2017 UC CEAS BattleBot Team

A Baccalaureate thesis submitted to the
Department of Mechanical and Materials Engineering
College of Engineering and Applied Science
University of Cincinnati

In partial fulfillment of the
requirements for the degree of

Bachelor of Science

In Mechanical Engineering Technology

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Table of Contents

Problem Statement

We will build, test, and compete a BattleBot as laid out by the 2017 BattleBot Rules. This collaborative endeavor will follow the achievement of previous UC teams who have championed in previous competition. Breaking the project into three sub-sections (Structure/Frame, Drive-train, and Weapons) our group will design and spec. components using the engineering design process.

Background

Over the past couple decades now, the art of building a BattleBot has gained quite a bit of popularity. The goal is to disarm and render your opponents BattleBot immobile, while protecting your own BattleBot from taking damage. By building a BattleBot that can successfully accomplish this, the “problem” we are faced with is essentially solved. Although, not a traditional form of a problem, the problem in our case is using our resources to build a durable enough and powerful robot to continue on to each proceeding round.

Customer Profile and Features

As part of competing in the RoboGames competition, we do not have a traditional senior design customer profile, but we still do have one. For this competition, we are designing a robot that will be following boxing style rules, trying to incapacitate another competitor’s robot. We will instantly win the match by knocking out the enemy robot during the time limit of the competition. In the event that neither robot is destroyed within the time limit, a three judge panel will award points based on the performance of our robot. This three judge panel will be our audience. The gender, age, and many other demographics are irrelevant for our judges as they are looking for categorized aggression and damage outlined in the official rulebook (found here, http://robogames.net/rules/combat.php). This year’s competition will be held April 21-23, 2017 at The Alameda County Fairgrounds in Pleasanton, California. While we are at competition, we will be up against very talented competition. We are expecting a high level of expertise in the STEM (Science, Technology, Engineering, and Mathematics) field with an expertise in: Mechanical engineering, Electrical engineering, machining, pneumatics and hydraulic control, as well as possibly computer science experts. In addition to these skills, we will be competing against competitors from all across the globe, composed of many different ages. This project will be very complex as far as our budget is concerned as well. To compete in this competition, we will need a large variety of electronics and components for our robot. To help ease some of this burden, we will try to salvage parts from previous years’ robots. Even with our fiscal plan, we will still have to provide transportation for 5 team members and our robot, pay for registration, and pay for a hotel. To accomplish this, we will require extensive funding from various sponsors.

Customer Features

-The Product must be attractive "Look Cool".

- The Product must put on an entertaining display while fighting.

- These can be found through survey or interview data.

The state of the art in the field of BattleBots involves using complex systems such as hydraulics and pneumatics as power for the weapon systems and more electronically complex systems for movement. This can include magnetic or lift driven systems as well as more robust wheel or track systems to defend against damage. The appeal to new advances in bot design and use of technology is to create bots that can deal more damage and fight longer against newer and more innovative offensive platforms.

Product Objectives

Contrary to typical product objectives, our "customer" product objectives are more along the lines of what our BattleBot will need to win the competition. Our BattleBots product objectives are:

- Durable
  - Use high strength materials
  - Solid frame design
- Quick to repair
  - Modular design
  - Use same fasteners on entire bot
- Long range attack
  - Weapon extends far past ends of bot
- Prevention of inversion of bot
  - Use weapon to flip bot to correct side
  - Angled top to tip bot over
- 360-degree security
  - Weapon extends out past bot
  - All sides of bot are protected with strong materials
- Simple design
  - Modular design
  - Consistent fasteners
  - Limit parts needing advanced machining and welding
- Affordable
  - Use parts from past years' competitions that are fully functional
  - Simple design
  - Eliminating unnecessary components
- Quick build time

Project Breakdown

The project was headed by Matt Riordan as the overall coordinator and then broken down into three teams: Frame and Armor (Matt Riordan and Thomas Mooney), Weapon (John Tzioumis and Vincent Sobocinski), and Drivetrain (Kyle Bohman). Each team was responsible for the design and specifics of their own subsection but all teams worked collaboratively in overall design, specifications, and manufacturing of the robot. This was necessary because each subsystem was critically tied to the specifications of the other systems though required a significant amount of work and attention to complete.

Frame and Armor

Background/Research

The design process of the frame was very systematic. Our first step was determining what type of robot we wanted to build. We spent many hours looking over previous year's reports and watching footage from previous competitions. This process resulted in our current design, a horizontally mounted, center spinning blade. With this decision made, we had a rough idea of what we wanted; a well-protected, square frame. Next, as a group, we made the decision to have a 120lb robot. With this in mind, we started to conduct further design.

Design

Through previous year recommendations, we found a guide to weight distribution. This weight distribution was as followed:

Weight Class	Drive	Weapons	Body/armor	Batteries/electronics
120	36	36	30	18

Table 1-Wight Breakdown

As part of the frame and armor team, we were responsible for designing both the frame and the armor and treated these two systems independently. One common issue we saw from previous years was that weight often was close to or exceeded the limit. With this in mind we decided to keep a 10% buffer weight for our section, meaning that our maximum design weight was only 27 pounds.

Our next step was determining rough weights for framing and armor material. Through simply weighing leftover parts from previous years we quickly realized that most frame material was minimal, yet strong; and that the armor was generally large and heavy. To account for this, we further divided our allowable 27 pounds between the frame and the armor. In this division, we set a goal of 12 pounds for the frame, and 15 pounds for the armor. Now that we knew our design constraints, we had to coordinate with the drive team and weapon team to acquire an estimate of their dimensions.

At this stage, we knew the rough concept of what we wanted, and the acceptable weights, but we had not yet set minimum dimensions. To complete this task, we received rough shapes, weights, and dimensions of the various drive and weapon components. Namely, wheel assemblies, weapon motors, and bearing blocks. From here, we had two critical decisions to make: frame profile, and frame material.

The decision of the profile was very important. We had a lengthy list of requirements that we wanted from the frame's performance. To make these decisions, we referred to our research and developed houses of quality (shown in references) to reach our final design. As previously stated, our robot had the following customer requirements: Durable, Quick to repair, Inversion protection/flippable, Long range attack, 360-degree security, Quick build time, Simple design, and Affordable. In order to accurately compare our concepts between each other, we came up with the following engineering requirements: material profile, number of independent drive wheels, frame weight (lb.), length of material used, top profile area, and the shape of the top profile. In our minds, the frame played a lot into these requirements. If we did our job right, our robot would be able to satisfy these requirements.

With these requirements in mind, we created several different concepts. First, we started with a simple, square design (shown below). We liked this design for several reasons: it was simple in design, cut lengths, and cut angles; it allowed four-wheel independent drive, had acceptable weight, and was a very versatile design. What we didn't like was that the square frame had a long flat area; which meant if we took a direct blow, a large force would be transferred into the frame. It was this design that we ultimately chose for the frame.

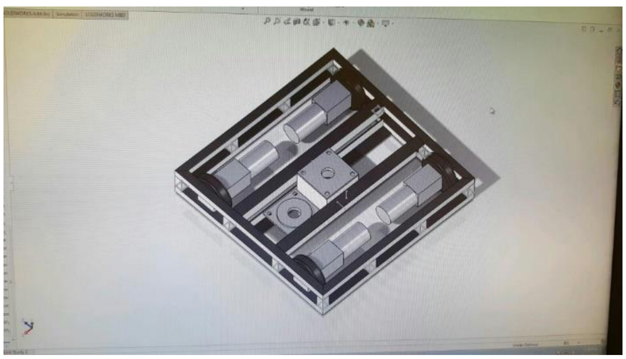


Figure 1-Square Frame Design

The next variation we created was a hexagon design (shown below). We liked this design for several reasons: it was simple in design, had acceptable weight, was a very versatile design, and most importantly, if we took a direct blow, the force can be deflected away from the frame. What we didn't like was that the frame required more complex cut lengths and cut angles, and only offered two-wheel drive.

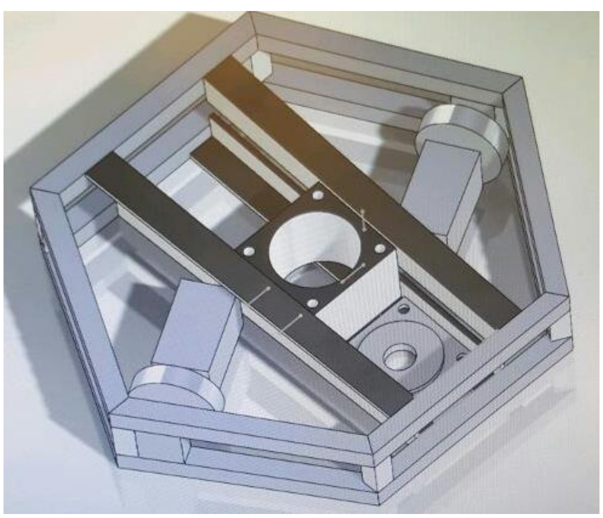


Figure 2-Hexagonal Frame Design

Finally, we created an octagon design (shown below). We liked this design for several reasons: it was simple in design, offered four-wheel independent drive, had acceptable weight, was a very versatile design, and most importantly, if we took a direct blow, the force can be deflected away from the frame. What we didn't like was that the frame required more complex cut lengths and cut angles, and was less stable then the square design.

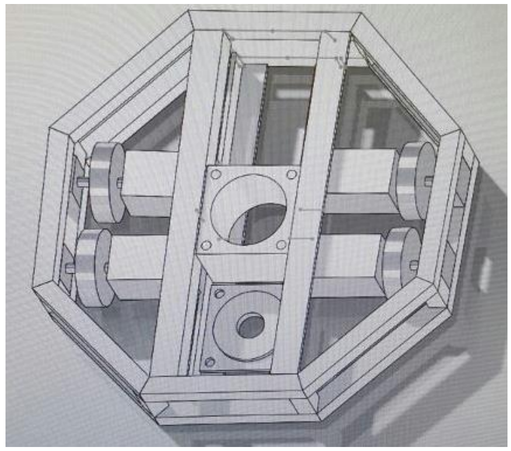


Figure 3-Octagonal Frame Design

When we made the decision of frame material, we made several decisions in this process. The first decision we made was in regard to the material of the frame. We spent a lot of time trying to decide between using aluminum and steel. In conducting our research, we noticed that steel was heavier, but it was cheaper, and had stronger welding strength. To help us determine what material we needed to use, we created a model in Solidworks and checked the weights using its internal material profiles. Working with a 12-pound weight limit for the frame, aluminum was our only viable option.

Once we decided to use aluminum, we made the decision of what metal profile to use. In an effort to balance weight and support, we limited our selection to hollow ⅛" thick 1" square tube, and ⅛" thick 1-inch aluminum angle. The reason for choosing these shapes was simple. In interest of weight reduction and metal strength, we determined that ⅛" thickness was the smallest wall thickness we could use. When we were creating concepts in Solidworks, we created two different models of frames. In an effort of maximizing weld area, minimizing dimensional inaccuracy, and maximizing dimensional tolerance; we first created a frame out of square tubing. With the square tubing, we found the weight to be acceptable; offered large weld areas, had good overall strength, and gave us some tolerance to welding imperfections. The other concept we created was creating models with aluminum angle. The main reason we did this was to save weight. When dimensionally equivalent, we found the aluminum angle to weigh approximately half the weight per linear foot when compared to square tube. Although we saw a great weight reduction with the aluminum angle, we ended up rejecting the aluminum angle for multiple reasons. The aluminum angle gave us more welding area, was structurally weaker, and gave us less tolerance for fitting pieces together. Ultimately, we decided that square tube was best for our application.

Our armor was influenced from previous years. Although we had over half of our allowable weight placed into the armor, we still had a tough time managing weight over such a large area. To help us decide what armor to use, we looked at designs from previous years. We noticed that these robots were generally fully protected units with heavy armor. Initially we liked this idea and tried to pursue it further.

After conducting research, we found several different options. These included: aluminum honeycomb, titanium honeycomb, aluminum plate, perforated aluminum, and expanded aluminum. These materials have different properties and characteristics, and we spent considerable time exploring all our options. We first explored the honeycombs. From previous years, we learned that they used a titanium honeycomb. This material offers excellent impact and force protection, and is very light. The next material we considered was the aluminum honeycomb. The advantages of aluminum are similar to the advantages of titanium honeycomb: it offers excellent impact and force protection, in lightweight, and is significantly cheaper than titanium. While this was advantageous, titanium is significantly harder than aluminum and is thus preferred. Unfortunately for us, the hardness of this material made it very difficult to work with. For accurate machining of this material, a water jet is required. We ultimately chose this material because we had extra parts laying around, but we wore through 3 drill bits and 2 cutting heads to make 4 panels and 8 holes.

The next material we explored was aluminum plate. Aluminum plate had several advantages. It offers excellent impact and force protection, is durable, and is relatively cheap. The negative aspects are that aluminum plate is relatively heavy, especially compared to our other choices. Next, we explored perforated aluminum. Similar to aluminum plate, it offers excellent impact and force protection, is durable, is relatively cheap, and is lighter than aluminum plate. The negative aspects are that the exposed holes allow the possibility of a direct attack penetrating our armor. Finally, we explored expanded aluminum. We considered using the expanded aluminum only underneath our robot. The advantages of expanded aluminum were: it was very lightweight, it offered protection against direct impacts, it offered great ventilation properties, and it was very cheap. The disadvantages were that the expanded aluminum was not very rigid and very thin.

With this research complete, we were able to create our armor design. As previously stated, we designed the robot to have armor everywhere. With this design we found weak, narrow sections of armor, we had excessive weight, and we were protecting durable square frame, which seemed like a waste to us. To adjust for this, we decided to protect what was necessary. Our final design consisted of three parts: acrylic sheet over the electronics, titanium honeycomb for protecting the drive motors, and plate aluminum for our wedge.

After this design process, our final frame and armor selections were as follows: A square frame constructed from 1”x1”x ⅛” aluminum tube with a combination of acrylic sheet, titanium honeycomb, and aluminum plate armor.

Analysis

With the design parameters set, we began to prove that our selected design would be sufficient to withstand repeated battles. Beyond having the frame crush from a direct impact, the greatest concern was metal fatigue from repeated hits. The life-cycle of our frame design was specified for only two, three minute matches before replacement. Based on our robot’s dimensions paired with general design criteria from Mott’s Applied Strength of Materials, fourth edition, we found that if the frame joins would flex less than one millimeter from a direct hit, the resulting metal fatigue would not impact the life of the frame.

Using Solidworks, we modeled the frame and subjected it to impacts on each side. Our impact force of 1000 lbs. was chosen based on an approximation of an opponent robot driving directly into us while being pinned against a wall. The simulation results are shown in the following figures:

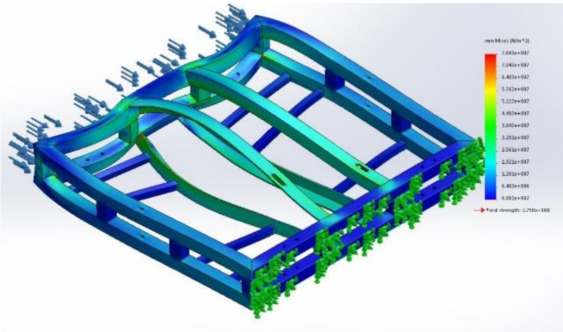


Figure 5-Side Crush, Stress

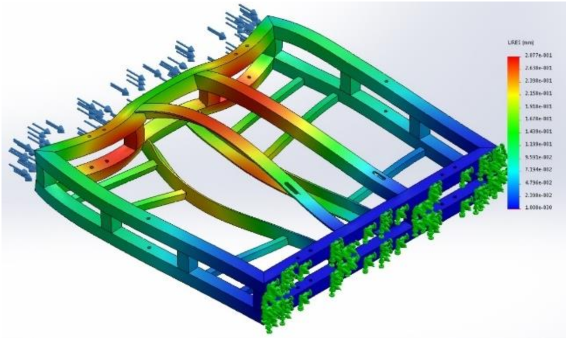


Figure 4-Side Crush, Displacement

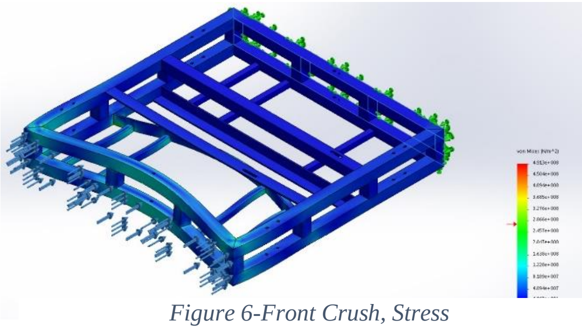


Figure 6-Front Crush, Stress

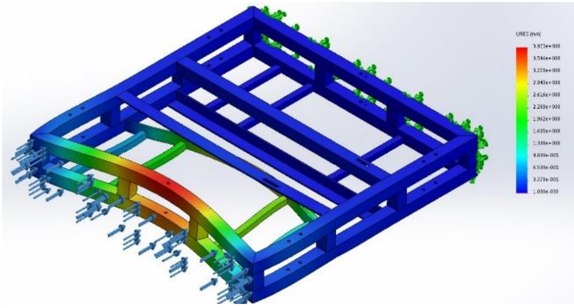


Figure 7-Front Crush, Displacement

As can be seen, no significant points on the frame exceed the yield strength of the aluminum and none of the joints experience a deflection of more than .5 mm.

The next simulation was a drop test. The worst scenario we could envision for our frame would be being thrown into the air some distance and falling flat onto its face or corner. Due to the lack of computational power, we could not effectively perform a complete drop test simulation in Solidworks because simulating all the constituent components inside the robot to achieve the appropriate weight would take over 48 hours. We chose to perform a simulation of just the frame but from a height that would develop the same kinetic energy as the full 120 lb. robot. The results listed in the appendix show how the frame would survive the experience either completely intact or with minimal damage.

Practical Testing

After construction of the first frame was complete, we performed a real drop test simulation using the same protocol as in our computer simulations. This culminated in a drop from over 15 feet to simulate a 4.5 foot drop in the arena. The frame survived with minimal structural damage.

Figure 8-Corner of test frame from practical drop test

Weapon System

Research

Selecting a weapon could be considered the most intricate part of the entire robot. Not only does weapon selection determine how effective a BattleBot's offense will be, but depending on which weapon type is selected, the weapon can also be used for defense. Utilizing resources such as past BattleBot competition outcomes, BattleBot design guide books, online BattleBot forums, and reports from previous UC BattleBot teams, the team can decide which weapon they would like to incorporate into the bot's design. When selecting a weapon, the most challenging part is finding a balance between what elaborate dream weapon the team can conceive and what the team is capable of constructing.

Other necessary considerations must be made when picking a weapon in regards to what strengths and weaknesses the weapon will have. Unfortunately, there is absolutely no weapon that has been created thus far that doesn't possess some sort of weakness when competing against another BattleBot. Some weapon types can rip certain opponents apart and be completely useless against others. When deciding upon a weapon, it is best to choose a weapon with as many strengths as possible while keeping its weaknesses to a minimum.
During the researching period, we had to consider what priorities were highest for our robot, as well as what would be feasible. Some of these considerations were durability, repair time, complexity of design, cost, weight of the weapon system, attack range, defense provided by weapon, mobility, and effectiveness of attack.

With these priorities in mind, we conducted further research and reduced the number of potential weapons down to a list of our top 3 weapon picks. The top 3 weapon types consisted of a flipper, a vertically spinning drum, and a horizontally spinning blade. Below is a breakdown of the pros and cons of each weapon type.

Flipper

Flipping weapons typically come in two varieties: electromechanical and pneumatic. Pneumatically powered flippers tend to be more effective, so they will be what is considered in this section. The powerful pneumatic systems often used in flipper robots make them capable of doing exactly what their name says – flipping their opponent. Flipping weapons work similarly to a spatula by sliding underneath an opponent and then literally throwing them into the air. Not only can sending an opponent airborne cause impact damage when they return to the ground, but it can also flip them upside-down, rendering certain styles of BattleBot useless.

Pros:

- Flipping an opponent could invert their robot and knock them out
- Capable of self-righting itself if inverted
- Durable
- Can deliver attack quickly

Cons:

- Limited compressed air supply
- Complex to design
- Expensive
- Must be able to get underneath opponent
- Small effective area/short reach

Figure 9-Flipper Style Weapon

Rotating Drum

The rotating drum design uses a large, horizontally-mounted, fast-spinning mass on the front of the robot. It can incorporate welded or machined teeth or bars and typically spins in the upward direction. These spinning drums are capable of tearing their opponents apart or throwing them up into the air which can deliver significant amounts of damage. The drum can be either chain or belt driven, and are usually powered an electric motor which allows the drum to spin incredibly fast. The configuration of rotating drum weapons allows for the robot to become inverted and still maintain functionality.

Pros:

- Compact and durable
- Able to deliver devastating hits
- Capable of operating when inverted
- Able to include other features on robot

Cons:

- Front end heavy
- Weapon bearings are susceptible to damage
- Small effective area/short reach
- Difficult to control because of the gyroscopic effect of the spinning drum

Figure 10-Rotating Drum Style Weapon

Horizontal Spinner

Horizontal spinners have the ability to cause the most damage to their opponents and are considered to be one of the deadliest weapons used in BattleBot competitions. Horizontal spinning weapons utilize their massive angular momentum to generate a huge amount of impact force, allowing them to do a great deal of direct damage. They are driven by powerful electric motors or gasoline engines (gasoline engines were not allowed in the 2017 RoboGames competition) which spin the blade up to very high speeds. Generally, the biggest danger when using a horizontal spinner bot is its own weapon. Self-destruction is a larger threat to horizontal spinners than many other styles of bot, and the weapon can tear itself apart if not designed correctly. Aside from itself, the horizontal spinner has very few weaknesses making it incredibly effective. Not to mention horizontal full-body spinner BattleBots provide the robot with 360-degree security because of the large spinning blade.

Pros:

- Offense is defense (360-degree protection)
- Easy to control (if balance properly)
- Deadly attack
- Simple to Design

Cons:

- Potentially self-destructive
- Difficult to add additional features to the bot
- Defenseless if weapon malfunctions

Figure 11-Horizontal Spinner Style Weapon

Decision and Reasoning

Based on our weapon selection criteria, we chose to design a full body horizontal spinner. As a team, we agreed on this weapon type because of its 360-degree security, deadly attack force, mechanical simplicity, attack range, and ease of driving while weapon is operational. Or design differed from the rotating drum designs previous University of Cincinnati seniors went with because we felt the horizontal spinner weapon offered more potential and would be more effective during competition. Also, because of its mechanical simplicity, we could machine most of the necessary parts ourselves, and in turn, reduce the overall cost of our BattleBot.

