases to regulate the velocity of the rocket.

   Failure Modes
   - Buckling of thin wall shells in the motor casing.
   - Local weld discontinuities – where the weld stress state includes residual stress and bending stress because of radial mismatch and angular mismatch.
   - External loads such as aerodynamic forces and maneuvering loads
   - Pressure failures
   - Attachment loads to the motor case – can cause various amount of tensile, compression, biaxial, bending, shear, and torsion loads.
   - Material selection (titanium, aluminum, steel, etc.)
   - FOD – foreign object debris
   - Corrosion
   - Low cycle fatigue
   - Ductile failure and brittle failure for material selections
   - Thrust misalignment

Part 2

4. The lessons learned from the document include the flowing
   - The material selection process is very important when designing a solid rocket motor because of its exposure to dynamic environments, conditions, loads, and cycles.
   - The case material is of the most importance to withstand all the failure modes because it encompasses the rocket motor and its components.
   - A safety factor should be used to account for contingencies.
   - Environmental factors such as being in a vacuum are considered in the design process.
   - NDI is employed in the design process.
   - According to the mission, appropriate propellant grain size and composition should be accounted for. The grain composition and shape influence the burn rate and performance of the rocket motor.

Part 2

5. Ariane 6 user manual:
   - Ariane 6 is a new generation launcher that will cover a wide range of missions, including GEO, Polar/SSO, MEO, and others, with an increase in payload capacity and high reliability compared to Ariane 5.
   - Components of the Launch vehicle include the Vulcain 2.1 engine and the Vinci engine.
   - The company was founded in 1980 and has over 324 launches and contracts for 850 payloads. Launches take play in Guiana Space Center in the French Guiana.
   - Data is collected on the performance of the launch and vehicle which includes payload mass, mission profiles, and accuracy of payload delivery. The average mission ranges from 1 to 6 hours.
   - The spacecraft has certain design, material selection, properties, and verification requirements to be able to launch.
   - The launch vehicle has slandered interface dimensions and properties to be able to fit various payloads. This is outlined in chapter 5 of the manual. The spacecraft interfaces that are detailed here include the payload adapter, faring, dual launch structure, and the electrical equipment. The payload usable volume is also stated, and the accessibility of the encapsulated spacecraft is provided through the fairings access door.
   - There are mechanical and electrical fit checks performed before launch campaign to confirm the parameters of the spacecraft. They work with the customer to see if their payload can properly fit.
   - The manual gives data on the location of the space center. This is important for delivery of the payload to the space center, logistics, the location of hazard processing facilities, propellant storage areas, secure areas, how close a airport runway is, how close a harbor is for shipping a pay load. All the various logistics will be determined based on the location of the space center.
   - The payload processing center is described in detail for the companies that contract the use of the Ariane 6.
   - Environment conditions are stated, communication networks are explained, transportation and handling of payload is explained.
   - Facilities for launch operations are discussed.
   - Chapter 7 discuses the mission launch parameters, which include the launch pad integration, timing of events (when everything happens), mission integration and launch service management. Then lastly, there is a final safety training, and quality assurance details.

Source: Ariane 6 User Manual Issue 2

Part 2 #4 Table

Potential Mechanisms	Function	Expected Failure Modes
Payload Fairing	Protects the payload from launch conditions	Stability, separation joint strength, contamination of spacecraft during separation, composite and sandwich failure modes, buckling
Payload adaptor	Secures the payload to the upper stage	Separation, buckling, sandwich structure/laminate failure modes
Dual launch structure	Allows the launch of two payload simultainsly	Release mechanism failure, mechanical failure
Launch vehicle adapter	Connects the launch vehicle to the ground structure	Detachment failure, structural failure
Upper liquid propulsion module	Houses the Vinci engine and provides thrust	Leakage, structural integrity failure, pressurization failure
Vinci engine and modernized vulcain engine	Vinci engine provides upper stage propulsion using liquid hydrogen and oxygen Vulcain engine provides the second stage with propulsion using liquid hydrogen and oxygen	Turbopump failure, combustion instability, pump failure, ignition system failure, vibration fatigue, thrust control, temperature control, combustion chamber pressure failures, cooling failures, pump failure, thrust decay, structural strength and yield failures
Lower liquid propulsion module	Provides thrust for the lower stage and houses the Vulcain engine	Skin rupture, buckling critical, fracture critical, structural failure, pressurization failure
P120C solid rocket motor	Gives additional thrust for the spacecraft during launch	Casing rupture, propellant burn rates, ignition timing failure

Part 3

1. FEM was used to characterize 10G's of load on a satellite structure to simulate harsh launch environment. The analysis was measured using ANSYS Workbench and the parameters consisted of the following.
   - A mesh of 0.005 m was used.
   - An acceleration of 98.06 m/s^2 was set to the X, Y, and Z directions to simulate the launch environment. 98.06 m/s^2 is 10G's of force.
   - A fixed support was placed on the edges of the satellite structure on all surfaces as told to do in the video.
   - The solution was then solved for total deformation and equivalent elastic strain (von-mises).