The following is a summary of our reasoning behind choosing to go with a horizontal spinner design:

- Consistent proven success from research of past competitions
- Durable
- Mechanically simple
- Easy to repair between rounds
- Deadly weapon attack force
- 360-degree defense provided by the blade spinning around the robot
- Easy to drive while weapon is operational
- Long range attack

Weapon Design Process

After selecting the horizontal spinner as the weapon for the 2017 BattleBot, the chassis had to be designed around the weapon system. Collectively, we decided our overall design would emphasize a modular design and minimize weight wherever possible so as not to exceed the 120lb weight limit. The weapon system design process involved three areas of focus: weapon blade material selection, weapon blade geometry, and weapon drive system.

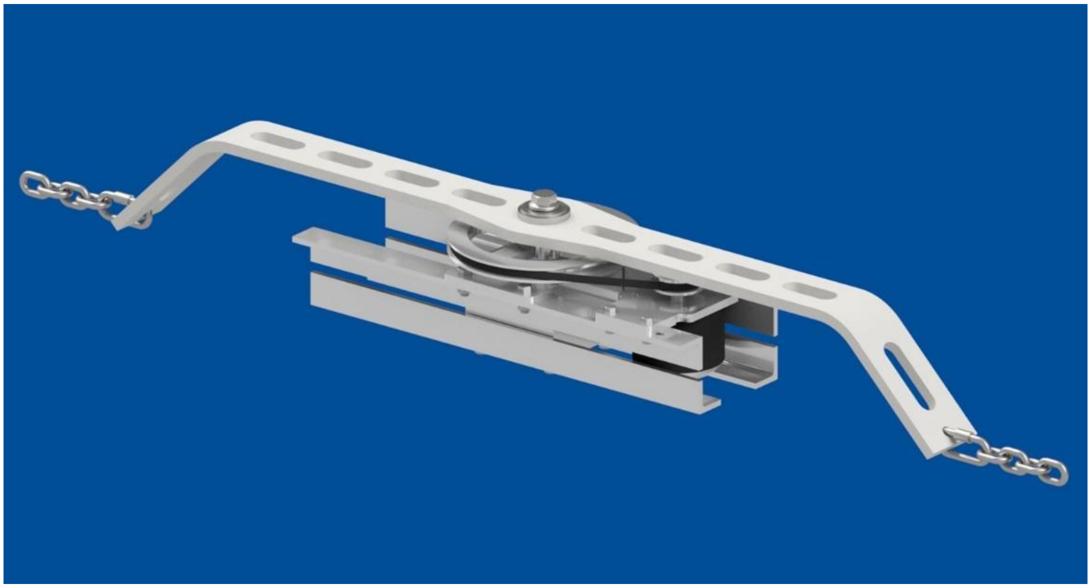


Figure 12-Final Weapon System

Weapon Blade Material Selection

Design Considerations:

- Material Strength
- Impact Resistance
- Weight
- Cost

Materials Considered:

- Titanium Alloy
- A36 Mild Steel
- AISI 4140 Steel
- S7 Tool Steel

Figure 13-Weapon Blade Before Heat Treatment

One of the first groups of materials that were considered for the weapon was that of titanium alloys. While titanium alloys have a very high strength to weight ratio, we had to eliminate them as possible weapon materials almost immediately due to their extremely high cost. The use of basic mild steel in the weapon was also eliminated immediately due to its low relative strength, in spite of its compelling cost. The next material considered was AISI 4140 steel. AISI 4140 is a little more expensive than mild steel, but is still readily available. It is commonly used for power transmission components, and is able to be heat treated. AISI 4140 was ultimately ruled out because its strength to weight ratio, while much better than mild steel, still wasn't quite high enough. The final material considered was S7 tool steel. S7 is an impact resist tool steel that maintains a high degree of toughness even when hardened. It is commonly used in shear blades, demolition tools, and injection molding dies, as well as by other BattleBot teams. While more expensive than other steels, we still ended up selecting S7 for use in our weapon because of its extremely high strength, ability to be hardened, and its impact resistance in a hardened state.

Weapon Blade Geometry

Considerations:

- Strength
- Weight
- Blade height

The main focus when designing the geometry of the weapon was to maximize strength and durability, while minimizing weight. The S7 tool steel chosen for the blade material is fairly heavy, so we immediately restricted the blade design to having no more than two arms. The length of the blade was determined using the estimated footprint of the body of the bot. Since we decided to incorporate a downward bend at the ends of our blade to prevent low profiled opponents from slipping underneath our weapon unharmed, the effective diameter of our blade needed to be significantly wider than the rest of the bot. In order to make use of such a long blade but still maintain a manageable weight, it was necessary to include cutouts down the length of the weapon. Both triangular and slot shaped cutouts were tested using finite element analysis (FEA) in Autodesk Inventor, and the slots were ultimately decided upon because they produced lower and more even stress concentrations within the blade. FEA was also used to determine the final width and thickness of the blade, as well as the final location and sizing of the cutouts by allowing us to see how adjusting these parameters effected the strength and weight of the weapon. The FEA simulations were all set up to replicate a worst-case scenario with the maximum possible impact force that the weapon can generate being applied directly to the weapon tip as a static load, while the center of the weapon is held rigidly by its mounting shaft. The maximum impact force of the weapon was calculated using its diameter, rotational speed, and the moment of inertia of the weapon assembly (calculated by Inventor).

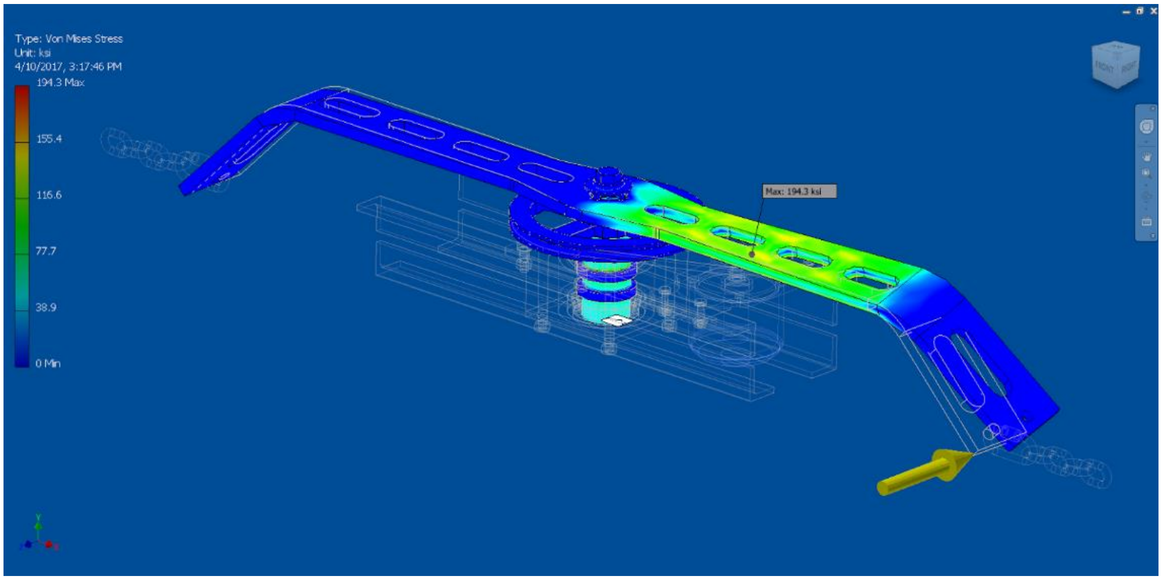


Figure 14-Weapon Blade FEA

While the weapon blade did pass the worst-case scenario test, weight limitations did not allow for a very high safety factor. Therefore, we decided to incorporate short lengths of chain at the ends of our weapon to help limit shock loading of the blade itself. Since the chain is able to deflect, it allows the weapon to dissipate its energy over a longer period of time by making multiple smaller hits to an opponent rather than one large one. Additionally, the chains act as a consumable wear item that is easily replaced between competition matches. If a single heavy hit from the weapon is desired, the effects of the chains can be mitigated by simply driving at an opponent faster, causing the tip of the weapon blade to make contact along with the chain.

Weapon Drive System

Considerations:

- Weapon Speed
- Weapon startup/reset time
- Weight
- Durability
- Cost

The design of the weapon drive system started out with two initial goals. The first goal was to attain a weapon tip speed of 100mph. Based on our research, we determined that this would be both an adequate and attainable target. The second goal was to have a weapon startup time (from dead stop to full speed) of under 5 seconds. Weapon startup time is particularly critical for this style of bot because a slow startup time leaves it vulnerable. To power the weapon, we selected a 900w Currie Technologies electric scooter motor. While there are many motor options available, this particular motor was significantly less expensive than any of the comparable alternatives. Additionally, this motor fit perfectly into the space allotted by our frame. To connect the motor to the weapon, we selected a V-belt system. We decide to go with a V-belt system because it is both significantly lighter than other possible forms of power transmission, and it allows for slippage in the event that the system is overloaded. Allowing the V-belt to slip in a scenario such as shock loading prevents damage from occurring to other parts of the weapon system. V-belts are both inexpensive and easy to replace, so pre-mature belt wear was not a concern in this application. To support the weapon, a 2” diameter AISI 4140 shaft and tapered roller bearings were used. The reduction and individual sheave sizes for the V-belt system were selected to optimize both weapon blade speed and torque (for the startup time), as well as to fit within the space allotted by the frame. In the end, we did have to compromise a little with a blade tip speed of 86mph and a calculated startup time of 5.53 seconds. While the actual blade speed was slower than we would have liked, the tip speed of the chain on the ends of the weapon blade did reach 111mph, and the actual weapon startup time during testing came closer to 4 seconds.

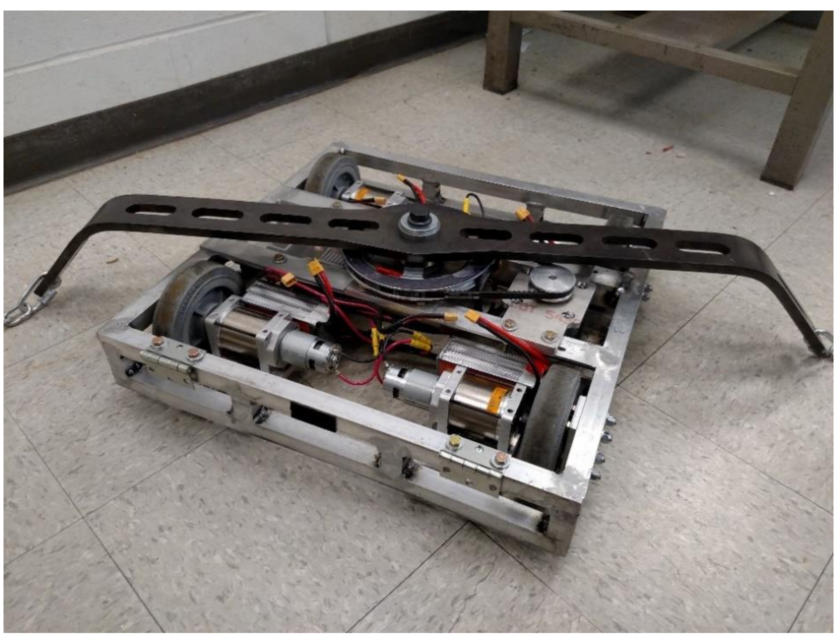


Figure 15-Assembled BattleBot: Note Weapon Drive System

Weapon System Calculations

Input Variables

RPM_m =	2600	Rated Motor RPM
D_1 =	2	Drive Pulley Diameter (in)
D_2 =	8	Driven Pulley Diameter (in)
D_{wb} =	44.495	Weapon Blade Diameter (in)
D_{wc} =	57.503	Weapon Chain Diameter (in)
W_m =	900	Motor Output Wattage (watts)
I_0 =	3672	Weapon Assembly Moment of Inertia ($lb_m in^2$)
w =	23.887	Weapon Assembly Weight (lbs)
t_i =	.01	Impact Duration (sec)

Table 2-Weapon Input Variables

Constant Values

g =	32.17	Gravitational Acceleration (ft/sec^2)
C_1 =	745.7	Watts per HP
C_2 =	5252	HP Constant

Table 3-Weapon Constants

Output Variables

R =	4	Pulley Reduction (_:1)
RPM_w =	650	Weapon RPM
ω =	68.07	Weapon Angular Velocity (rad/sec)
V_b =	86.04	Weapon Blade Tip Speed (mph)
V_c =	111.20	Weapon Chain Tip Speed (mph)
I =	25.50	Weapon Moment of Inertia ($lb_m ft^2$)
HP_m =	1.21	Motor Horsepower
T_m =	2.44	Motor Torque (ft-lb_f)
T_w =	9.75	Weapon Torque (ft-lb_f)
KE_w =	1836.30	Weapon Kinetic Energy (ft-lb_f)
L_w =	53.95	Weapon Angular Momentum (ft-lb_f-sec)
F_w =	2910.26	Weapon Impact Force @ Blade Tip (lb_f)
t_s =	5.53	Weapon Start-up Time (sec)

Table 4-Weapon Output Variables

Output Variable Equations

$$R = \frac{D_2}{D_1}$$

Equation 1-Pulley Reduction

$$RPM_w = \frac{RPM_m}{R}$$

Equation 2-Weapon Rotation Speed

$$\omega = RPM_w \times \frac{2\pi}{60}$$

Equation 3-Weapon Angular Velocity

$$V_b = RPM_w \times \frac{60min}{1hr} \times D_{wb} \times \pi \times \frac{1ft}{12in} \times \frac{1mile}{5280ft}$$

Equation 4-Weapon Tip Speed

$$V_c = RPM_w \times \frac{60min}{1hr} \times D_{wc} \times \pi \times \frac{1ft}{12in} \times \frac{1mile}{5280ft}$$

Equation 5-Weapon Chain Tip Speed

$$I = I_0 \times \frac{1ft^2}{144in^2}$$

Equation 6-Weapon Moment of Inertia

$$HP_m = \frac{W_m}{C_1}$$

Equation 7-Motor Power

$$T_m = \frac{HP_m C_2}{RPM_m}$$

Equation 8-Motor Torque

$$T_w = T_m \times R$$

Equation 9-Weapon Torque

$$KE_w = \frac{I\omega^2}{2g}$$

Equation 10-Weapon Kinetic Energy

$$L_w = \frac{I\omega}{g}$$

Equation 11-Weapon Angular Momentum

$$F_w = \frac{I\left({}^{\omega}/_{t_i}\right)}{\left({}^{D_{wb}}/_{24}\right) g}$$

Equation 12-Weapon Impact Force

$$t_s = \frac{I\omega}{T_w g}$$

Equation 13-Weapon Calculated Start-up Time

Drivetrain

Research

The research for drivetrain was extremely reliant on the weapon selection of our robot. Depending on the weapon style of the robot, there can be several types of drivetrain combinations that are optimal for various robot configurations. The weapon style chosen was a horizontal spinning blade on the top of the robot. This type of weapon requires a drivetrain that offers exceptional control and stability. With a top spinning weapon, the ability to drive and maneuver quickly and efficiently is crucial to the effectiveness of the BattleBot.

Design Considerations

There are two main types of wheel formats for this type of robot. A two wheel and a four-wheel configuration were considered. Having two wheels would offer less weight and lower cost. After trying out different frame shapes, it was discovered that a two-wheel setup would not be an option. There is a potential for a bending moment to be created across the centerline of the wheels making the robot tilt. Since stability is a key requirement for this weapon, a four-wheel configuration was chosen.

Now that the wheel arrangement is chosen, the next step was to decide on the drivetrain behind the wheels. The decision was between a larger motor and gearbox running one wheel per side or four smaller motors and gearboxes running all the wheels. An independent, four motor designs offered better control and stability. The smaller motors would also cut costs, weight, and power requirements of the robot. Another benefit of the four-motor setup is that if one of the motors gets damaged or stops working, the robot will still be drivable. Having the drivetrain spread out in four separate quadrants, offers better balancing in weight. Each of the quadrants instills a modular design by being easily accessed and replaced if necessary.

Wheel Selection

The wheel selection was based off keeping our robot low to the ground while providing adequate traction. Based off assumptions and research, it was decided to have our robot drive roughly one inch off the ground. This clearance will allow for hardware bolt heads and to keep the ends of our blade off the ground. A six-inch Colson wheel was selected. This tire is very common among BattleBots based on our research. The image below shows a side view of the chosen wheel.

Figure 16-Selected Wheel

Motor Selection

The motor requirements were to have a 24V, lightweight motor that can handle our application. Our weapon ran on a 24V motor, so to keep the voltage consistent, a 24V drivetrain motor was needed as well. It was difficult to find a motor to fit our application because there just was not a wide selection available. The motor picked was the RS775 motor from Banebots. This motor is only 11.9 ounces in weight and has an RPM of 12600. Below is an image of the RS775 motor.

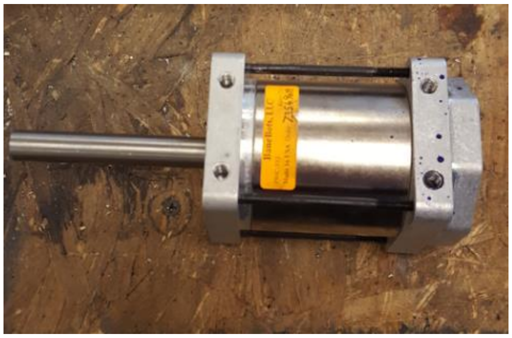


Figure 17-P80 Gearbox

Gearbox Selection

Based on our research, we wanted a drive system that will make our robot travel around eight miles per hour. This speed is approximately the average running speed of a person. To reach this speed with our motor and wheel selection, a gearbox with a reduction of 27:1 was necessary. We could not find a gearbox that had the proper mounting to work with our motor, so we chose a P80 gearbox with a reduction of 27:1 and decided to make our own adapter to make it work. The adapter we made had a hole for the shaft of the motor of one side and a hole for keyed shaft on the other side. The keyed shaft would fit into the gearbox. Below is an image of the gearbox.

Figure 18-RS775 Motor

Schedule and Budget

After a preliminary run through the design process we sat down to put together a budget. Based on previous year's projects costing upwards of $7,500 we endeavored to find a way to keep the budget down. This involved manufacturing a majority of components ourselves and simplifying the design. Given the constrains of what we wanted to accomplish and the amount of money we were able to raise through sponsorships and donations; the budget was set at $5,000. We were able to keep within this budget.

The schedule was set based on the scheduled competition date. In years past the project was completed with only a day or even only hours before the BattleBot had to be shipped to the competition. This left teams with little time to test. Knowing that fabricating components is a large strain on the schedule due to unforeseen issues, we set a goal of completing fabrication with at least a full week before shipment. This required us to begin putting several hours a week in the shop right away in order to get ahead. Even though due to registration issues we were unable to compete, we did meet this timeline having a fully testable BattleBot a full week and a half before our ship date.

Assembly and Fabrication

All assembly and fabrication was completed at the Victory Parkway Campus' North Lab machine and welding shop.

Frame

The frame was constructed with aluminum tube as specified in the frame design section. All joints were welded by Matt Riordan who learned aluminum TIG welding for this purpose. Throughout the process, the realities of aluminum welding were made aparent when examing the results of the welds. Many of them required being ground out and re-welded. In future it would be benifical for any aluminum welding to be sent out to a professional regardless of the cost advantage of perfoming the task in house. The time expenditure delayed other critial components manufacturing.

All holes in the frame were made on the two-ton Morris Dill press. This machine allowed the frame to by toed down to a square workpiece holder to ensure that all holes were as square to the surfacses as possible. It also allowed for rapid alignment when compared to a traditional drill press.

Weapon

The majority of machining and assembly time, aside from frame welding, was dedicated to the weapon system. John Tzioumis and Matt Riordan, with the assistance of fellow-student Brian Yockey and shop advisor Nicholas Plataniotis, directed, cordianted, and/or performed all machining operations. Major machined components in the weapon system include the weapon shaft, motor plates, bearing blocks, pulley system, and the weapon blade. The blade itself was laser cut from plate and bent to shape with the assistance of Cincinnait Incorperated at their production facility in Harrison, Ohio. Final machining of the blade was perfomed at Victory Parkway before it was sent out to be heat treated.

The primary machines used for these operations at Victory Parkway were the Prototrak vertical mill, Cincinnati lathe, and Hass V1 vertical cnc mill.

Figure 19-Weapon Bearing Block Before and After Turning

Figure 20-Shaft Being Turned

Figure 23-Facing Motor Mounting Plate

Figure 21-Main Weapon Pulley After First CNC Pass

Figure 22-Weapon Blade Final Machining Before Heat Treatment

Drivetrain

The assembly of the drivetrain is very simple because of our designs and choices of parts. Our goal was a four independently driven motor design that is modular and provides exceptional control and stability. The image below shows the drivetrain assembly for one quadrant of the robot. Starting from the right, there is the bearing block mounted to the frame, six inch diameter Colson wheel, P80 series gearbox, and finally the RS775 motor. The gearbox is mounting of aluminum C-channels that are welded on the inside of the frame. This assembly can be easily accessed and replaced if damaged.