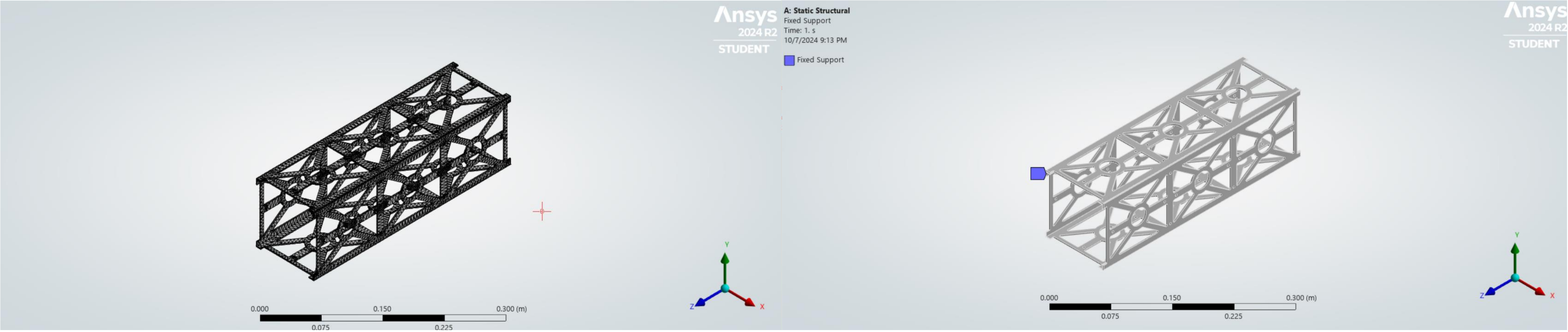

Figure 5 : Images of the mesh (left) and the fixed support (right) in ANSYS.