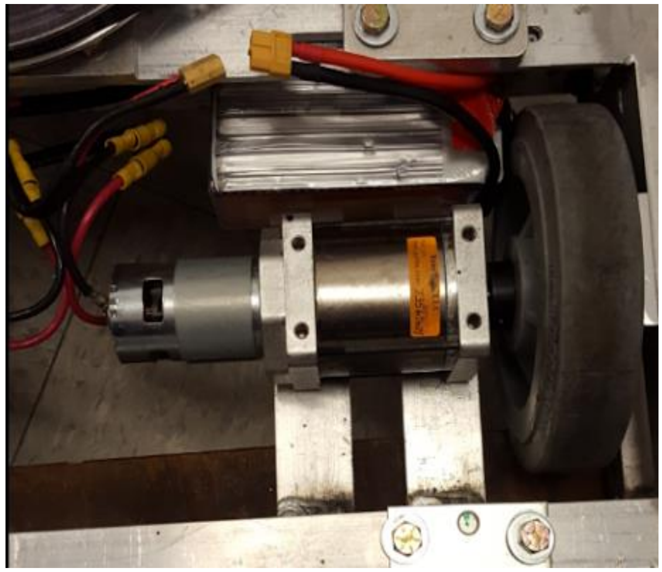


Figure 24-Installed Motor and Wheel Assembly

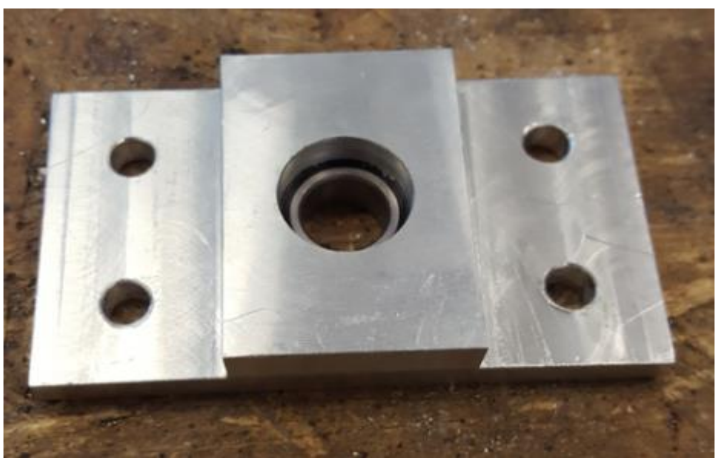


Figure 25-Bearing Block

Bearing Block Fabrication

The bearing block is what provides support to the spinning shaft from the gearbox. Initially, the thought was to have a simple bearing block that would fit into the side of the frame and bolt in from the top. This design would not work because the mounting bolts would be put into shear stress if an impact from another robot was taken from the side. Bolts break easy when put under shear stress, so a different design was needed. We ended up going with a bearing block design that is mounted from the outside of the frame. This reduces the chance of the bolts being put under shear stress. The images below show the bearing block and how it is mounted.

Figure 26-Installed Drivetrain Bearing Block

Figure 27-Gearbox to Wheel Shaft Adapter

Figure 28-Motor to Gearbox Adapter Parts

System Testing

Full system testing was performed in a multi-stage process. Upon completion of final assembly, the battlebot was fully powered up. A comprehensive systems check was performed to ensure that all controls were functioning and that the system would fail to a safe condition if signal was interrupted, a requirement of the competition. The receiver connected to the BattleBot's electronics did not fail to a safe condition. It instead continued to perform the last command given by the controller on all channels other than the throttle when signal from the controller was cut. The throttle channel was the only one to fail to the safe position, in this case off. This was a serious safety concern and a replacement with multi-channel "fail-safe" was sourced.

The first system tested was the weapon platform. The blade was spun up slowly until full power was reached. Throughout the test, all observers were behind concrete barriers and were viewing the test remotely via a camera. The primary fear was that the blade, while balanced, may not remain stable at high speeds, causing the BattleBot to wobble and possibly launch itself into the air when the blade touched the ground. The weapon spun up to full speed without drama, gaining stability as it gained speed. This was due to the increased angular momentum requiring a larger force to move the BattleBot around the weapon's axis.

The next system tested was the drivetrain. Tests were performed on flat ground and the BattleBot drove smoothly with the blade stationary and spinning. We did notice a clearance issue with parts of the drivetrain mounting hardware underneath the BattleBot. These protruding bolts were cut down to a more appropriate length and reinstalled.

These tests were followed up by a practical demonstration of the full combat systems. This was performed by having the BattleBot attack a variety of targets to simulate opponents. First were small objects such as cans and fruit. These were a stand-in for the light armor that many BattleBots use. The weapon was able to completely demolish these targets without altering its trajectory or loosing stability.

The final target used was a spare frame that had faulty welds. This frame, while strong, was not up to our standards for dimensional accuracy as it was the first frame assembled. The BattleBot performed much the same as with the smaller targets but its ability to deal damage was much easier to recognize. The target was completely destroyed after being flung into a concrete wall. The weapon functioned as designed with the chains transferring the majority of the energy on contact. The images below are the results.

Figure 29--Dents and Holes in Target Frame

Figure 30-Target Frame, Multiple Weld Failure

Figure 31-Cosmetic Damage on Blade

Conclusions

As a team, we were able to work together each step of the way from conceptualization to final product to produce a fully functioning and lethal BattleBot. The robot as a whole was functioning a week or so before the anticipated ship date. Unfortunately, given the issues we ran into with registering for the competition and every spot being filled by the time the issues were settled, we were not able to successfully register our BattleBot and compete in the RoboGames tournament. We hope to reunite next year and enter into the 2018 RoboGames Competition to see the destruction our robot is truly capable of producing.

Throughout the project, our team as a whole was faced with challenge after challenge. From meeting our self-imposed deadlines, to making accurate engineering assumptions, designing each of the BattleBot's systems, machining components, securing funding for the project, and planning for any unexpected events along the way. As a team, we used our knowledge of mechanical, material, and electrical properties to produce a terrifying BattleBot.

The team put together a timeline with deadlines to ensure we would have adequate time to test the robot before shipping it to the competition. What the timeline didn't consider were potential speed-bumps which ended up delaying the completion of our robot, however, we still ended up having enough time to get some testing and practice with the robot.

While designing the robot, we had to communicate effectively with members of each system so the overall assembly would fit together correctly. Another area each respective team had to focus on with design was reducing weight and cost, but not weakening our design with too many sacrifices. We had to confirm our calculations for each system were correct in order to meet our performance expectations. To do this, we had to use the resources available to us. After FEA testing and some light testing once the robot was assembled, we were able to confirm our design met the performance expectations.

When it came time to do the machining, we ran into problems with dimensions and assembling parts correctly. For example, a part that needed an interference fit ended up being too loose, so we had to go back and remake the part. This prolonged the machining portion of the project. Through the machining process, our team gained a much better understanding of how to properly operate the machines available to us and how we could have designed parts more effectively.

Funding was an intricate part of building a successful BattleBot. We formed a BattleBot Club in hopes that we could receive some funding that way, however, we were unable to receive any money for our project. A result of establishing a BattleBot Club this year will allow for future teams to receive funding through the club. We compiled a list of potential companies to reach out to for funding and contacted them. Although a response was not received by most companies, the ones who responded donated enough money to fully fund our project.

Future Recommendations

Considering all of the challenges we faced, we recommend future BattleBot teams do the following:

- REGISTER IMMEDIATELY – even if the online registration does not provide enough event passes for the full team, register for the competition anyway and sort out the passes later.

- EVERYTHING WILL TAKE LONGER THAN EXPECTED – create a schedule with deadlines taking into consideration time for any unexpected issues that may come up during the project, while allowing sufficient time for testing and shipping to the competition.

- Testing is a must – allow significant time to test and practice driving the bot before it needs to be shipped.

- Utilize any and all resources, financial or otherwise.

- Make use of available shop time BOTH SEMESTERS. The manufacturing projects course is open both fall and spring semester, and is essentially open shop time. Even while still in the design phase, show up to the shop and make *something*. Becoming familiar with the machines and their capabilities, as well as machining methodology will make things go quicker and smoother when it comes time to actually build the bot.

- If any significant welding is required, it is best to leave it to an experienced welder, particularly if aluminum is involved.

- Do extensive research and consider many options for each system before making their final design selections.

- Emphasize weight restrictions, cost, and time with respect to complexity of design.

- Reach out early to co-op companies for sponsorship.

- Be prepared for unexpected issues to pop up and plan accordingly.

Appendix A

List of Figures

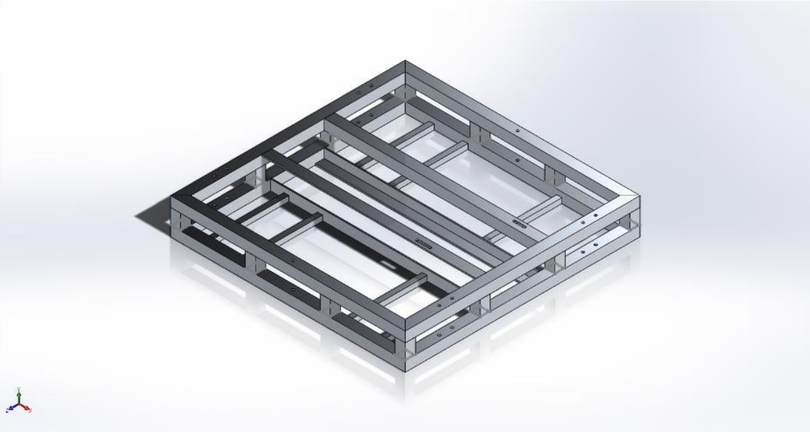
List of Tables

List of Equations

List of Simulations

Appendix B: Solidworks Simulations

Simulation 1-Side Crush



Simulation of Crush: Side

Date: Friday, April 21, 2017
Designer: Solidworks
Study name: Static 1
Analysis type: Static

Table of Contents

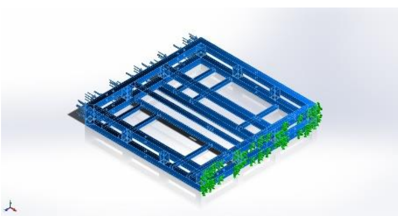
Study Properties

Study name	Static 1
Analysis type	Static
Mesh type	Solid Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Include fluid pressure effects from SOLIDWORKS Flow Simulation	Off
Solver type	FFEPlus
Inplane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off
Incompatible bonding options	Automatic
Large displacement	Off
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off
Result folder	SOLIDWORKS document (\\clusterfsnew.ceas1.uc.edu\students\riordamv\desktop\final frame-20170421T184351Z-001\final frame)

Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

Material Properties

Model Reference	Properties	Components
	Name: **6061-T6 (SS)** Model type: **Linear Elastic Isotropic** Default failure criterion: **Unknown** Yield strength: **2.75e+008 N/m^2** Tensile strength: **3.1e+008 N/m^2** Elastic modulus: **6.9e+010 N/m^2** Poisson's ratio: **0.33** Mass density: **2700 kg/m^3** Shear modulus: **2.6e+010 N/m^2** Thermal expansion coefficient: **2.4e-005 /Kelvin**	**SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-3), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-5), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-6), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_2-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_3-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_4-1), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-1), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-10), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-11), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-12), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-2), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-3), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-4), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-5),**

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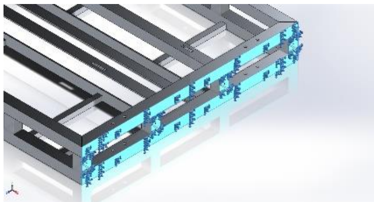
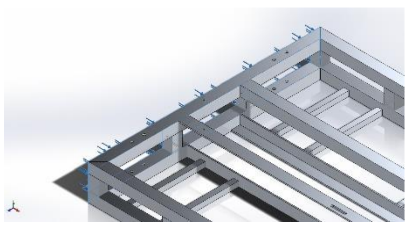
Curve Data/A		

Loads and Fixtures

Fixture name	Fixture Image	Fixture Details
Fixed-1		**Entities:** **6 face(s)** **Type:** **Fixed Geometry**

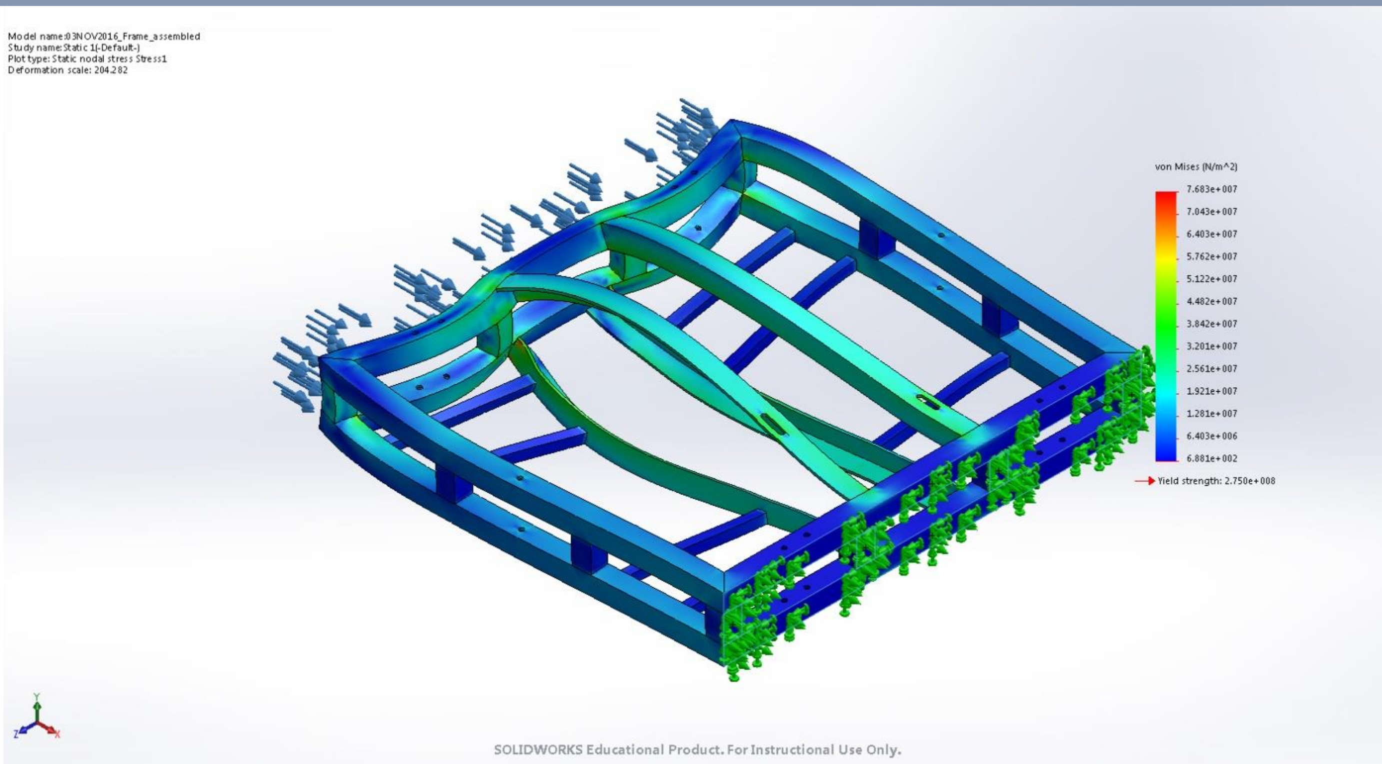
Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	**-26689**	**0.226249**	**-0.221465**	**26689**
Reaction Moment(Nm)	**0**	**0**	**0**	**0**

Load name	Load Image	Load Details
Force-1		**Entities:** **6 face(s)** **Type:** **Apply normal force** **Value:** **1000 lbf**

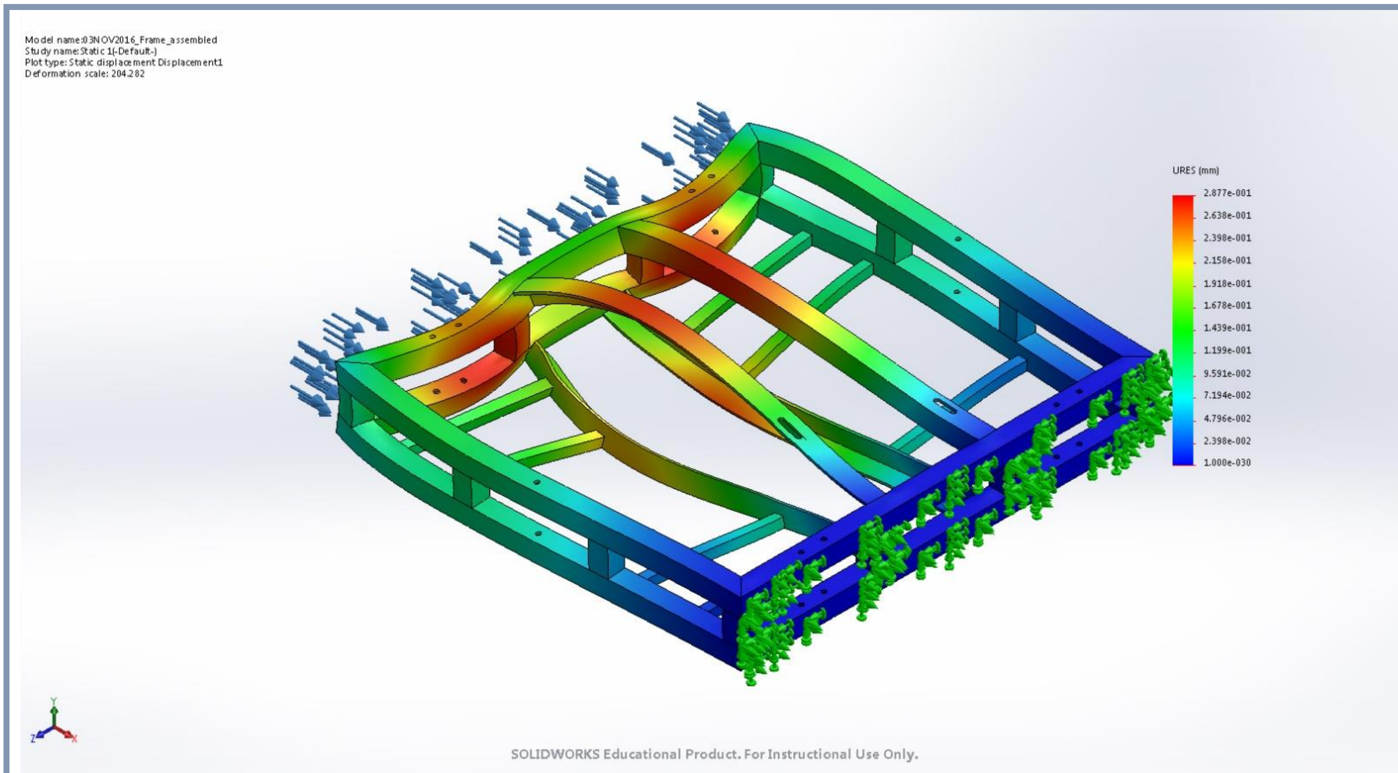
Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	688.131 N/m^2 Node: 15688	7.68316e+007 N/m^2 Node: 56972



03NOV2016_Frame_assembled-Static 1-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0 mm Node: 7161	0.287741 mm Node: 203



03NOV2016_Frame_assembled-Static 1-Displacement-Displacement1

Name	Type	Min	Max
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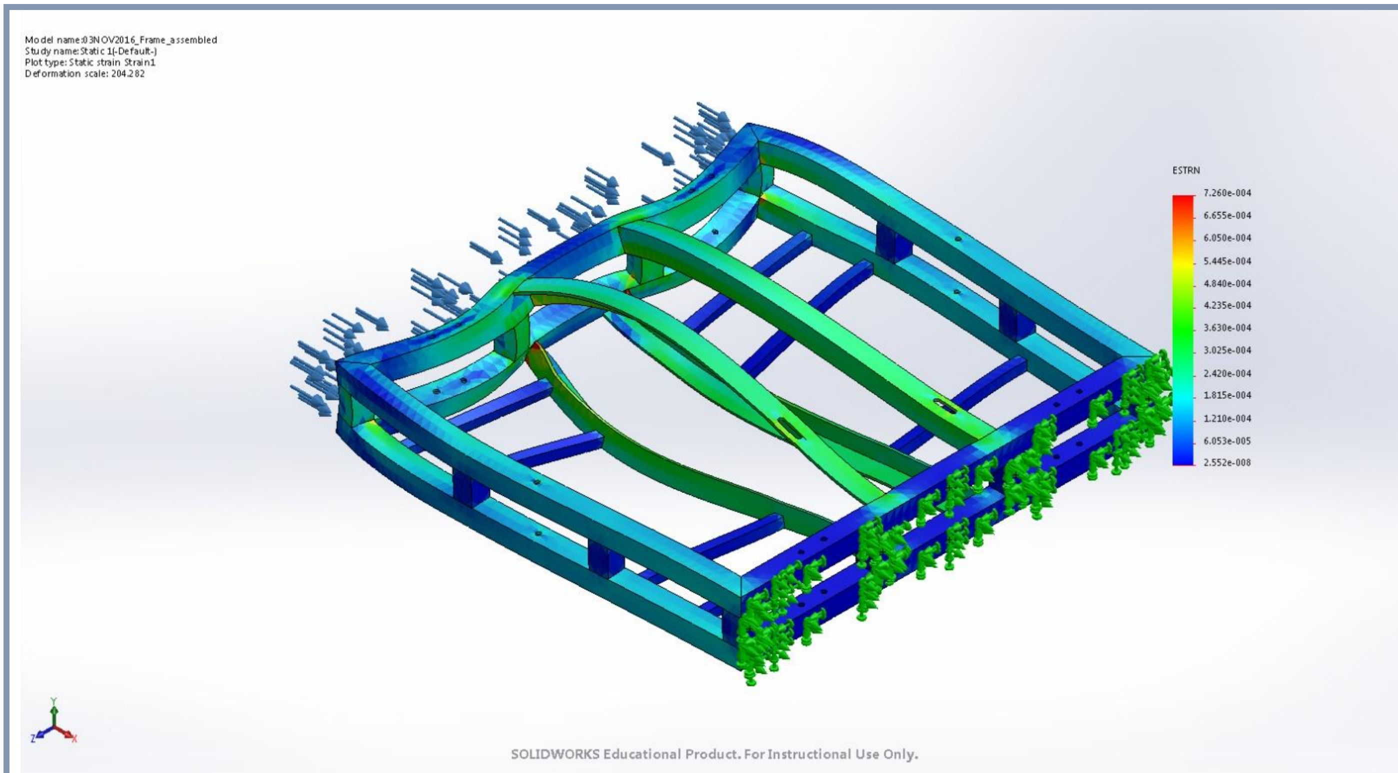


03NOV2016_Frame_assembled-Static 1-Strain-Strain1

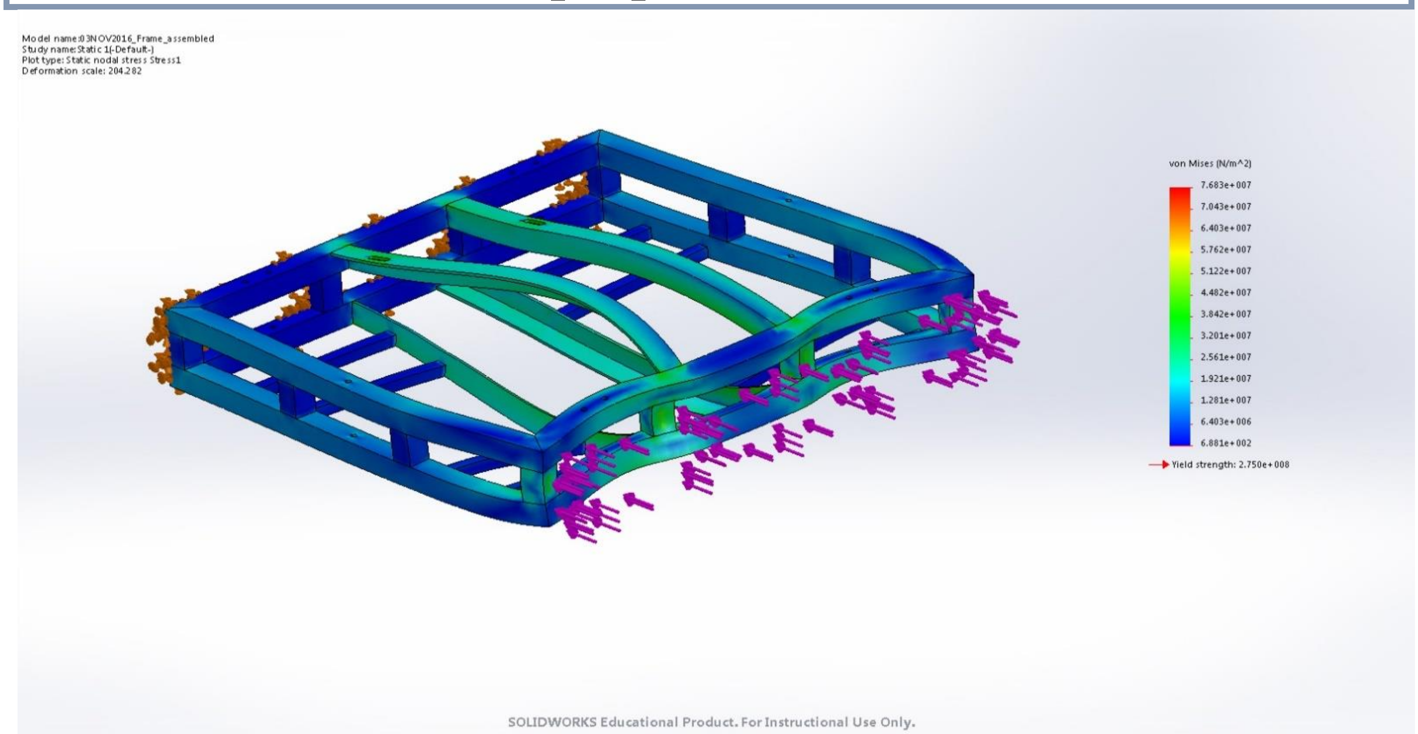
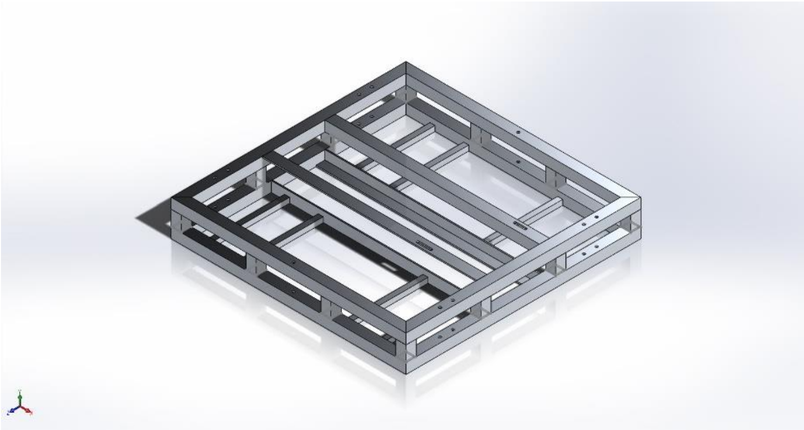


Image-1

Simulation 2-Crush Front



Simulation of Crush: Front

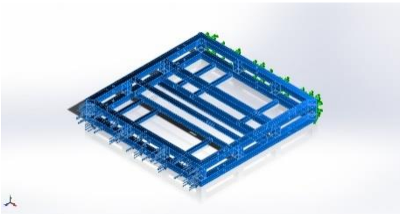
Date: Friday, April 21, 2017
Designer: Solidworks
Study name: Static 2
Analysis type: Static

Table of Contents

Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

Material Properties

Model Reference	Properties	Components
	Name: **6061-T6 (SS)** Model type: **Linear Elastic Isotropic** Default failure criterion: **Unknown** Yield strength: **2.75e+008 N/m^2** Tensile strength: **3.1e+008 N/m^2** Elastic modulus: **6.9e+010 N/m^2** Poisson's ratio: **0.33** Mass density: **2700 kg/m^3** Shear modulus: **2.6e+010 N/m^2** Thermal expansion coefficient: **2.4e-005 /Kelvin**	**SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-3), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-5), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-6), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_2-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_3-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_4-1), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-1), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-10), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-11), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-12), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-2), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-3), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-4), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-5), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-6), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-7), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-8), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-9), SolidBody 1(Boss-Extrude1)(27OCT2016_Angle_Weapon_Support-1), SolidBody 1(Boss-Extrude1)(27OCT2016_Angle_Weapon_Support-2),**

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Loads and Fixtures

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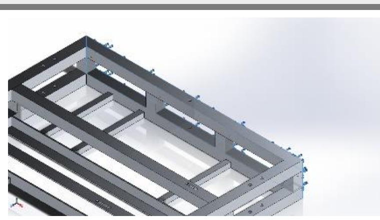
Fixed-1		**Entities:** **6 face(s)** **Type:** **Fixed Geometry**

Resultant Forces

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Reaction Moment(Nm)	**0**	**0**	**0**	**0**

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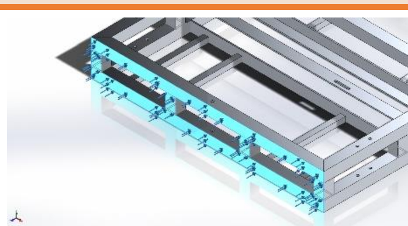
Force-1		**Entities:** **6 face(s)** **Type:** **Apply normal force** **Value:** **1000 lbf**

Study Results

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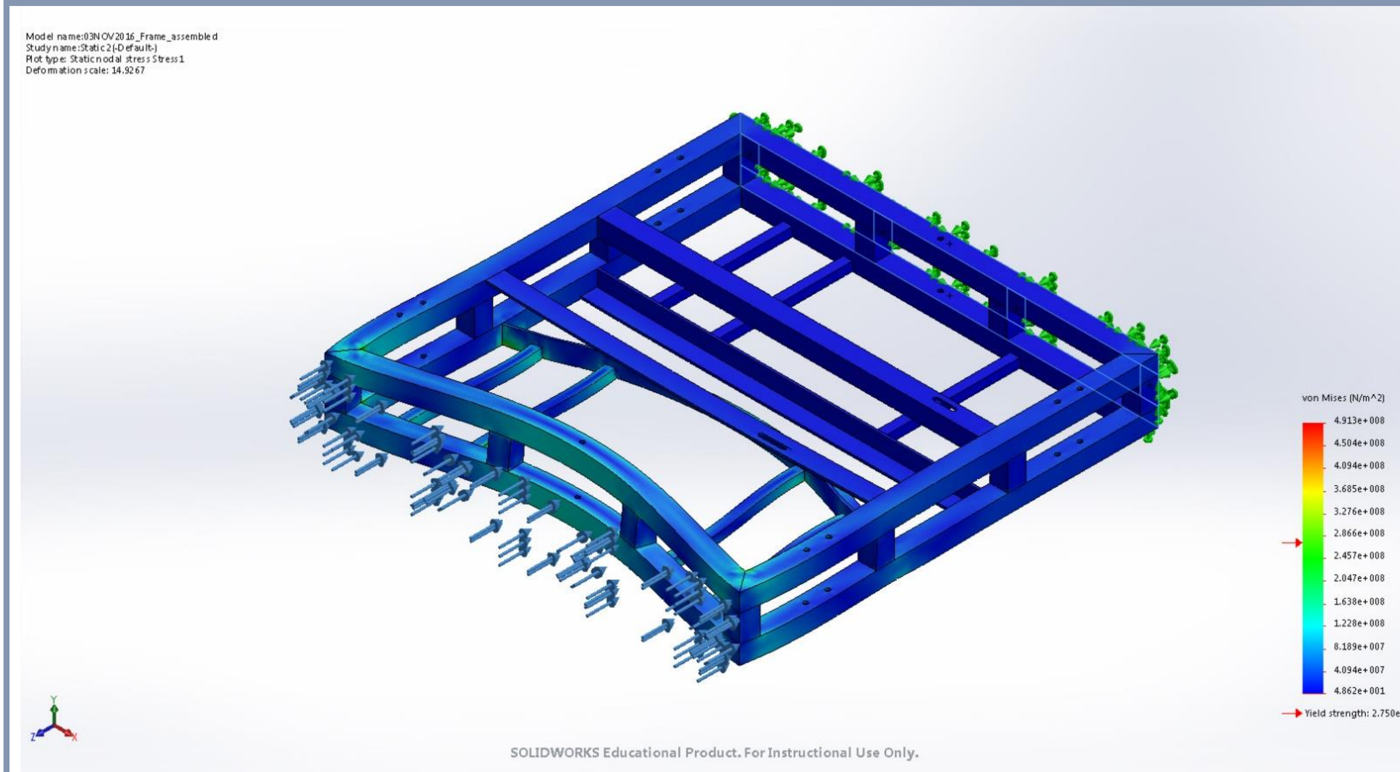

03NOV2016_Frame_assembled-Static 2-Stress-Stress1

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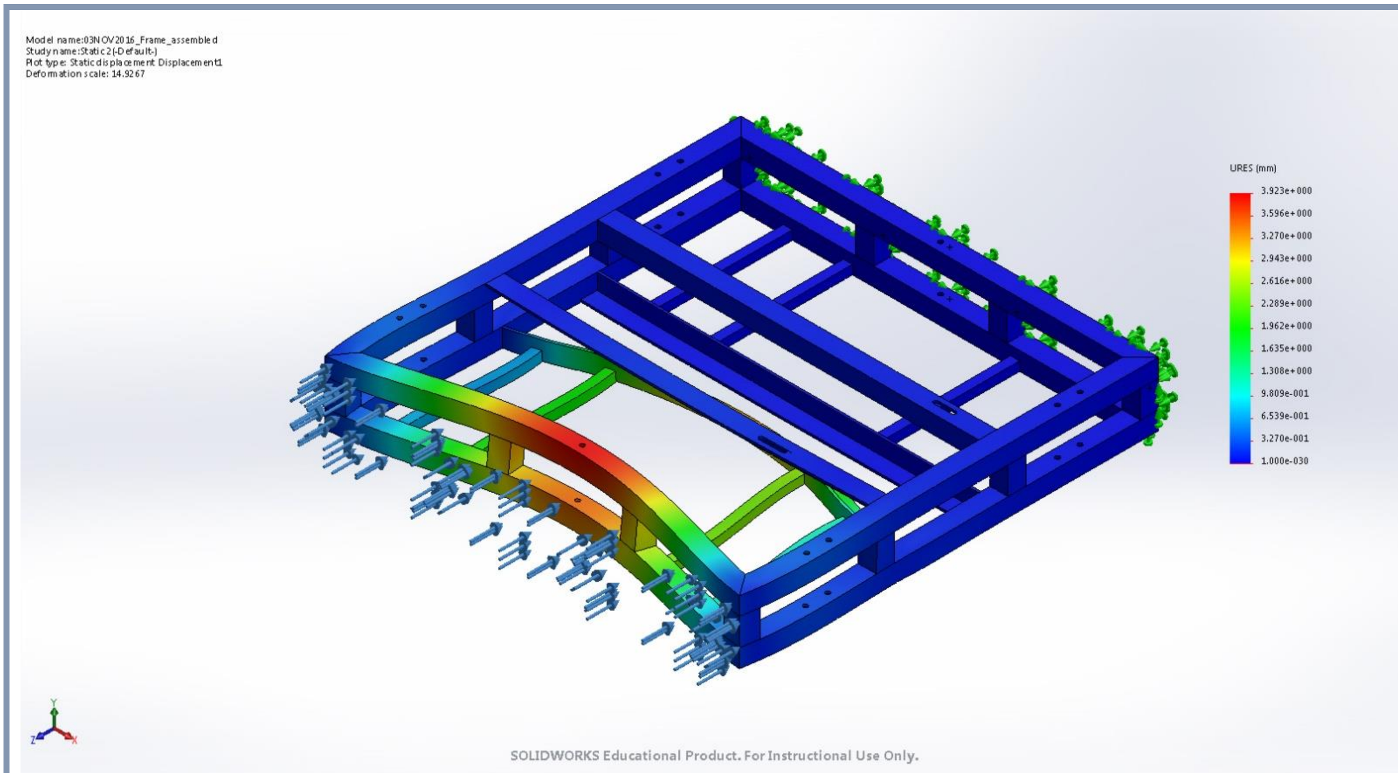
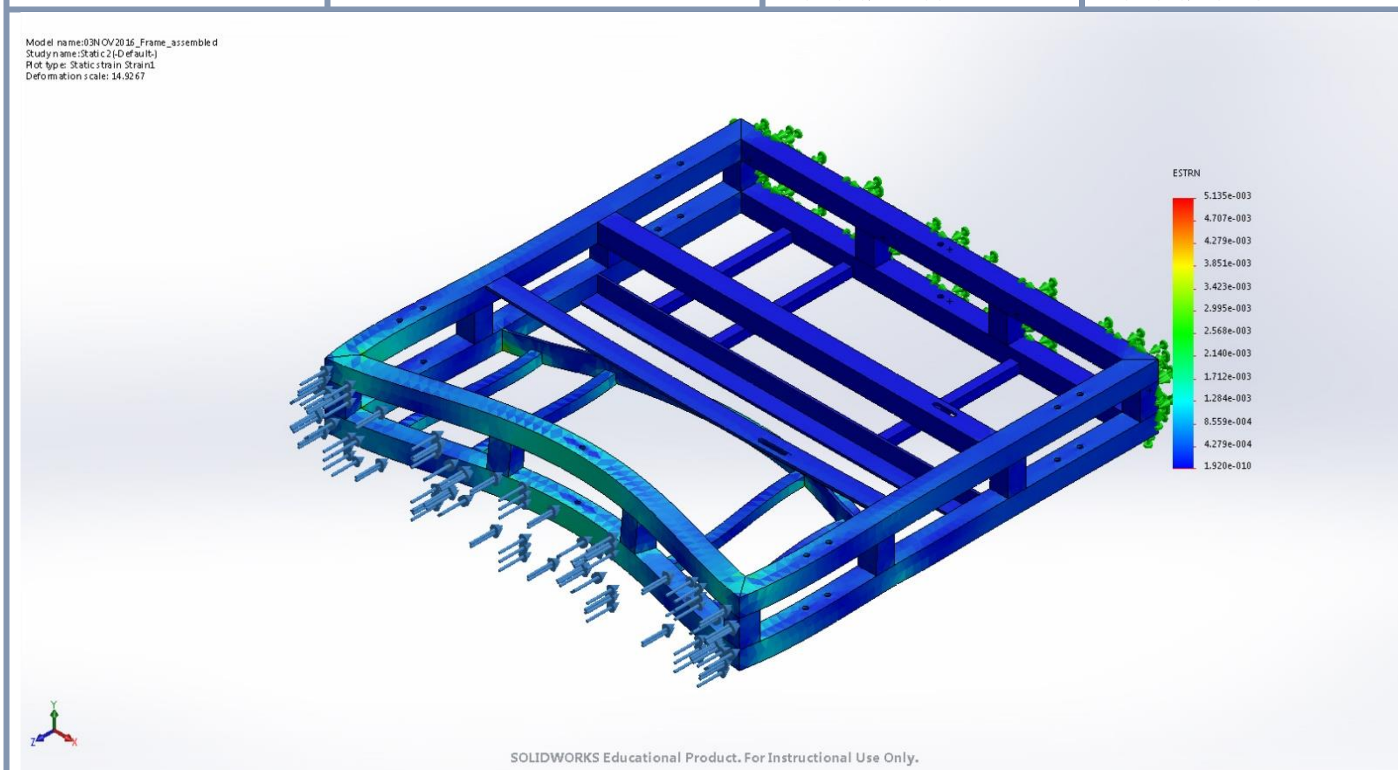


03NOV2016_Frame_assembled-Static 2-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	1.92016e-010 Element: 22108	0.00513514 Element: 28443



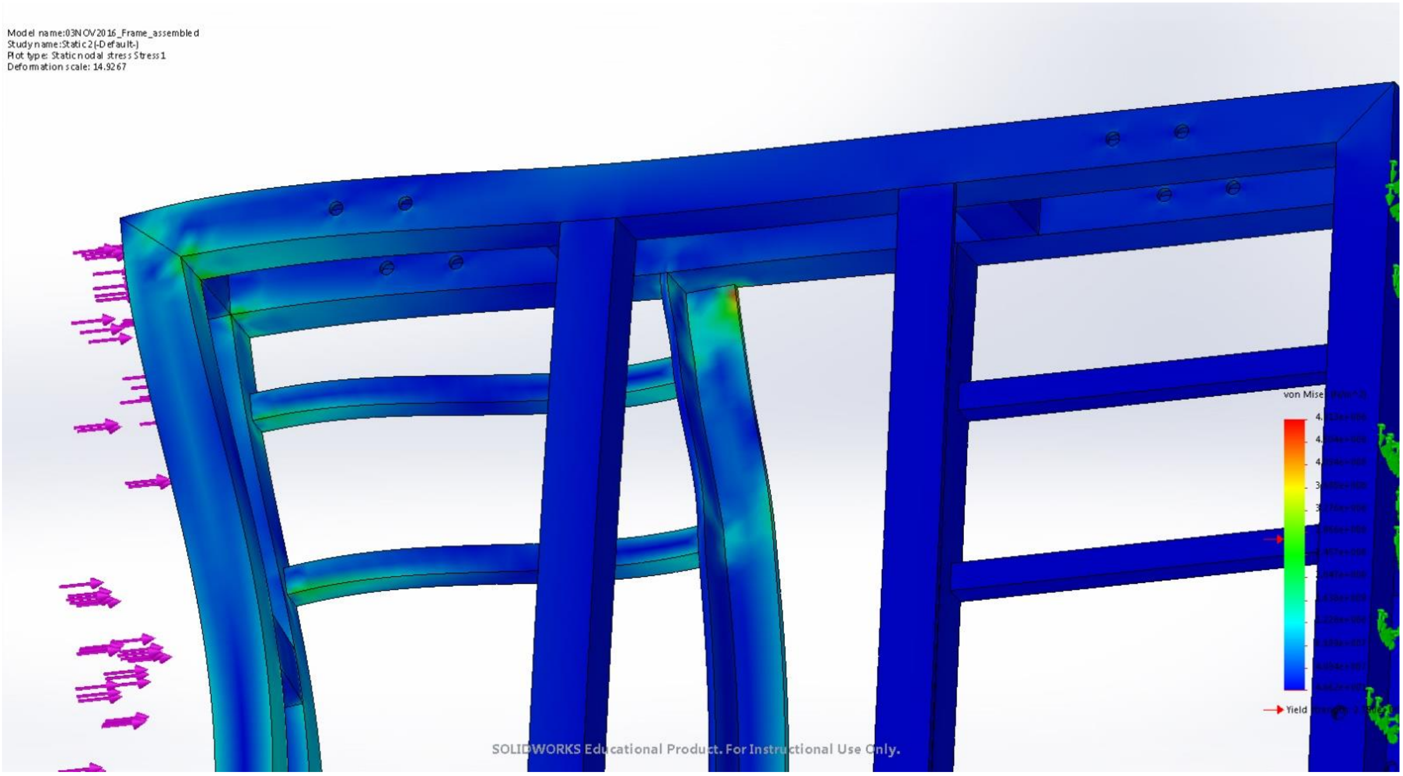

Model name:03NOV2016_Frame_assembled
Study name:Static 2(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 14.9267
SOLIDWORKS Educational Product. For Instructional Use Only.

Image-1

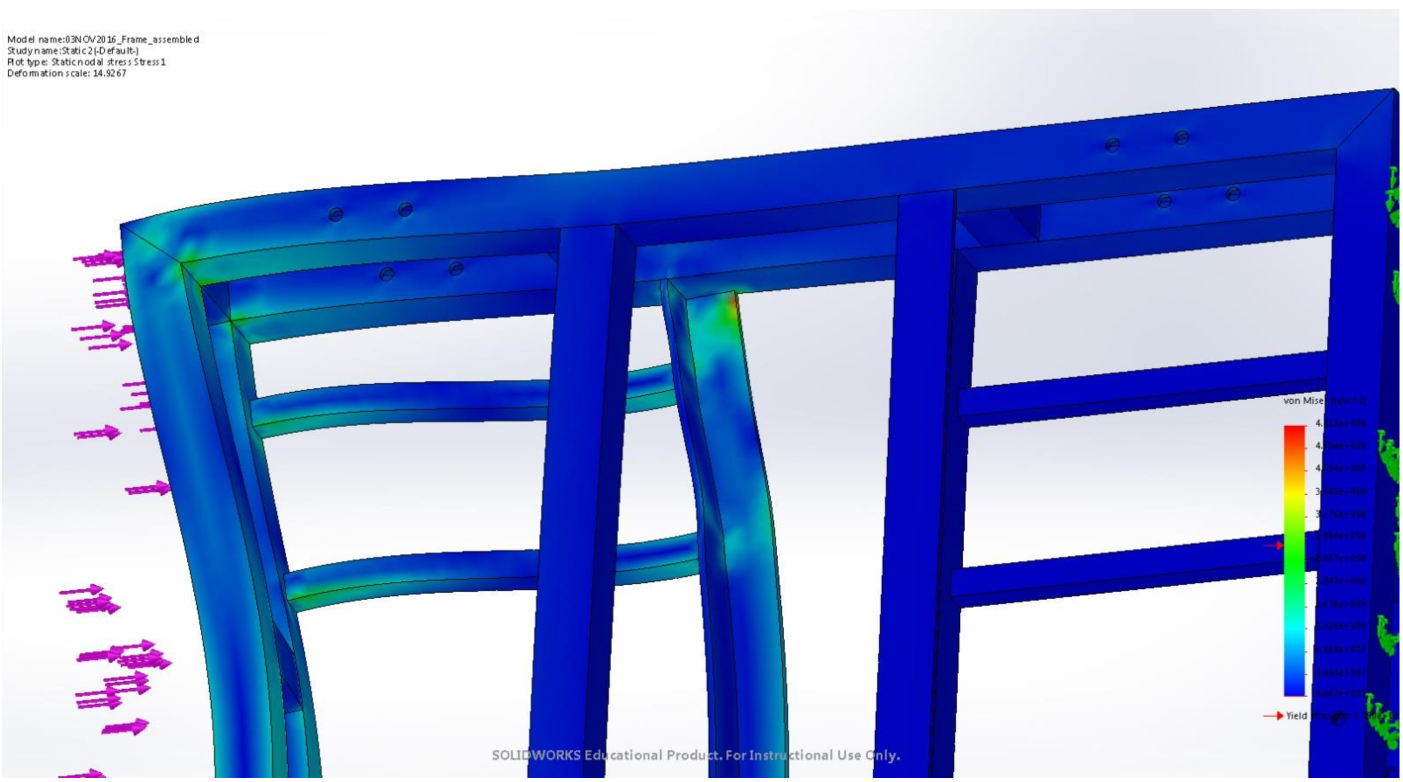

Model name:03NOV2016_Frame_assembled
Study name:Static 2(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 14.9267
SOLIDWORKS Educational Product. For Instructional Use Only.