Part 3

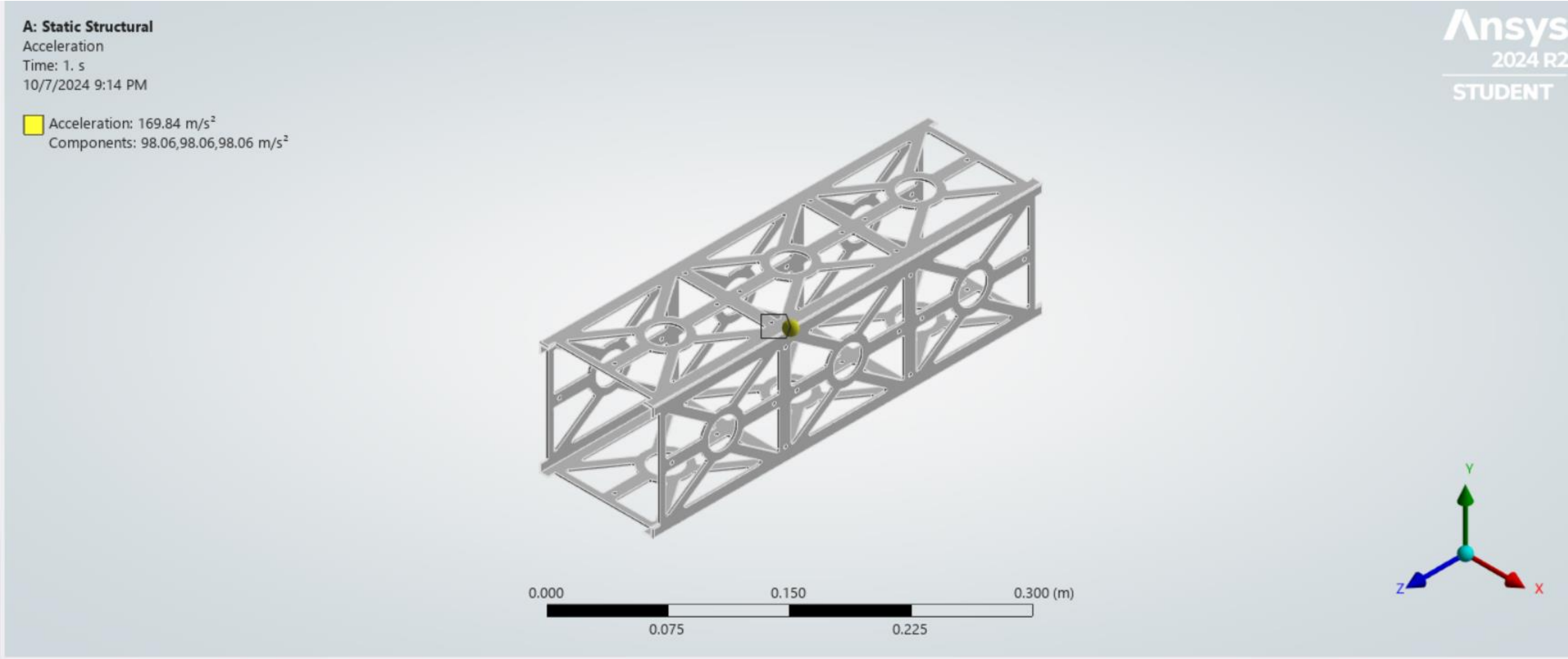

Figure 6 : Image of the static structure and its acceleration components in the X, Y, and Z directions. Acceleration was set to 98.06 m/s^2.

Part 3

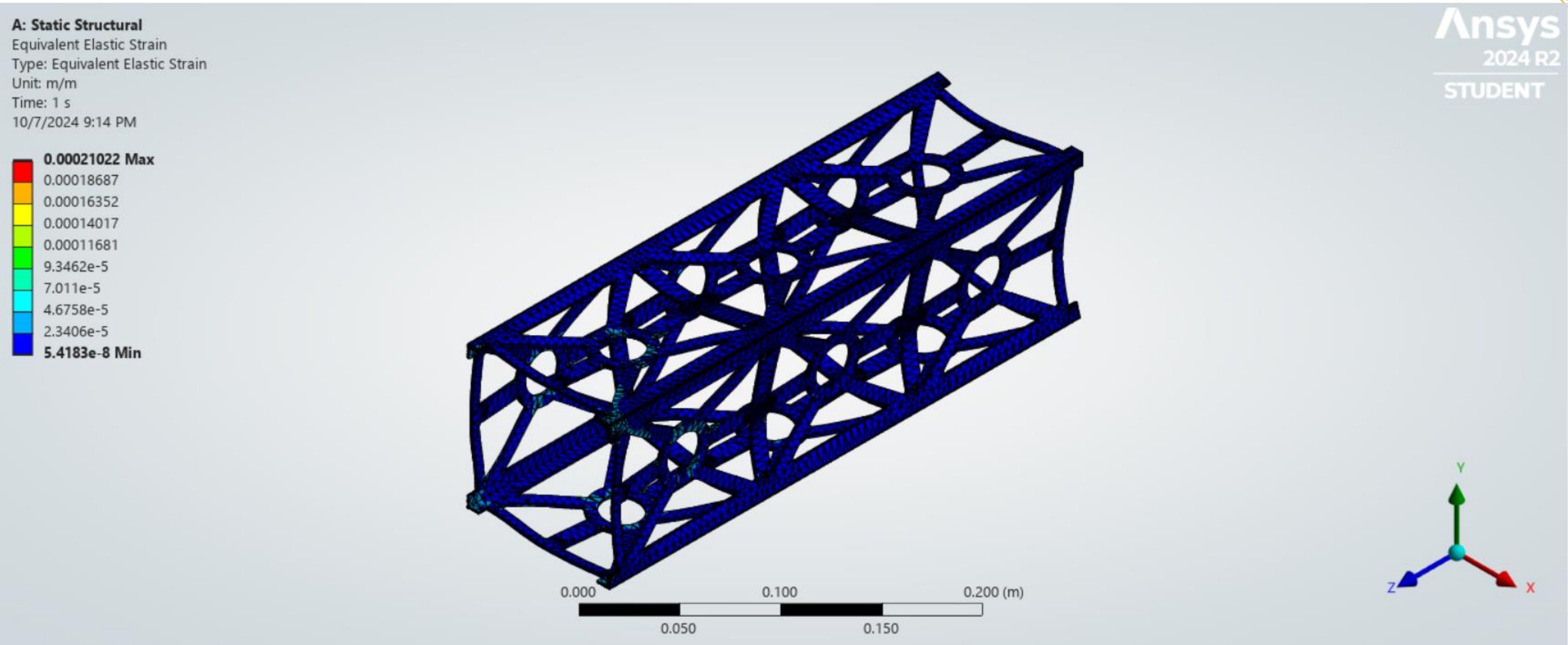

Figure 7 : Image of the equivalent elastic strain which represents the intensity of the strain at each point. We see here that in this deforming body, there is an increase in strain at the aqua colored mesh nodes indicating an increase to 4.675 x10^{-5} m/m.