Image-2

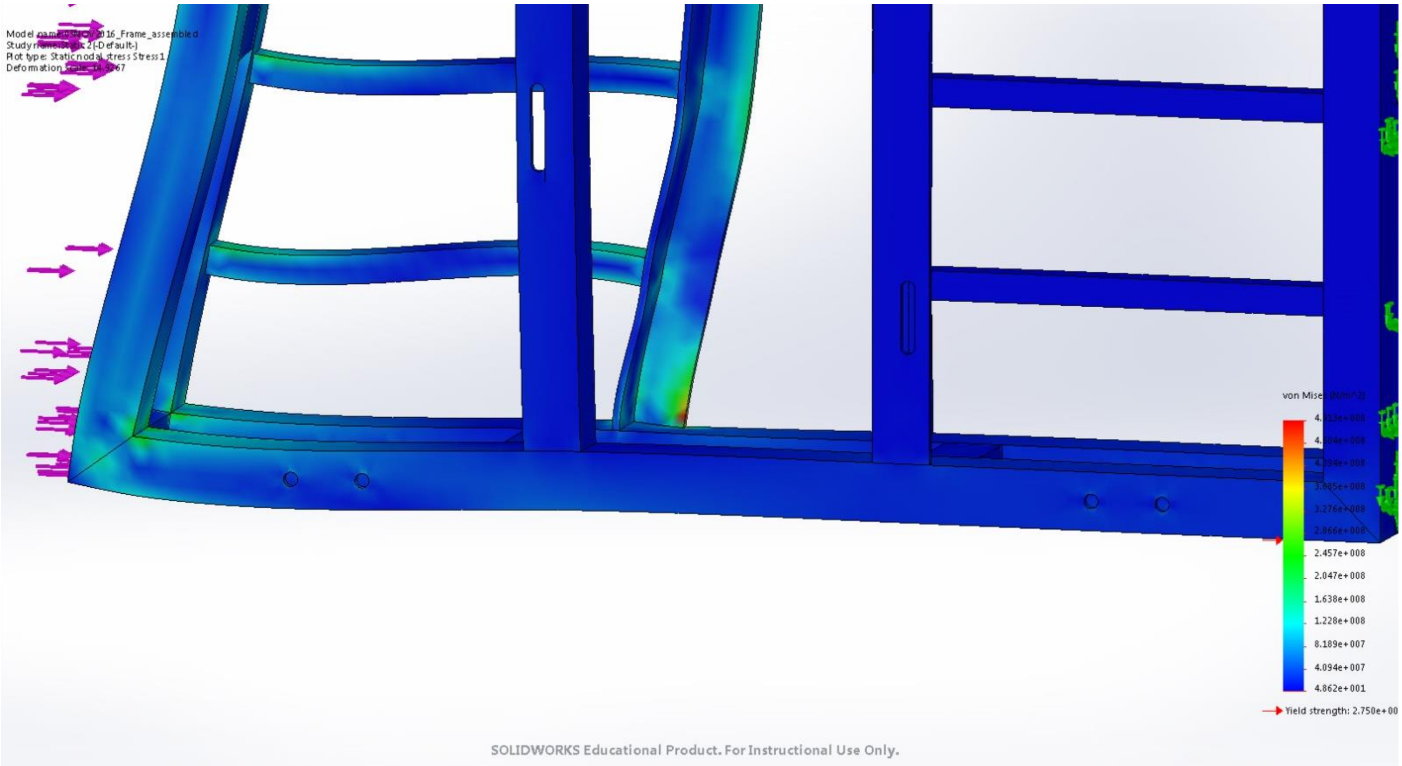
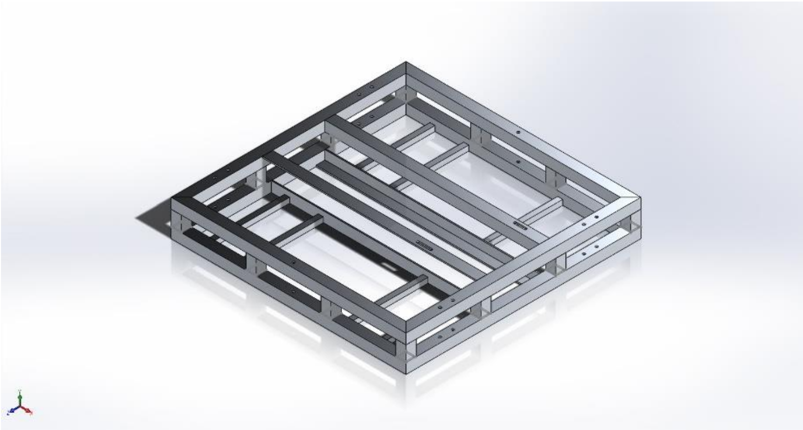


Image-3

Simulation 3-Crush Corner



Simulation of Crush: Corner

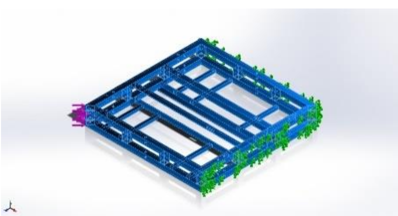
Date: Friday, April 21, 2017
Designer: Solidworks
Study name: Static 3
Analysis type: Static

Table of Contents

Units

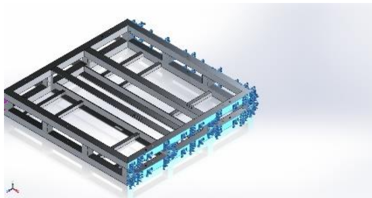
Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

Material Properties

Model Reference	Properties	Components
	Name: **6061-T6 (SS)** Model type: **Linear Elastic Isotropic** Default failure criterion: **Unknown** Yield strength: **2.75e+008 N/m^2** Tensile strength: **3.1e+008 N/m^2** Elastic modulus: **6.9e+010 N/m^2** Poisson's ratio: **0.33** Mass density: **2700 kg/m^3** Shear modulus: **2.6e+010 N/m^2** Thermal expansion coefficient: **2.4e-005 /Kelvin**	**SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-3), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-5), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-6), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_2-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_3-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_4-1), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-1), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-10), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-11), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-12), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-2), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-3), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-4), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-5), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-6),**

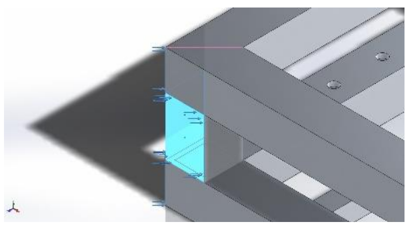
		SolidBody 1(Boss-Extrude1) (18OCT2016_Frame_Vertical-7), SolidBody 1(Boss-Extrude1) (18OCT2016_Frame_Vertical-8), SolidBody 1(Boss-Extrude1) (18OCT2016_Frame_Vertical-9), SolidBody 1(Boss-Extrude1) (27OCT2016_Angle_Weapon_Support-1), SolidBody 1(Boss-Extrude1) (27OCT2016_Angle_Weapon_Support-2), SolidBody 1(Cut-Extrude1) (27OCT2016_Angle_Weapon_Support_Top-1), SolidBody 1(Cut-Extrude1) (27OCT2016_Angle_Weapon_Support_top2-1), SolidBody 1(Boss-Extrude1) (wheel assembly support-1), SolidBody 1(Boss-Extrude1) (wheel assembly support-2), SolidBody 1(Boss-Extrude1) (wheel assembly support-3), SolidBody 1(Boss-Extrude1) (wheel assembly support-4), SolidBody 1(Boss-Extrude1) (wheel assembly support-5), SolidBody 1(Boss-Extrude1) (wheel assembly support-6), SolidBody 1(Boss-Extrude1) (wheel assembly support-7), SolidBody 1(Boss-Extrude1)(wheel assembly support-8)
Curve Data:N/A		

Loads and Fixtures

Fixture name	Fixture Image	Fixture Details
Fixed-1		**Entities:** 12 face(s) **Type:** Fixed Geometry

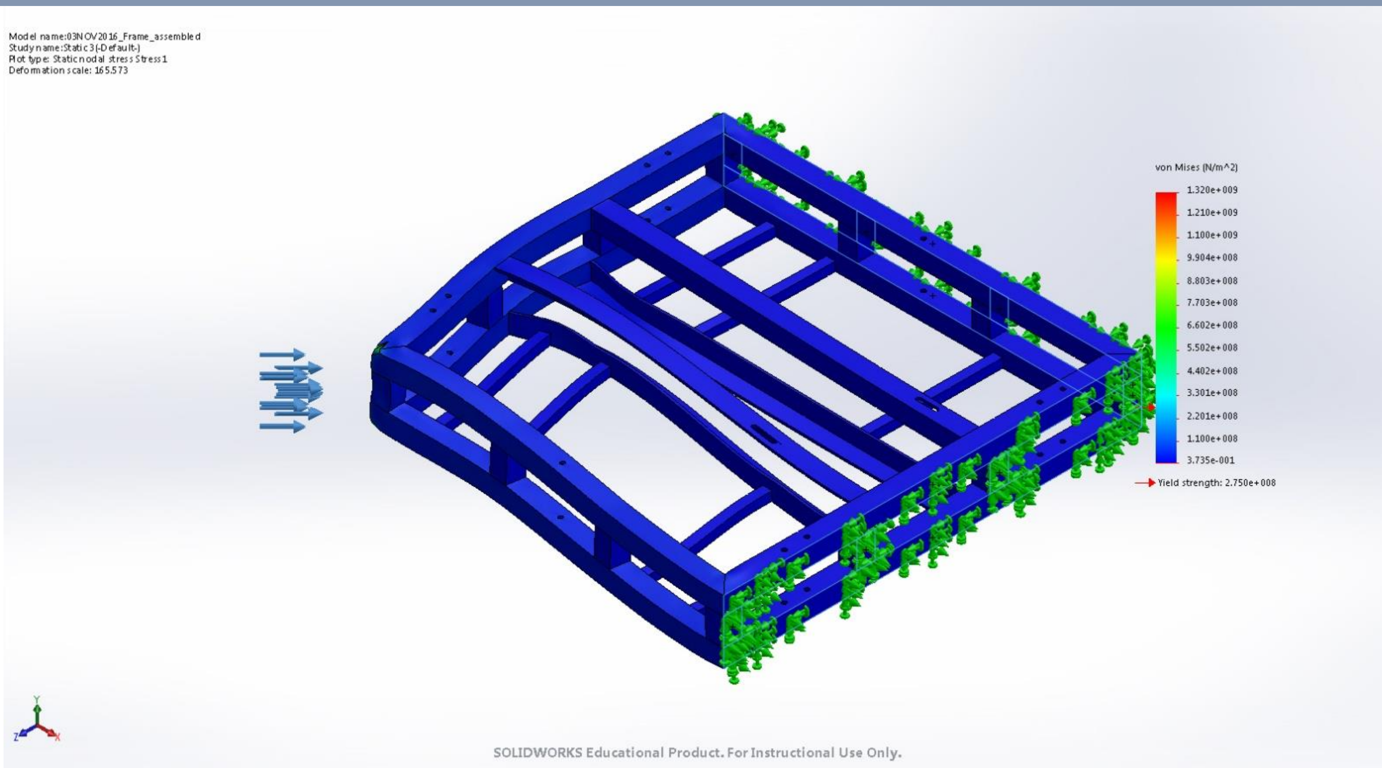
Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	**-18872.4**	**-0.0687841**	**18872.6**	**26689.7**
Reaction Moment(Nm)	**0**	**0**	**0**	**0**

Load name	Load Image	Load Details
Force-1		**Entities:** 2 vertex(s), 2 edge(s), 2 face(s) **Reference:** Edge< 1 > **Type:** Apply force **Values:** ---, ---, 1000 lbf

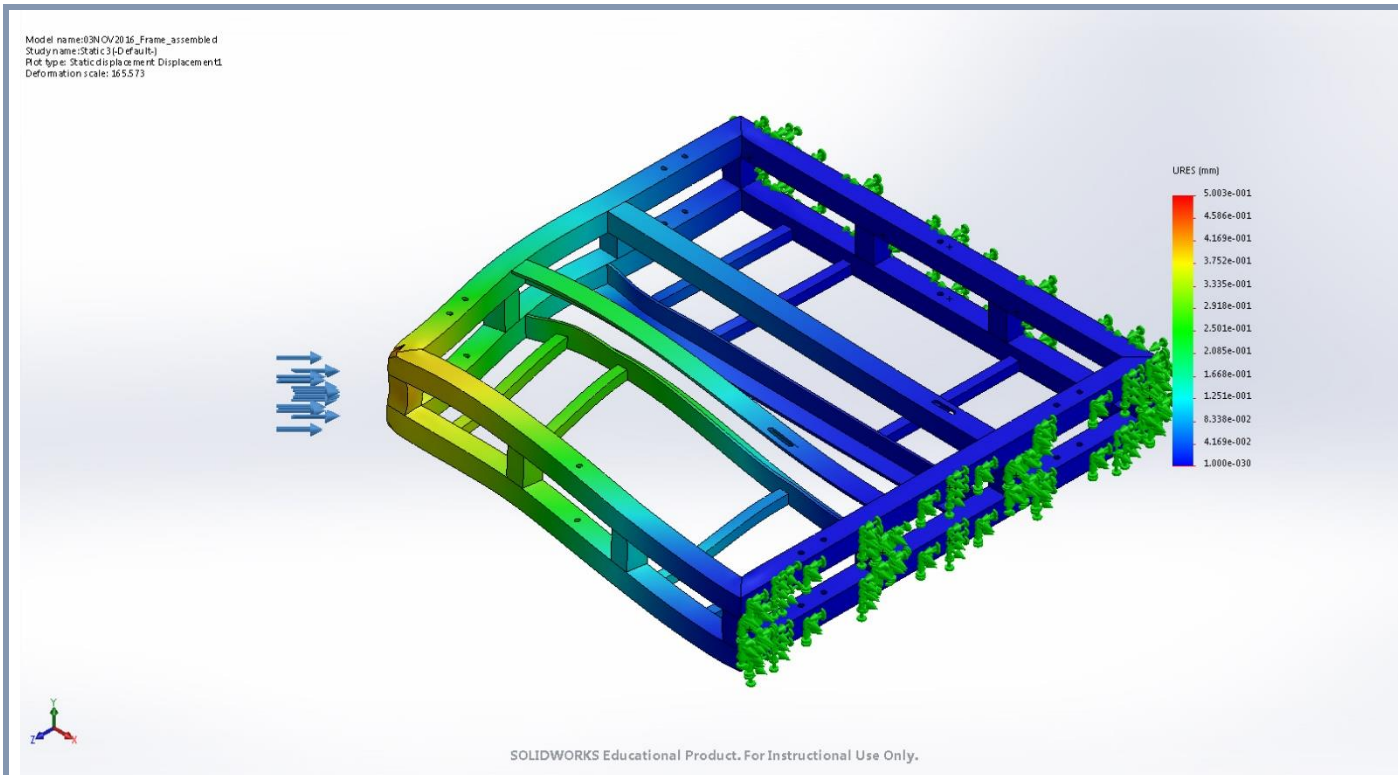
Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	0.373543 N/m^2 Node: 50363	1.32049e+009 N/m^2 Node: 490



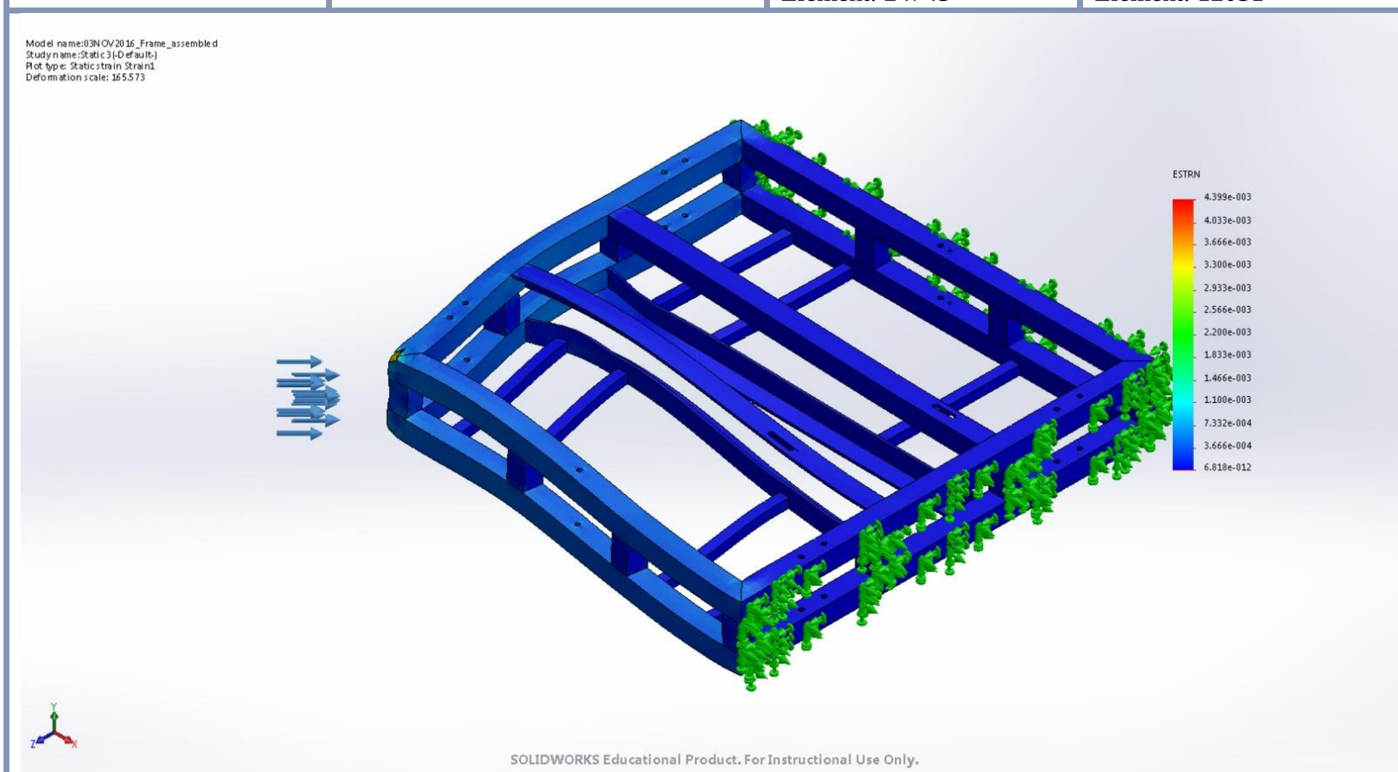
03NOV2016_Frame_assembled-Static 3-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0 mm Node: 245	0.500297 mm Node: 21440



03NOV2016_Frame_assembled-Static 3-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	6.8181e-012 Element: 24745	0.00439937 Element: 12051



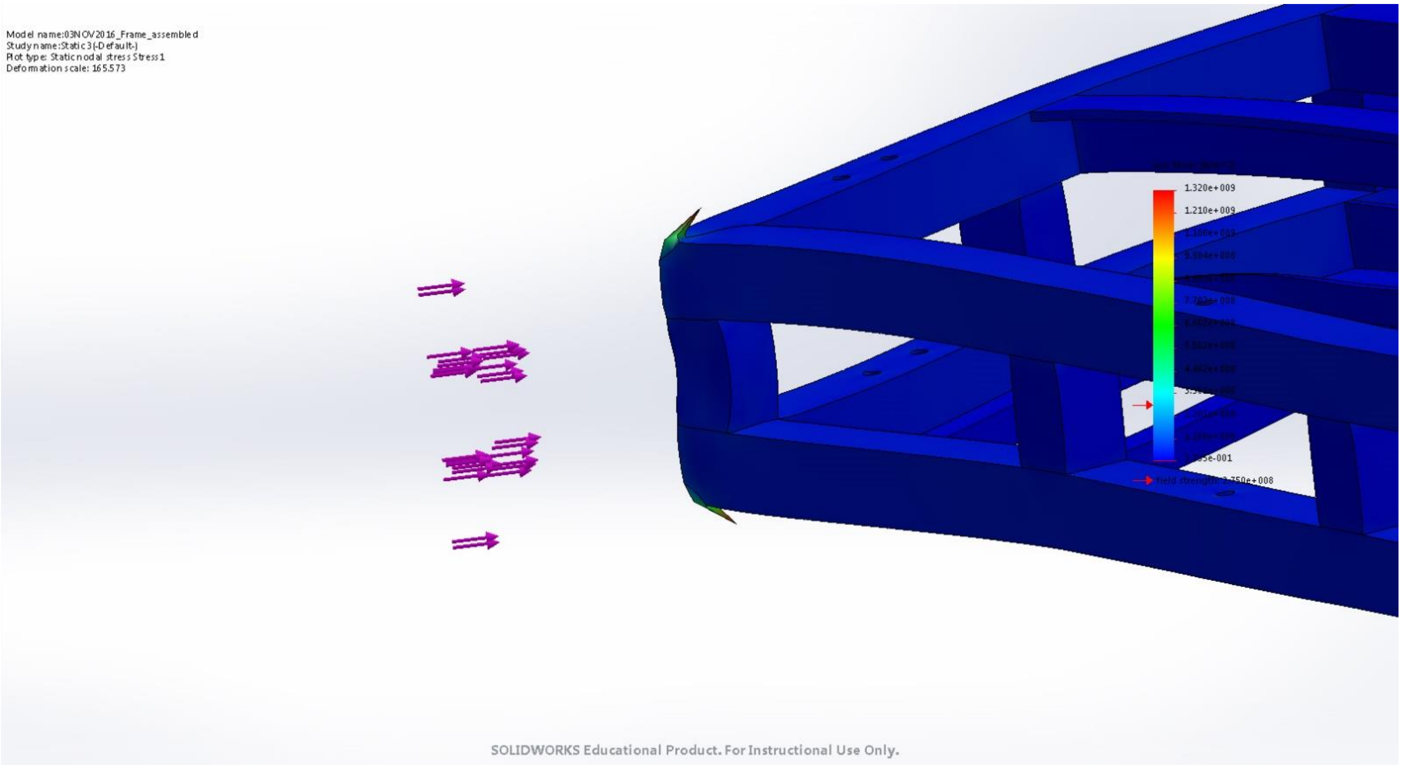

Model name:03NOV2016_Frame_assembled
Study name:Static 3(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 165.573
1.320e+009
1.210e+009
SOLIDWORKS Educational Product. For Instructional Use Only.

Image-1

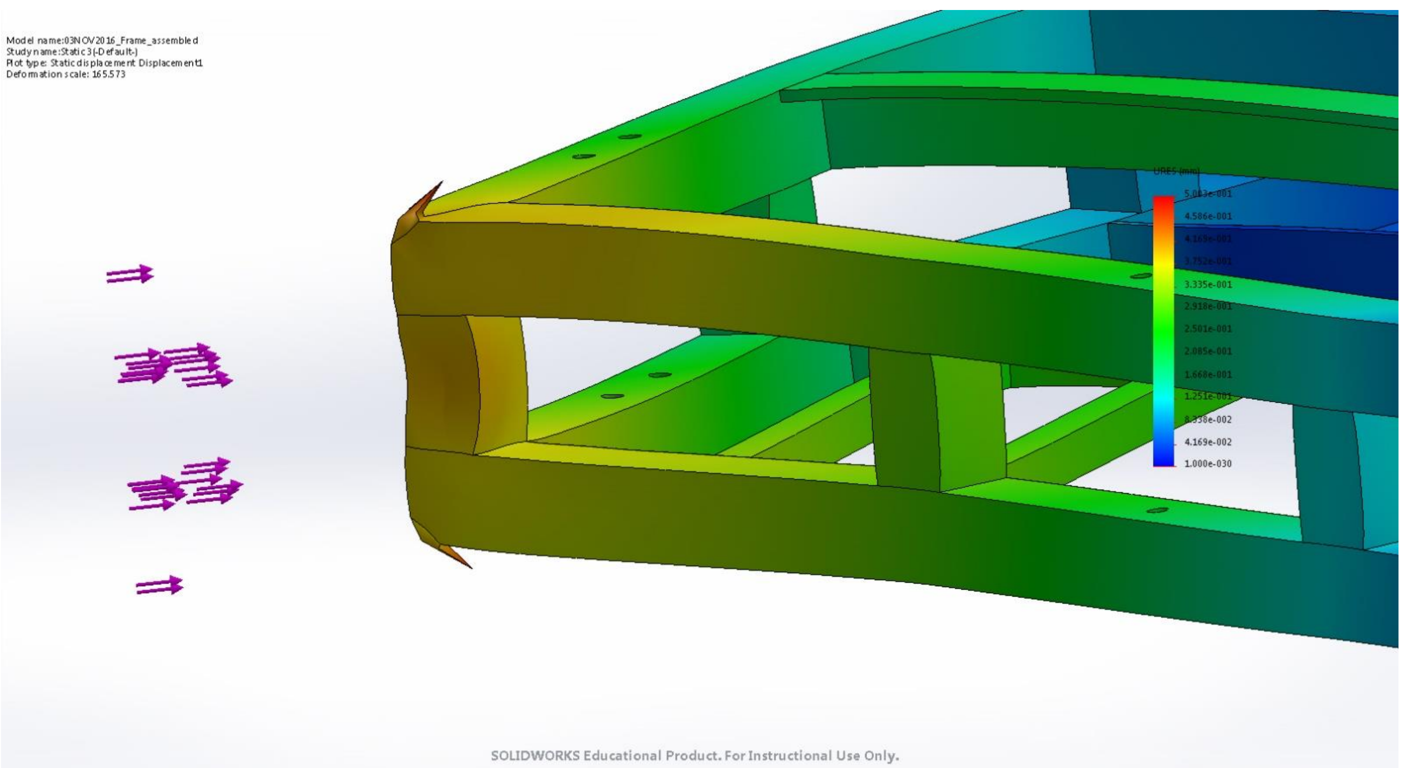

Model name:03NOV2016_Frame_assembled
Study name:Static 3(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 165.573
4.586e-001
3.335e-001
2.918e-001
2.501e-001
2.085e-001
1.668e-001
4.169e-002
1.000e-030
SOLIDWORKS Educational Product. For Instructional Use Only.

Image-2

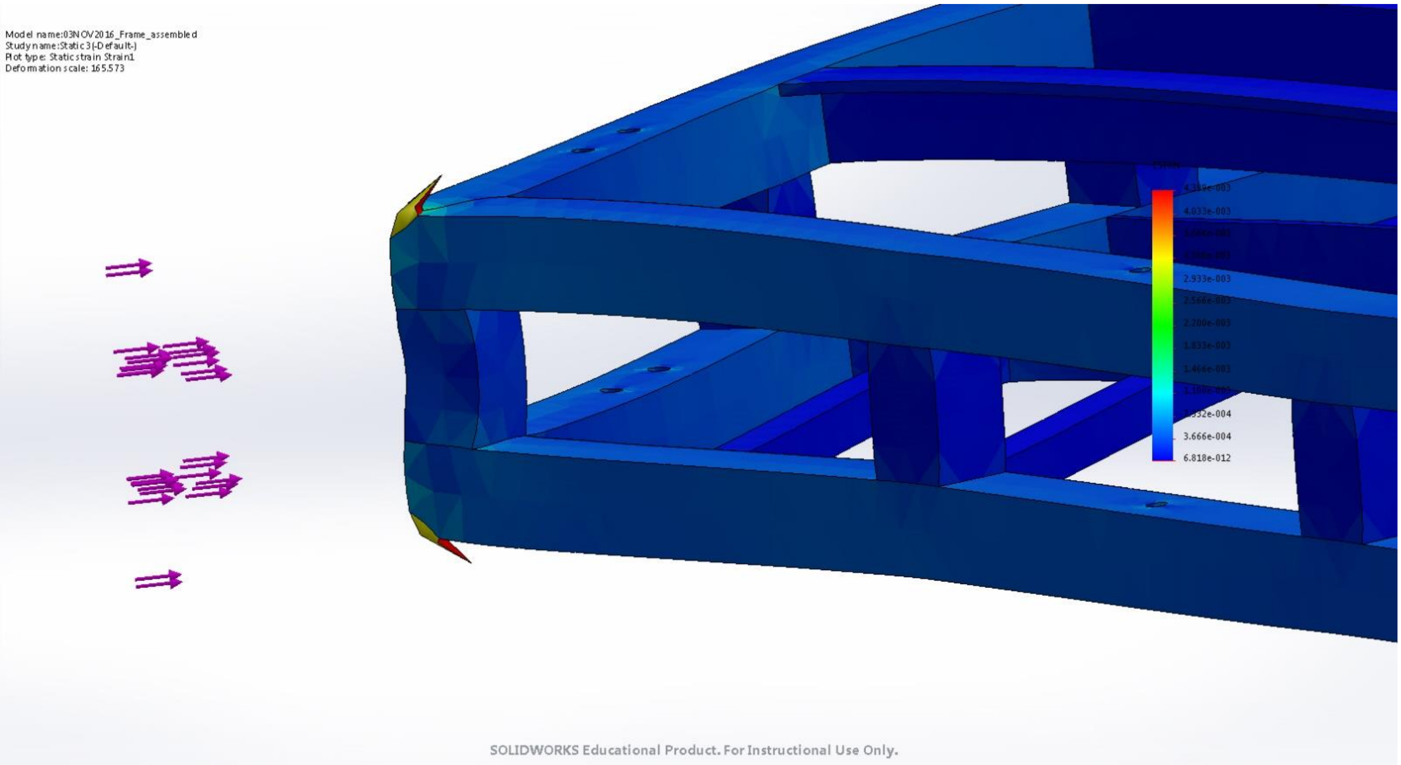
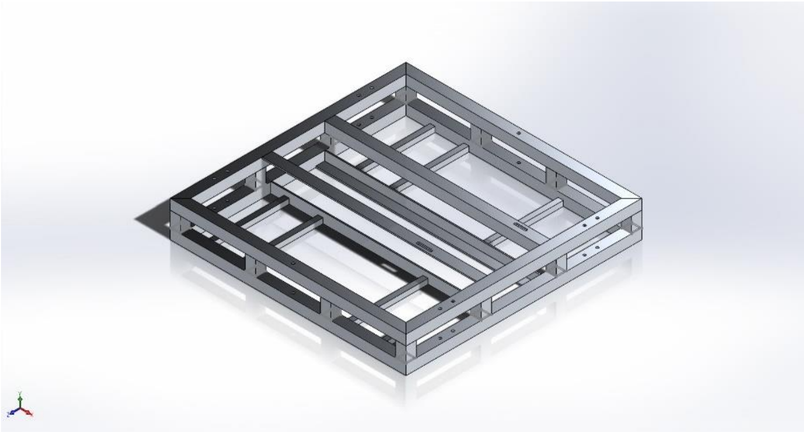


Image-3

Simulation 4-3ft Drop: Side



Simulation of 3ft Drop: Side

Date: Tuesday, April 25, 2017
Designer: Solidworks
Study name: Drop Test 1
Analysis type: Drop Test

Table of Contents

Study Properties

Study name	Drop Test 1
Analysis type	Drop Test
Mesh type	Solid Mesh
Large displacement	On
Result folder	SOLIDWORKS document (\\clusterfsnew.ceas1.uc.edu\students\riordamv\desktop\Final Report\Solidworks Simulations\final frame)

Setup Information

Type	Drop height
Drop height from lowest point	9.62828 ft.
Gravity	9.81 m/s^2
Gravity Reference	Edge<1>
Friction Coefficient	0
Target Stiffness	Rigid target
Critical Damping Ratio	0

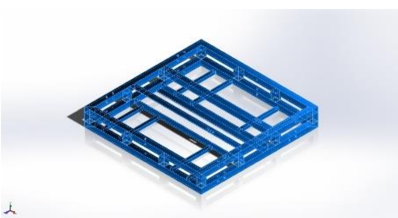
Result Options

Solution Time After Impact	495.5 microsec
Save Results Starting From	0 microsec
No. of Plots	25
No. of Graph Steps Per Plot	20
Number of vertex	0

Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

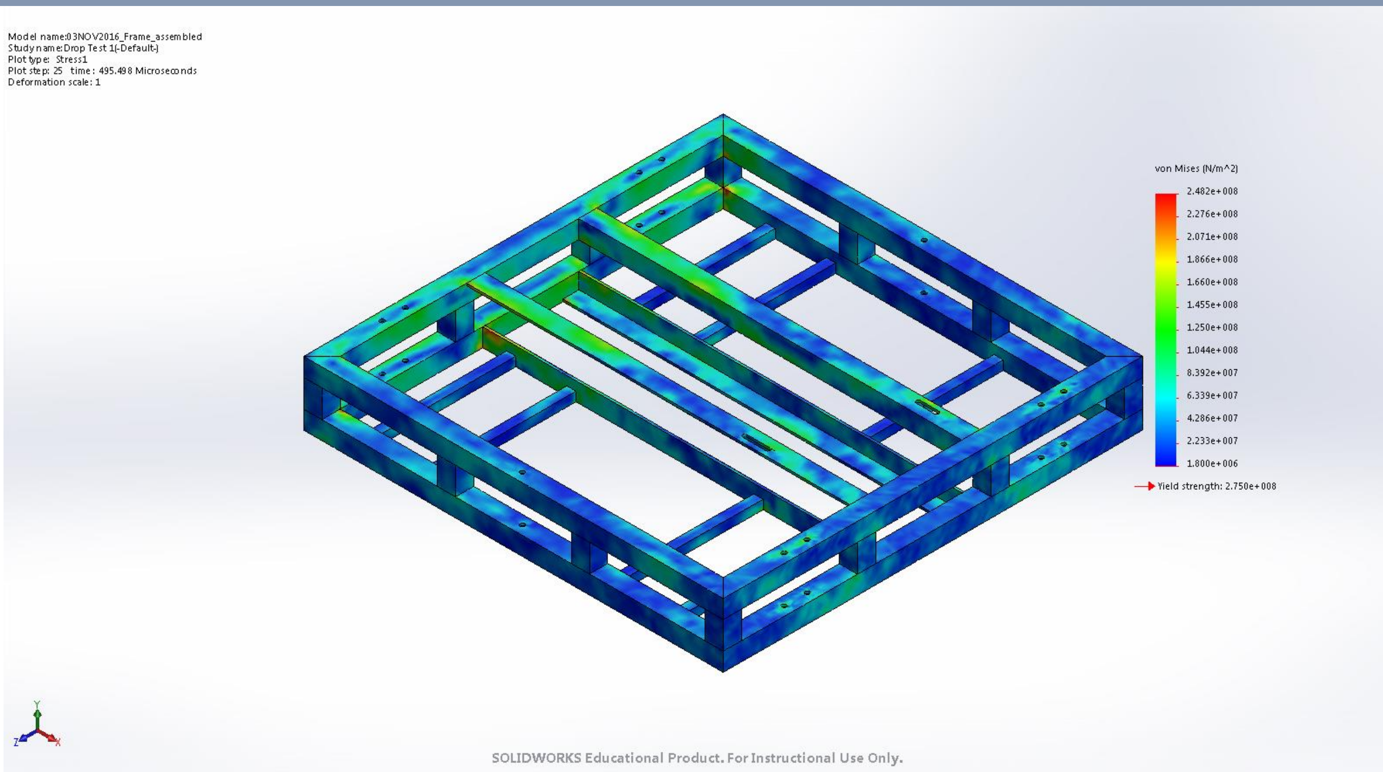
Material Properties

Model Reference	Properties	Components
	Name: **6061-T6 (SS)** Model type: **Plasticity - von Mises** Default failure criterion: **Unknown** Yield strength: **2.75e+008 N/m^2** Hardening factor (0.0-1.0; 0.0=isotropic; 1.0=kinematic): **0.85** Elastic modulus: **6.9e+010 N/m^2** Poisson's ratio: **0.33** Mass density: **2700 kg/m^3**	**SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-3), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-5), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-6), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_2-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_3-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_4-1), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-1), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-10), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-11), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-12), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-2), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-3), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-4), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-5), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-6),**

		SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-7), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-8), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-9), SolidBody 1(Boss-Extrude1)(27OCT2016_Angle_Weapon_Support-1), SolidBody 1(Boss-Extrude1)(27OCT2016_Angle_Weapon_Support-2), SolidBody 1(Cut-Extrude1)(27OCT2016_Angle_Weapon_Support_Top-1), SolidBody 1(Cut-Extrude1)(27OCT2016_Angle_Weapon_Support_top2-1), SolidBody 1(Boss-Extrude1)(wheel assembly support-1), SolidBody 1(Boss-Extrude1)(wheel assembly support-2), SolidBody 1(Boss-Extrude1)(wheel assembly support-3), SolidBody 1(Boss-Extrude1)(wheel assembly support-4), SolidBody 1(Boss-Extrude1)(wheel assembly support-5), SolidBody 1(Boss-Extrude1)(wheel assembly support-6), SolidBody 1(Boss-Extrude1)(wheel assembly support-7), SolidBody 1(Boss-Extrude1)(wheel assembly support-8)
Curve Data:N/A		

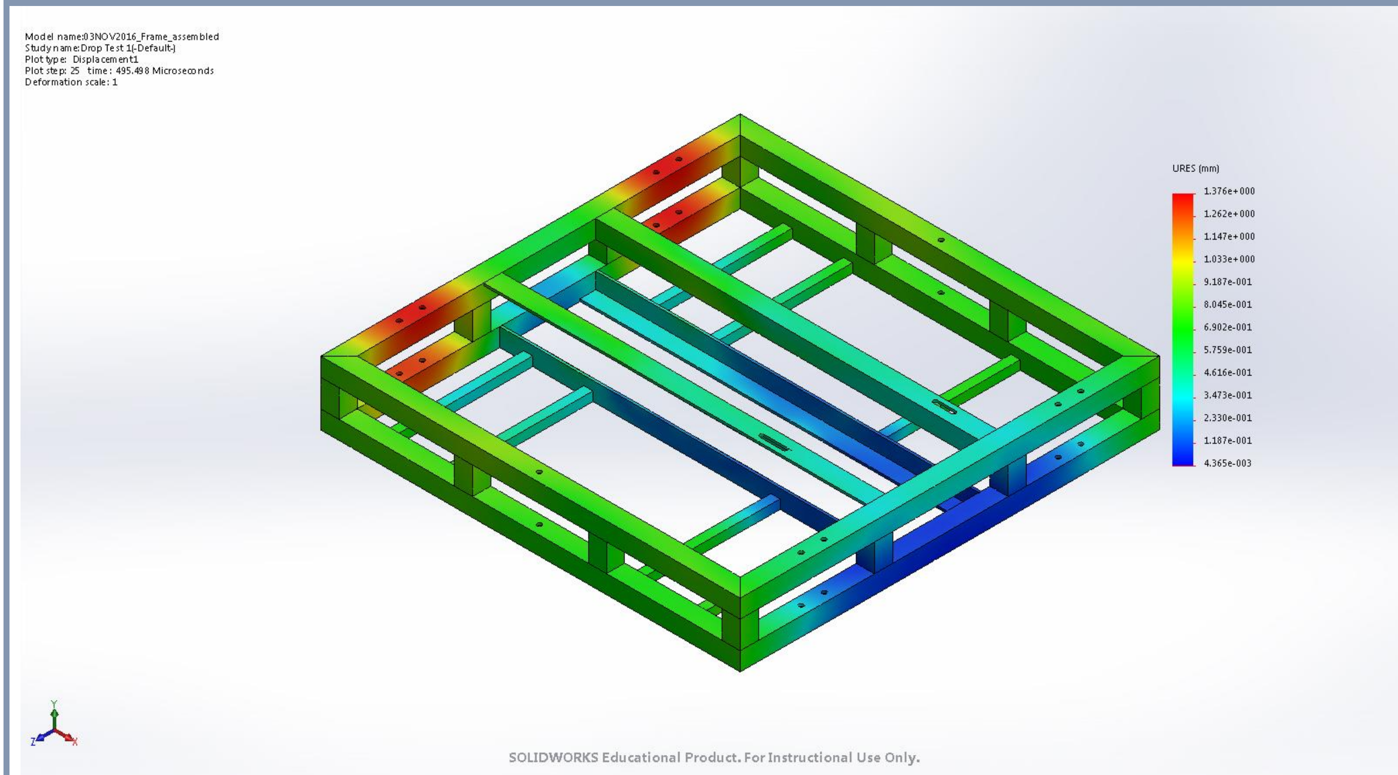
Study Results

Name	**Type**	**Min**	**Max**
Stress1	VON: von Mises Stress	1.79956e+006 N/m^2 Node: 49238	2.48151e+008 N/m^2 Node: 37820



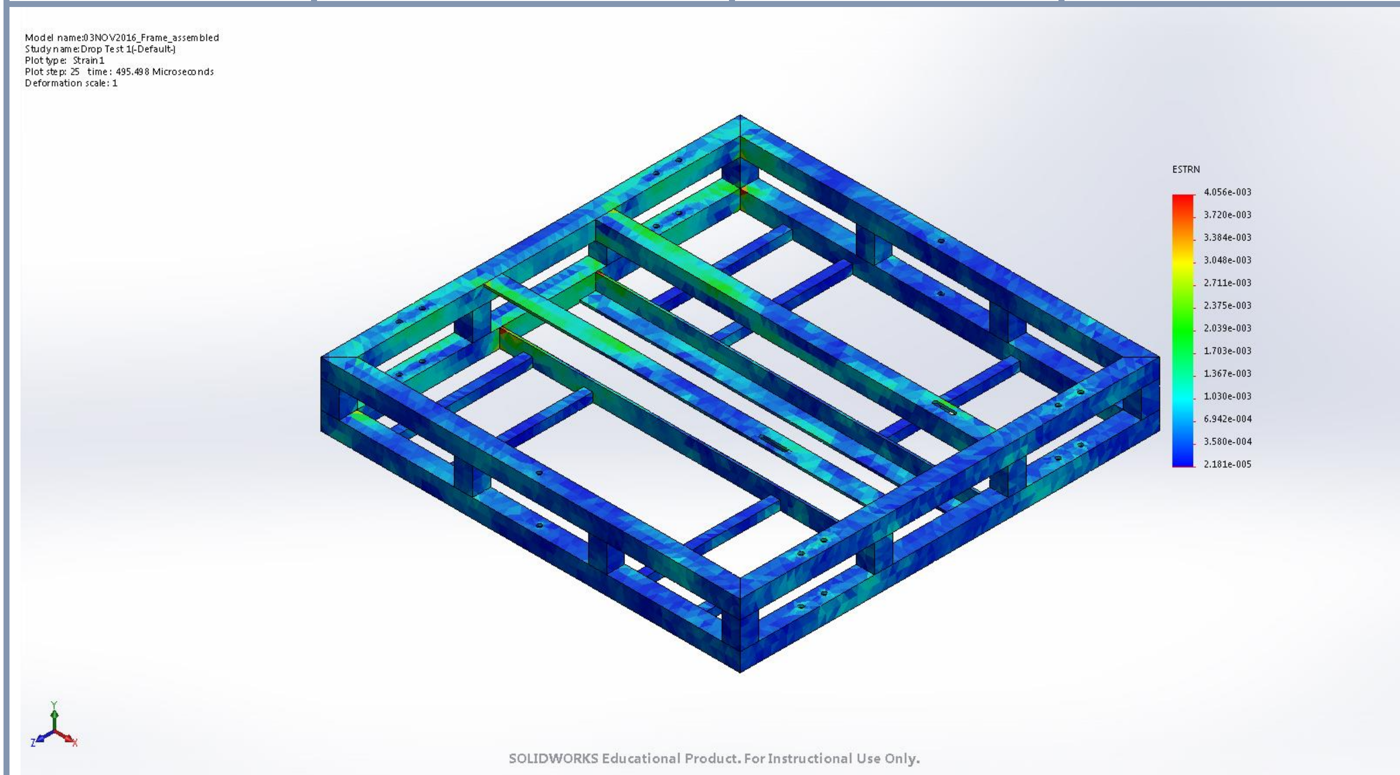
03NOV2016_Frame_assembled-Drop Test 1-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.00436535 mm Node: 10142	1.37594 mm Node: 5616