Part 3

We see form this side view of the elastic strain that most of the strain is located where the fixed support is hence the red/yellow coloring. The side view also give a visualization of the amount of deformation caused by the acceleration load. We hit a max strain of 0.00021022 as indicated in the color chart next to the structure. We hit a minimum strain of 5.4183 x 10^{-8} m/m.

Figure 8 : Image of the equivalent elastic strain from the z-direction

Part 3

The total deformation is shown below. We can see here that the fixed support sides underwent zero deformation while the free ends and the rest of the structure underwent severe deformations. We also see a trend, the further away from the fixed support the more total deformation occurred. We had a max deformation of 2.4629 $x10^{-5}$ m. We had a minimum of 0 m.

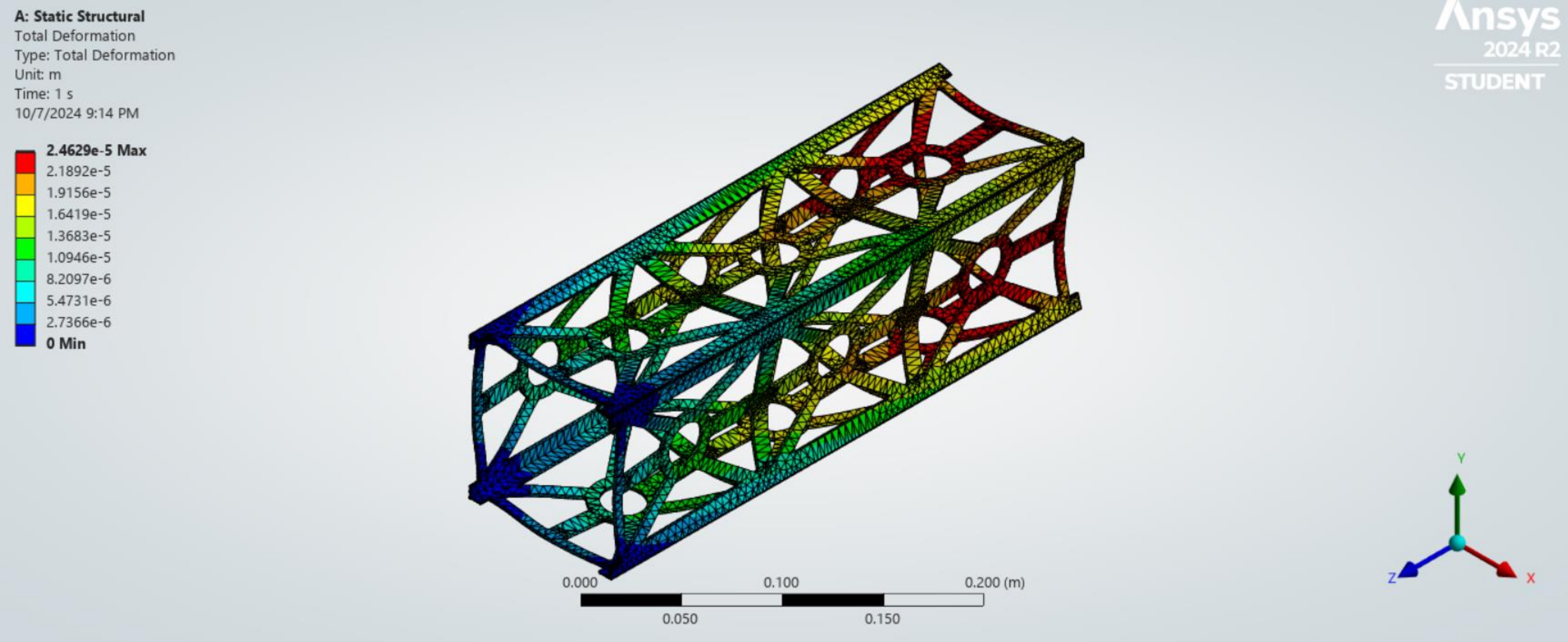

Figure 9 : Image of the total deformation in ANSYS with an applied load of 10G's.