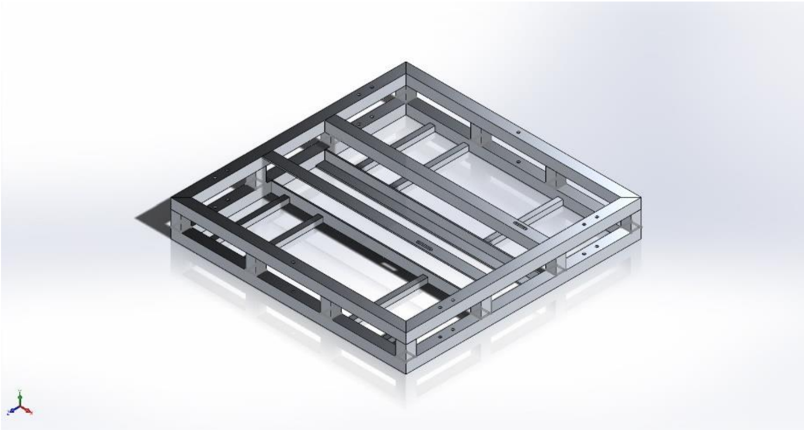
03NOV2016_Frame_assembled-Drop Test 1-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	2.18056e-005 Element: 33835	0.00405614 Element: 27153



03NOV2016_Frame_assembled-Drop Test 1-Strain-Strain1

Simulation 5-3ft Drop: Front



Simulation of 3ft Drop: Front

Date: Friday, April 21, 2017
Designer: Solidworks
Study name: Drop Test 2
Analysis type: Drop Test

Table of Contents

Study Properties

Study name	Drop Test 2
Analysis type	Drop Test
Mesh type	Solid Mesh
Large displacement	On
Result folder	SOLIDWORKS document (\\clusterfsnew.ceas1.uc.edu\students\riordamv\desktop\final frame-20170421T184351Z-001\final frame)

Setup Information

Type	Drop height
Drop height from lowest point	9.62828 ft.
Gravity	9.81 m/s^2
Gravity Reference	Edge<1>
Friction Coefficient	0
Target Stiffness	Rigid target
Critical Damping Ratio	0

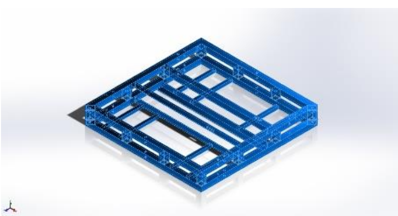
Result Options

Solution Time After Impact	495.5 microsec
Save Results Starting From	0 microsec
No. of Plots	25
No. of Graph Steps Per Plot	20
Number of vertex	0

Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

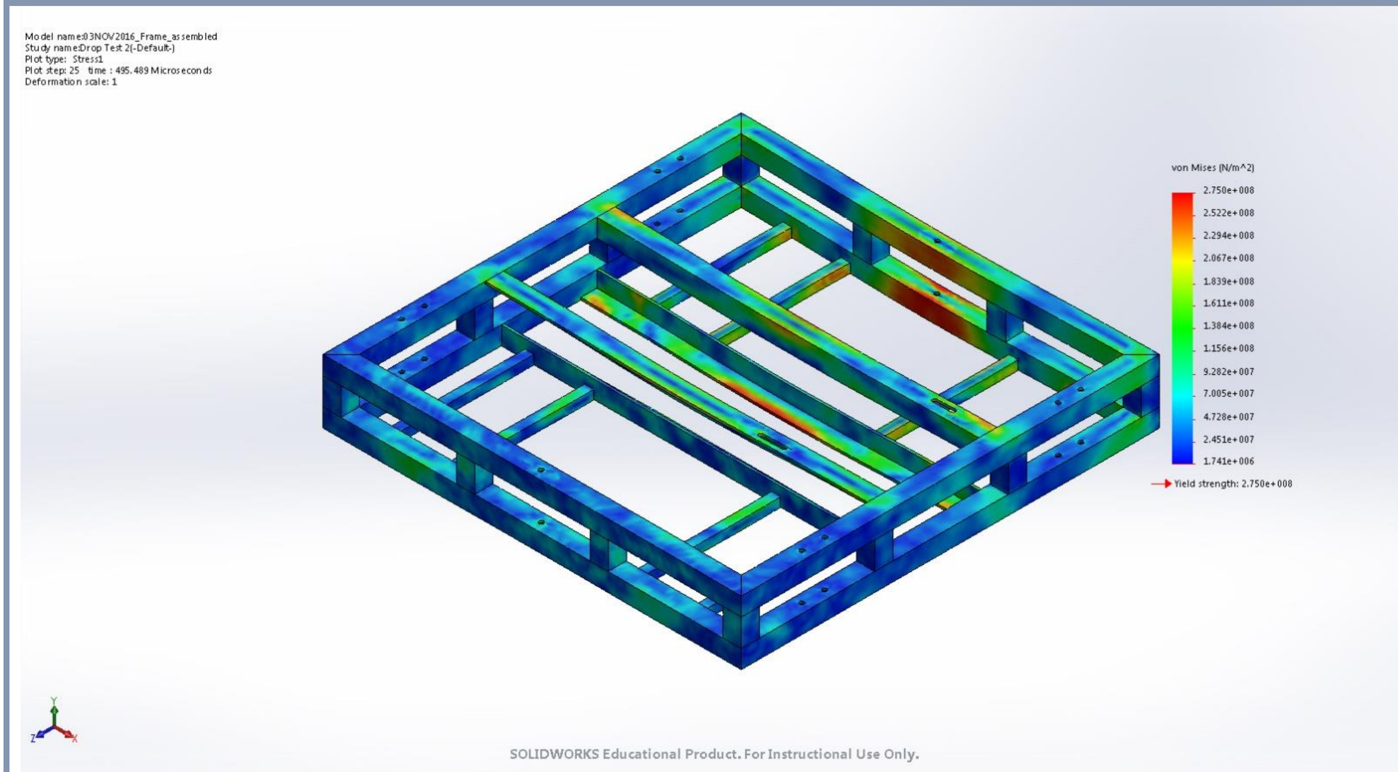
Material Properties

Model Reference	Properties	Components
	Name: **6061-T6 (SS)** Model type: **Plasticity - von Mises** Default failure criterion: **Unknown** Yield strength: **2.75e+008 N/m^2** Hardening factor (0.0-1.0; 0.0=isotropic; 1.0=kinematic): **0.85** Elastic modulus: **6.9e+010 N/m^2** Poisson's ratio: **0.33** Mass density: **2700 kg/m^3**	**SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-3), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-5), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-6), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_2-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_3-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_4-1), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-1), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-10), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-11), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-12), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-2), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-3), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-4), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-5), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-6),**

		SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-7), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-8), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-9), SolidBody 1(Boss-Extrude1)(27OCT2016_Angle_Weapon_Support-1), SolidBody 1(Boss-Extrude1)(27OCT2016_Angle_Weapon_Support-2), SolidBody 1(Cut-Extrude1)(27OCT2016_Angle_Weapon_Support_Top-1), SolidBody 1(Cut-Extrude1)(27OCT2016_Angle_Weapon_Support_top2-1), SolidBody 1(Boss-Extrude1)(wheel assembly support-1), SolidBody 1(Boss-Extrude1)(wheel assembly support-2), SolidBody 1(Boss-Extrude1)(wheel assembly support-3), SolidBody 1(Boss-Extrude1)(wheel assembly support-4), SolidBody 1(Boss-Extrude1)(wheel assembly support-5), SolidBody 1(Boss-Extrude1)(wheel assembly support-6), SolidBody 1(Boss-Extrude1)(wheel assembly support-7), SolidBody 1(Boss-Extrude1)(wheel assembly support-8)
Curve Data:N/A		

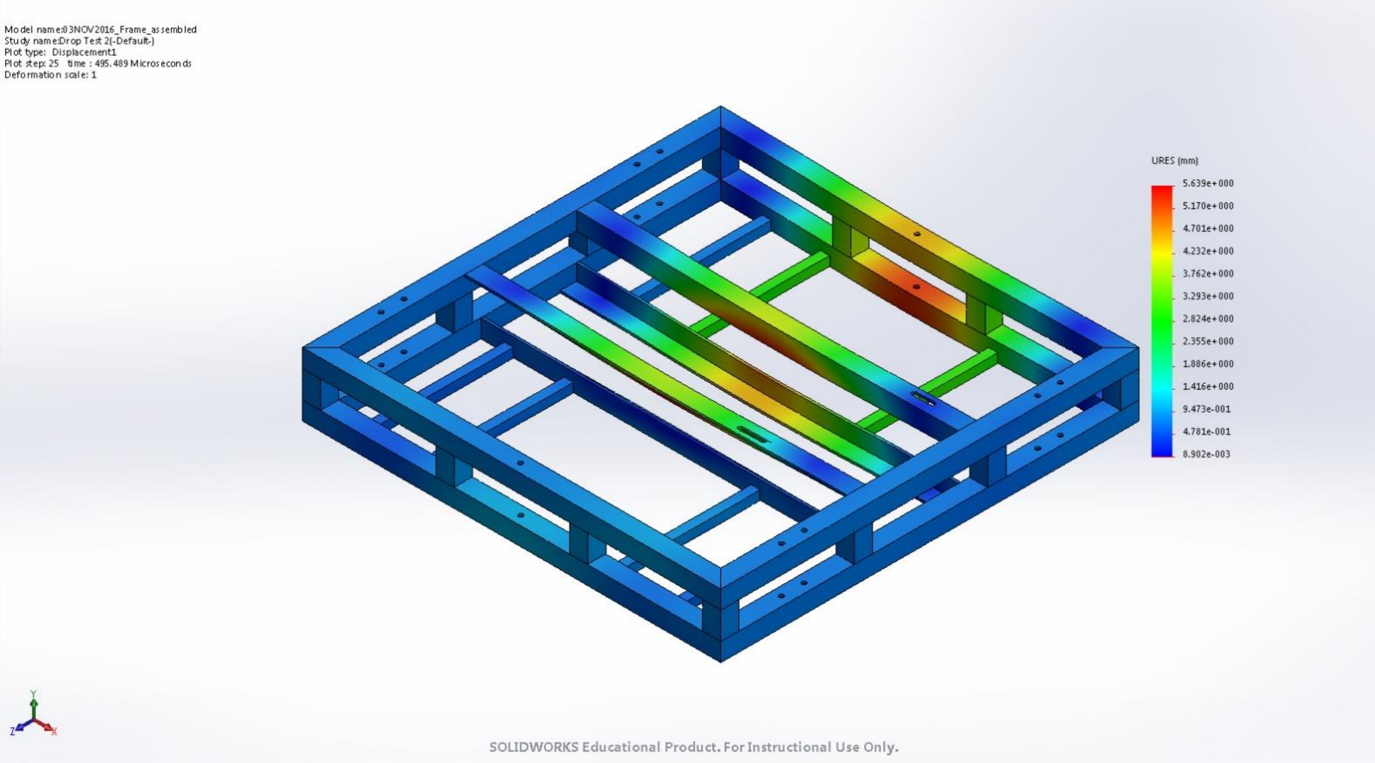
Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	1.7412e+006 N/m^2 Node: 65927	2.74984e+008 N/m^2 Node: 47674



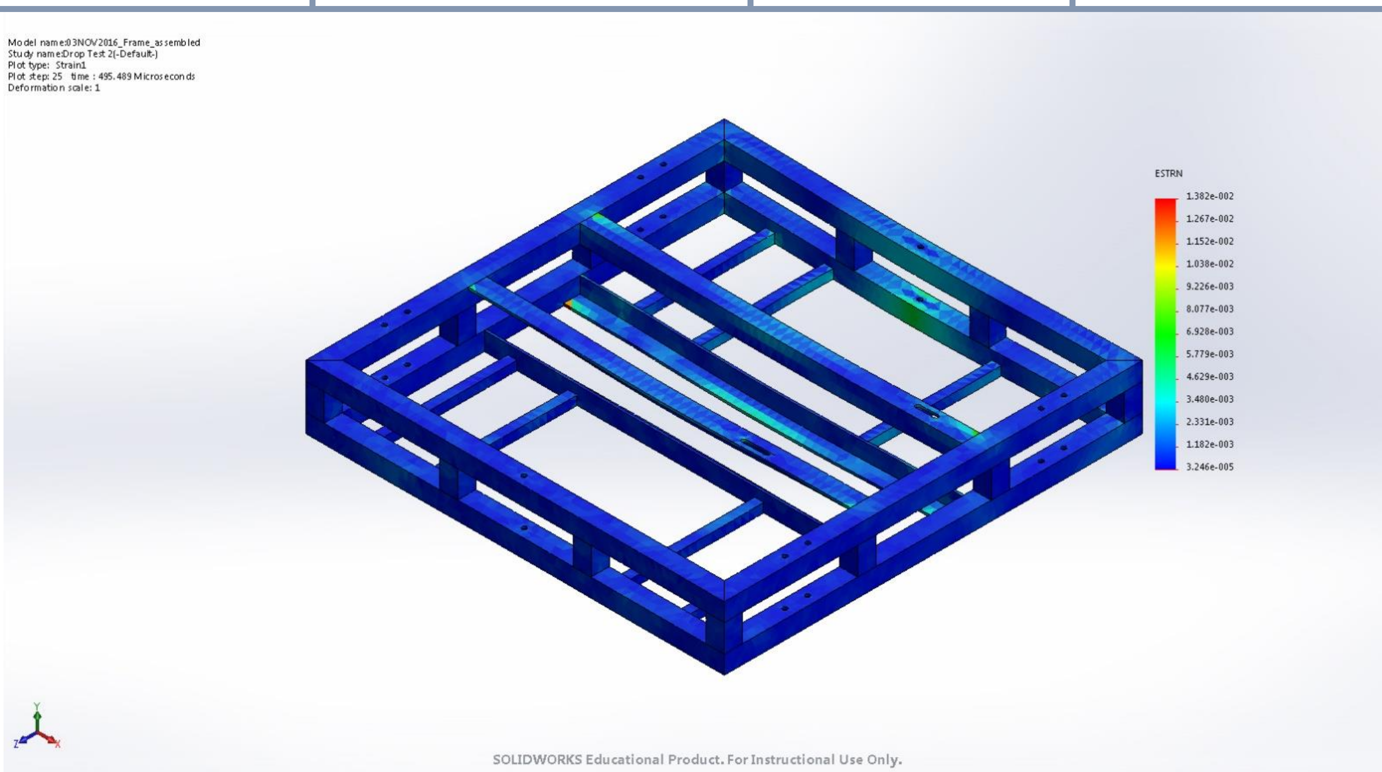
03NOV2016_Frame_assembled-Drop Test 2-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.00890186 mm Node: 58904	5.63928 mm Node: 60683



03NOV2016_Frame_assembled-Drop Test 2-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	3.24616e-005 Element: 32834	0.0138235 Element: 28358



03NOV2016_Frame_assembled-Drop Test 2-Strain-Strain1

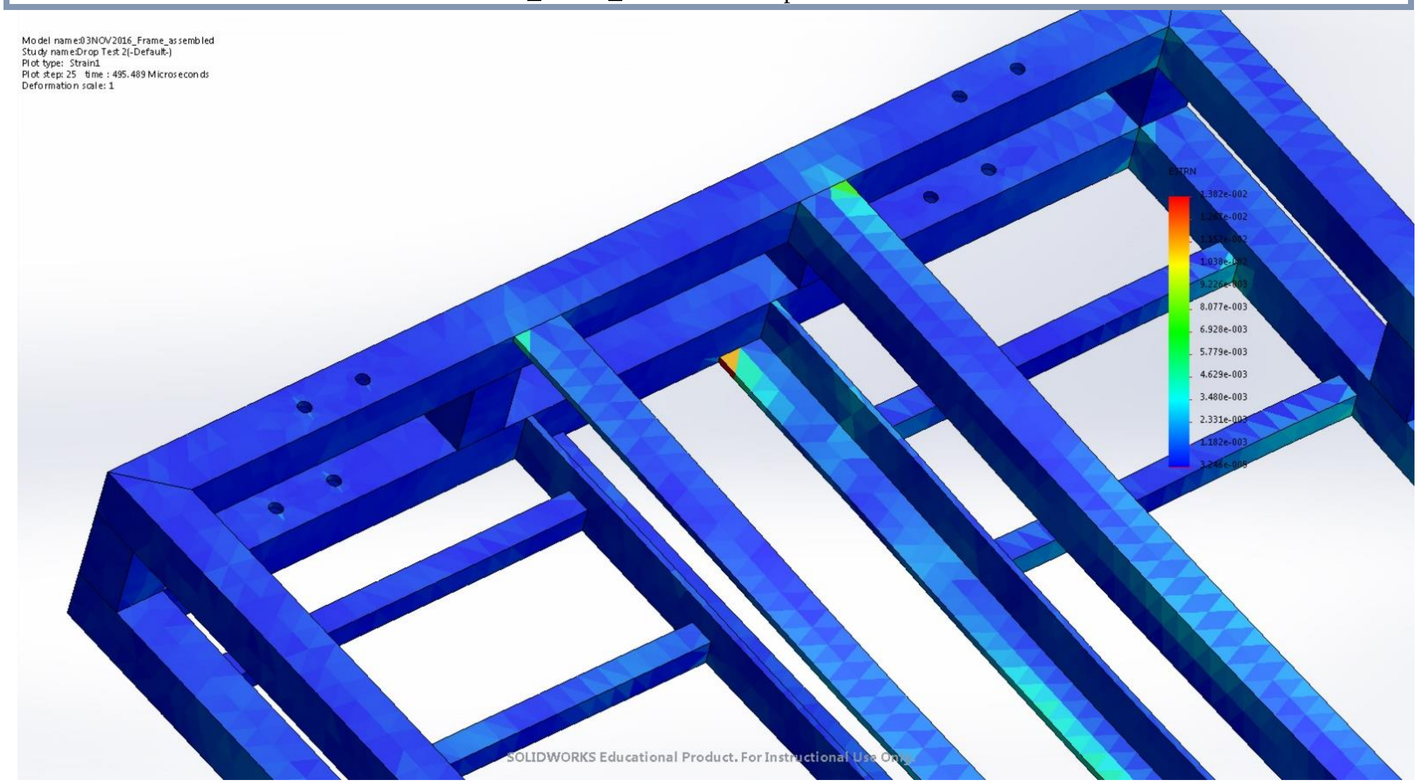
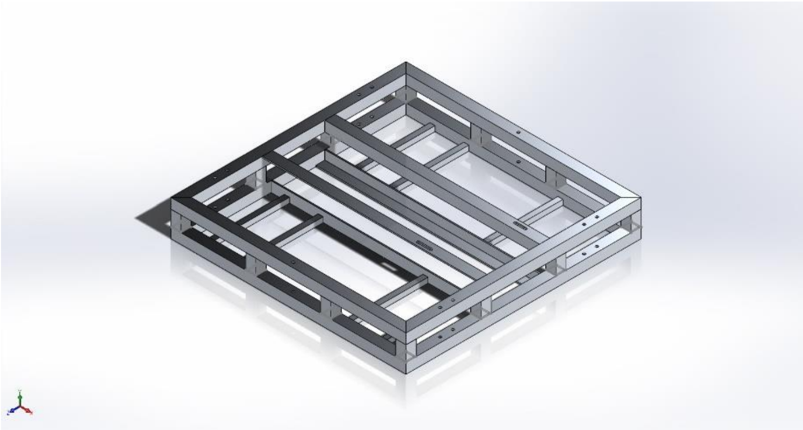


Image-1

Simulation 6-3ft Drop: Corner



Simulation of 3ft Drop: Corner

Date: Friday, April 21, 2017
Designer: Solidworks
Study name: Drop Test 3
Analysis type: Drop Test

Table of Contents

Study Properties

Study name	Drop Test 3
Analysis type	Drop Test
Mesh type	Solid Mesh
Large displacement	On
Result folder	SOLIDWORKS document (\\clusterfsnew.ceas1.uc.edu\students\riordamv\desktop\final frame-20170421T184351Z-001\final frame)

Setup Information

Type	Drop height
Drop height from lowest point	9.62828 ft.
Gravity	9.81 m/s^2
Gravity Reference	Edge<1>
Friction Coefficient	0
Target Stiffness	Rigid target
Critical Damping Ratio	0

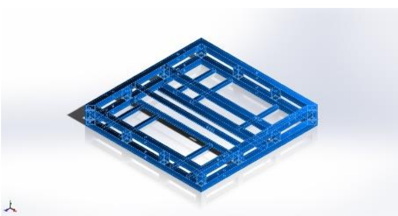
Result Options

Solution Time After Impact	495.5 microsec
Save Results Starting From	0 microsec
No. of Plots	25
No. of Graph Steps Per Plot	20
Number of vertex	0

Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

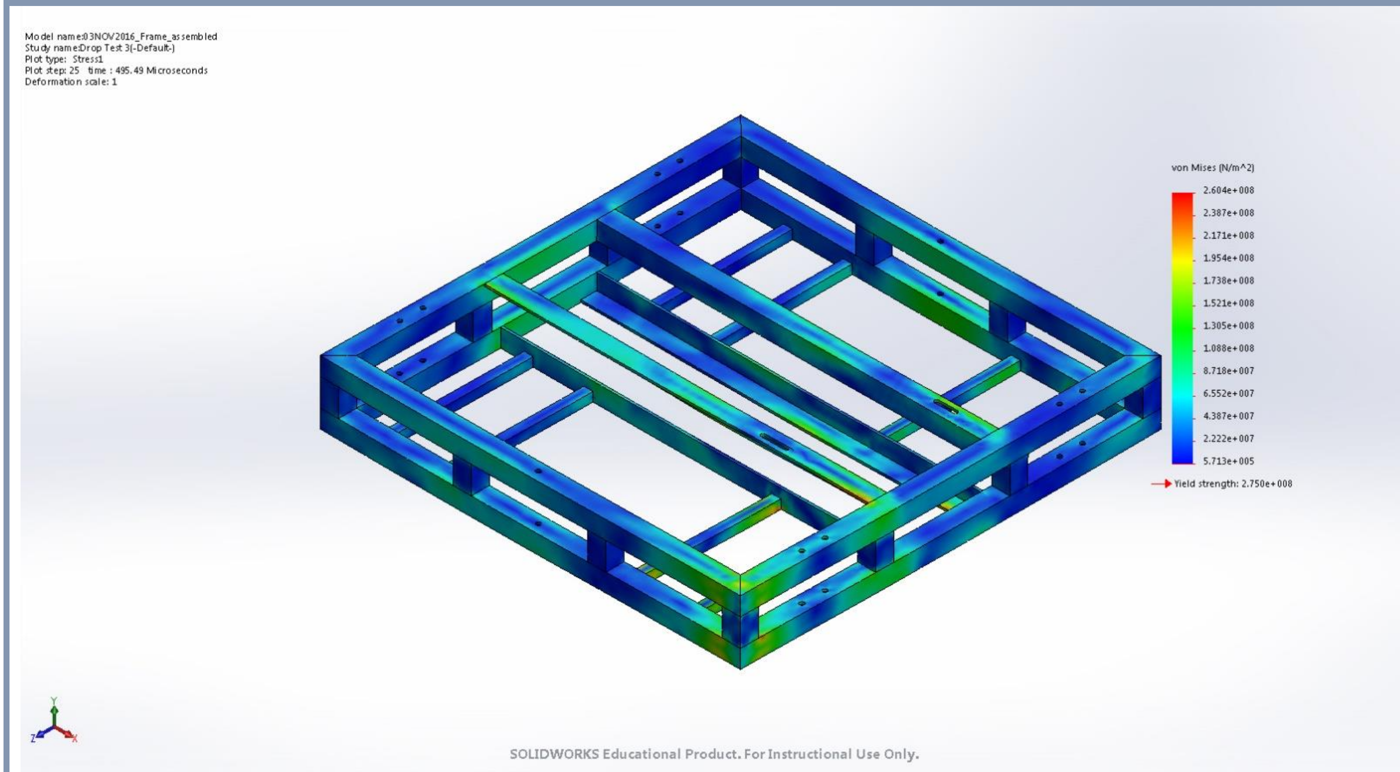
Material Properties

Model Reference	Properties	Components
	Name: **6061-T6 (SS)** Model type: **Plasticity - von Mises** Default failure criterion: **Unknown** Yield strength: **2.75e+008 N/m^2** Hardening factor (0.0-1.0; 0.0=isotropic; 1.0=kinematic): **0.85** Elastic modulus: **6.9e+010 N/m^2** Poisson's ratio: **0.33** Mass density: **2700 kg/m^3**	**SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-3), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-5), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-6), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_2-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_3-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_4-1), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-1), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-10), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-11), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-12), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-2), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-3), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-4), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-5), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-6),**

		SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-7), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-8), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-9), SolidBody 1(Boss-Extrude1)(27OCT2016_Angle_Weapon_Support-1), SolidBody 1(Boss-Extrude1)(27OCT2016_Angle_Weapon_Support-2), SolidBody 1(Cut-Extrude1)(27OCT2016_Angle_Weapon_Support_Top-1), SolidBody 1(Cut-Extrude1)(27OCT2016_Angle_Weapon_Support_top2-1), SolidBody 1(Boss-Extrude1)(wheel assembly support-1), SolidBody 1(Boss-Extrude1)(wheel assembly support-2), SolidBody 1(Boss-Extrude1)(wheel assembly support-3), SolidBody 1(Boss-Extrude1)(wheel assembly support-4), SolidBody 1(Boss-Extrude1)(wheel assembly support-5), SolidBody 1(Boss-Extrude1)(wheel assembly support-6), SolidBody 1(Boss-Extrude1)(wheel assembly support-7), SolidBody 1(Boss-Extrude1)(wheel assembly support-8)
Curve Data:N/A		

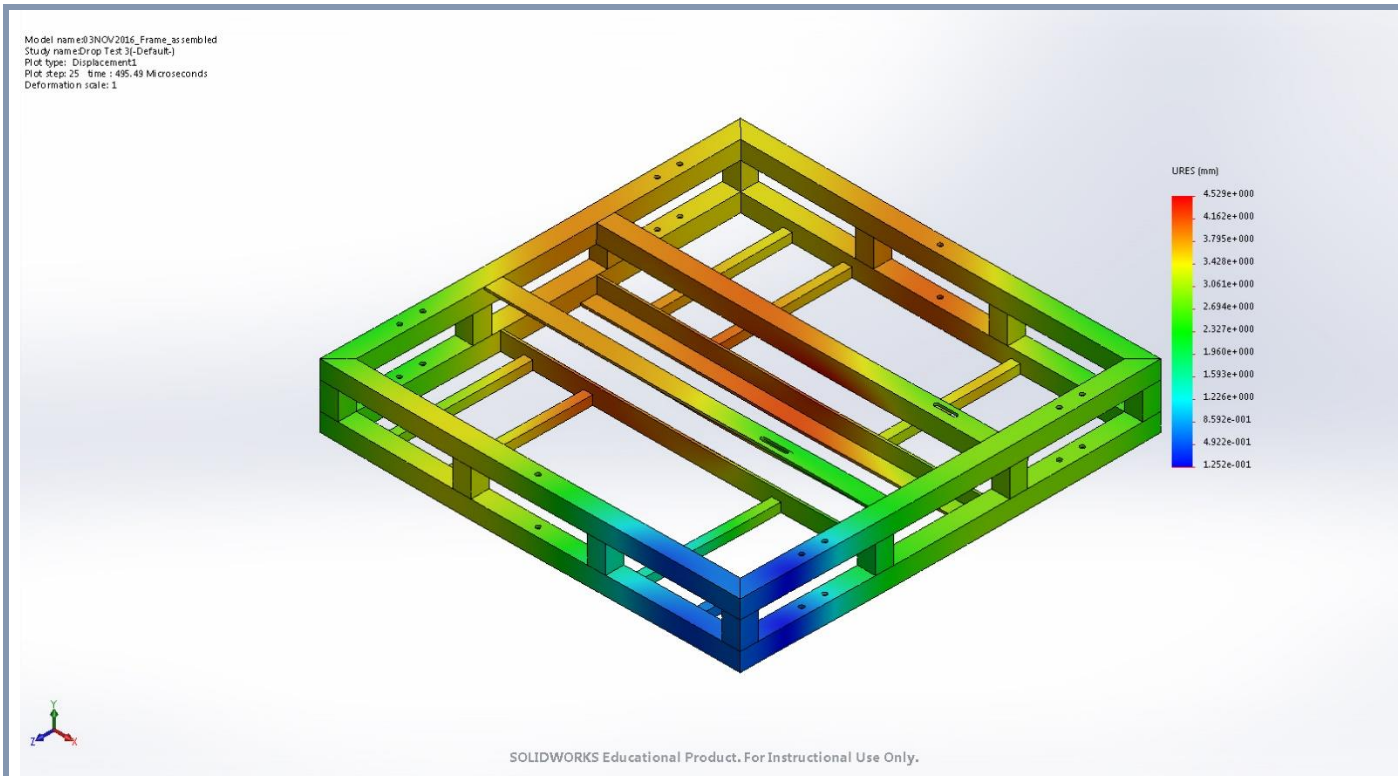
Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	571295 N/m^2 Node: 544	2.60386e+008 N/m^2 Node: 58438



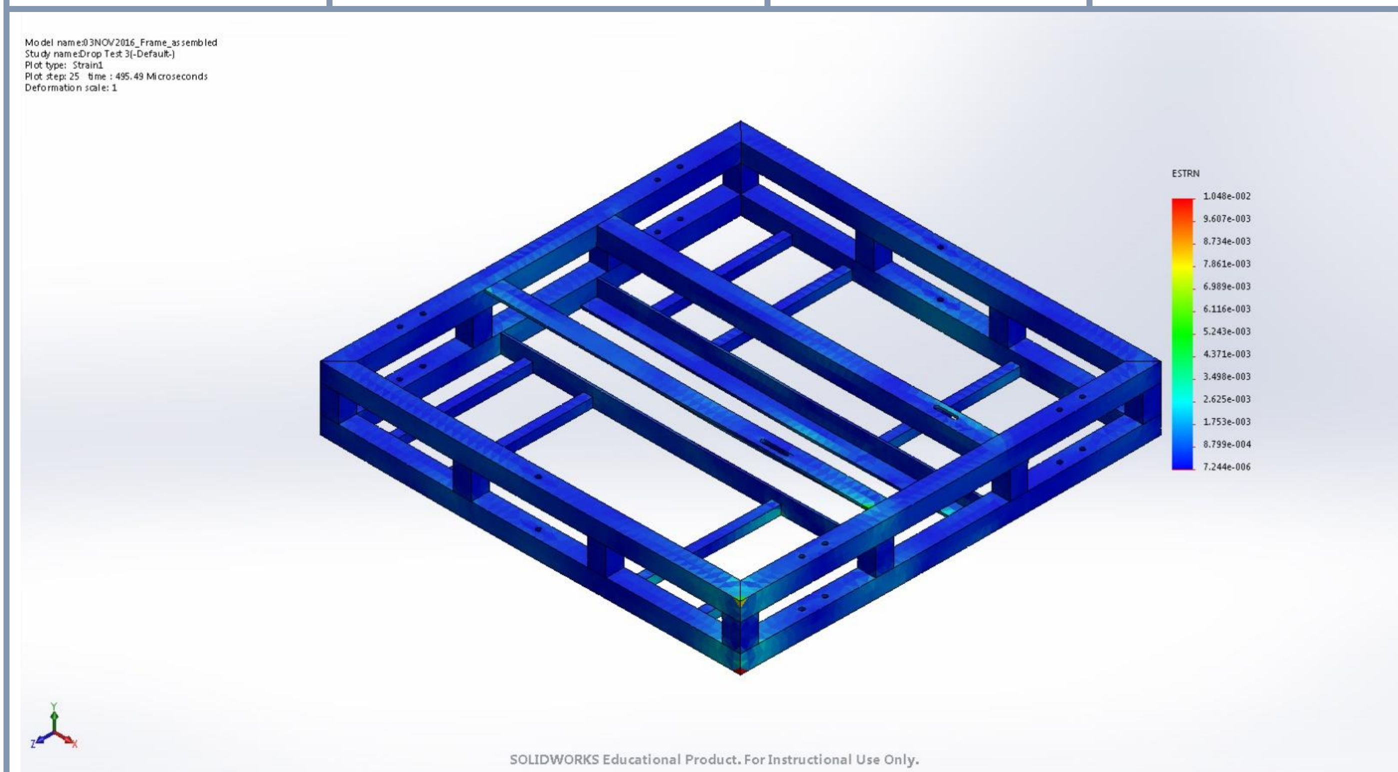
03NOV2016_Frame_assembled-Drop Test 3-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.125229 mm Node: 10550	4.52878 mm Node: 63552



03NOV2016_Frame_assembled-Drop Test 3-Displacement-Displacement1

Name	**Type**	**Min**	**Max**
Strain1	ESTRN: Equivalent Strain	7.24377e-006 Element: 32775	0.0104792 Element: 18348



03NOV2016_Frame_assembled-Drop Test 3-Strain-Strain1

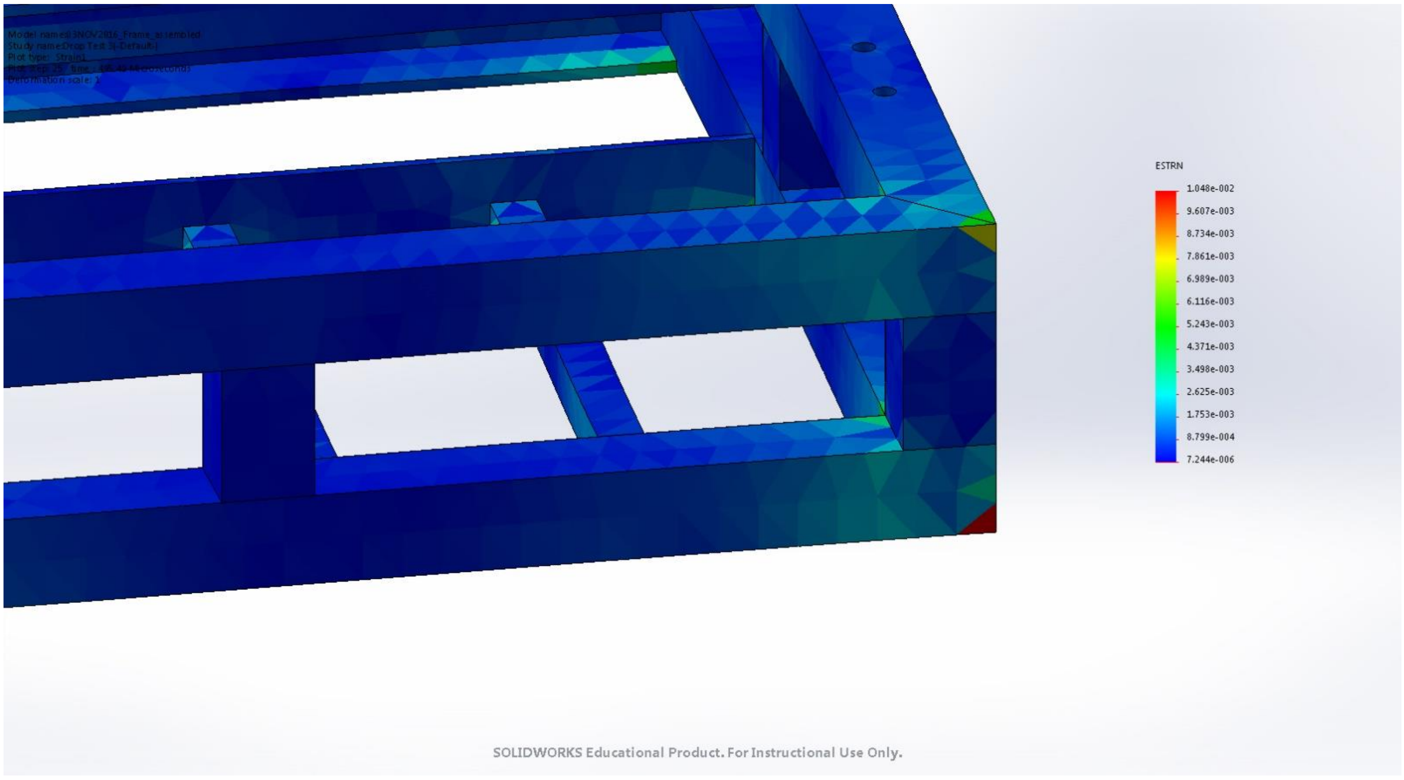
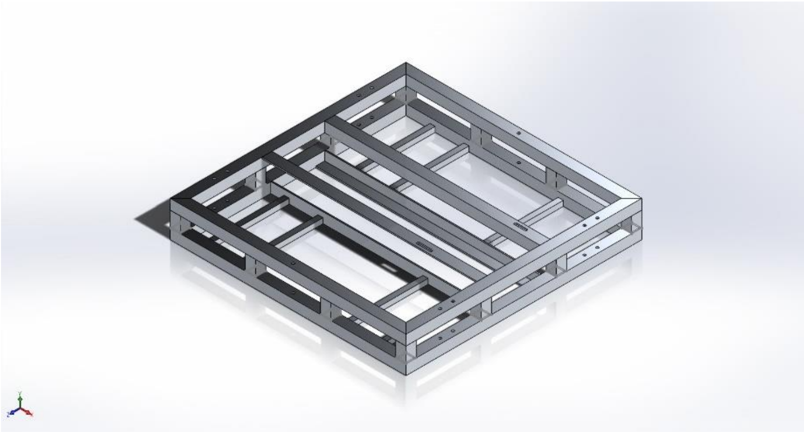


Image-1

Simulation 7-4ft Drop: Side



Simulation of 4ft Drop: Side

Date: Wednesday, April 26, 2017
Designer: Solidworks
Study name: Drop Test 1
Analysis type: Drop Test

Table of Contents

Study Properties

Study name	Drop Test 1
Analysis type	Drop Test
Mesh type	Solid Mesh
Large displacement	On
Result folder	SOLIDWORKS document (\\clusterfsnew.ceas1.uc.edu\students\riordamv\desktop\Final Report\Solidworks Simulations\final frame)

Setup Information

Type	Drop height
Drop height from lowest point	12.8377 ft.
Gravity	9.81 m/s^2
Gravity Reference	Edge<1>
Friction Coefficient	0
Target Stiffness	Rigid target
Critical Damping Ratio	0

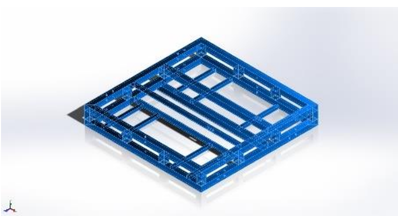
Result Options

Solution Time After Impact	495.5 microsec
Save Results Starting From	0 microsec
No. of Plots	25
No. of Graph Steps Per Plot	20
Number of vertex	0

Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

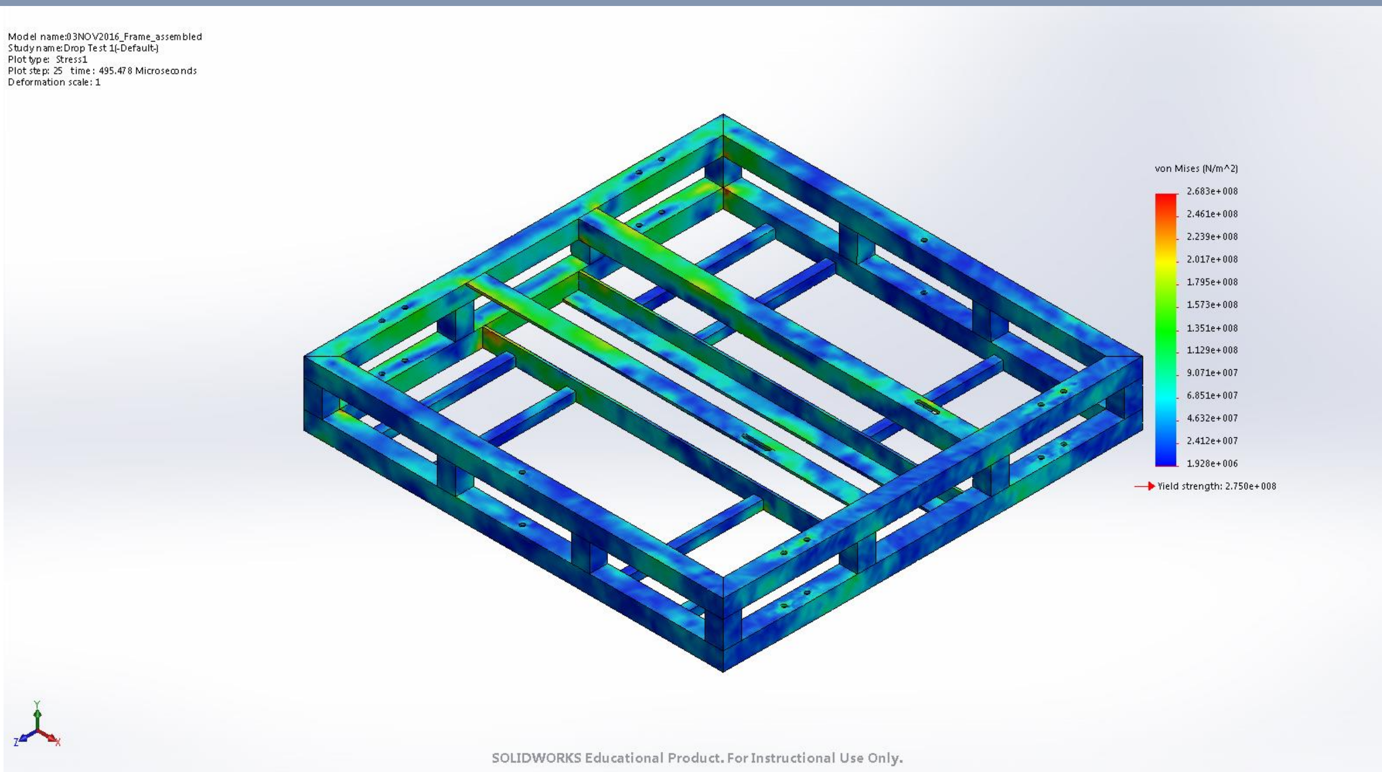
Material Properties

Model Reference	Properties	Components
	Name: **6061-T6 (SS)** Model type: **Plasticity - von Mises** Default failure criterion: **Unknown** Yield strength: **2.75e+008 N/m^2** Hardening factor (0.0-1.0; 0.0=isotropic; 1.0=kinematic): **0.85** Elastic modulus: **6.9e+010 N/m^2** Poisson's ratio: **0.33** Mass density: **2700 kg/m^3**	**SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-3), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-5), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-6), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_2-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_3-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_4-1), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-1), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-10), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-11), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-12), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-2), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-3), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-4), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-5), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-6),**

		SolidBody 1(Boss-Extrude1) (18OCT2016_Frame_Vertical-7), SolidBody 1(Boss-Extrude1) (18OCT2016_Frame_Vertical-8), SolidBody 1(Boss-Extrude1) (18OCT2016_Frame_Vertical-9), SolidBody 1(Boss-Extrude1) (27OCT2016_Angle_Weapon_Support-1), SolidBody 1(Boss-Extrude1) (27OCT2016_Angle_Weapon_Support-2), SolidBody 1(Cut-Extrude1) (27OCT2016_Angle_Weapon_Support_Top-1), SolidBody 1(Cut-Extrude1) (27OCT2016_Angle_Weapon_Support_top2-1), SolidBody 1(Boss-Extrude1) (wheel assembly support-1), SolidBody 1(Boss-Extrude1) (wheel assembly support-2), SolidBody 1(Boss-Extrude1) (wheel assembly support-3), SolidBody 1(Boss-Extrude1) (wheel assembly support-4), SolidBody 1(Boss-Extrude1) (wheel assembly support-5), SolidBody 1(Boss-Extrude1) (wheel assembly support-6), SolidBody 1(Boss-Extrude1) (wheel assembly support-7), SolidBody 1(Boss-Extrude1)(wheel assembly support-8)
Curve Data:N/A		

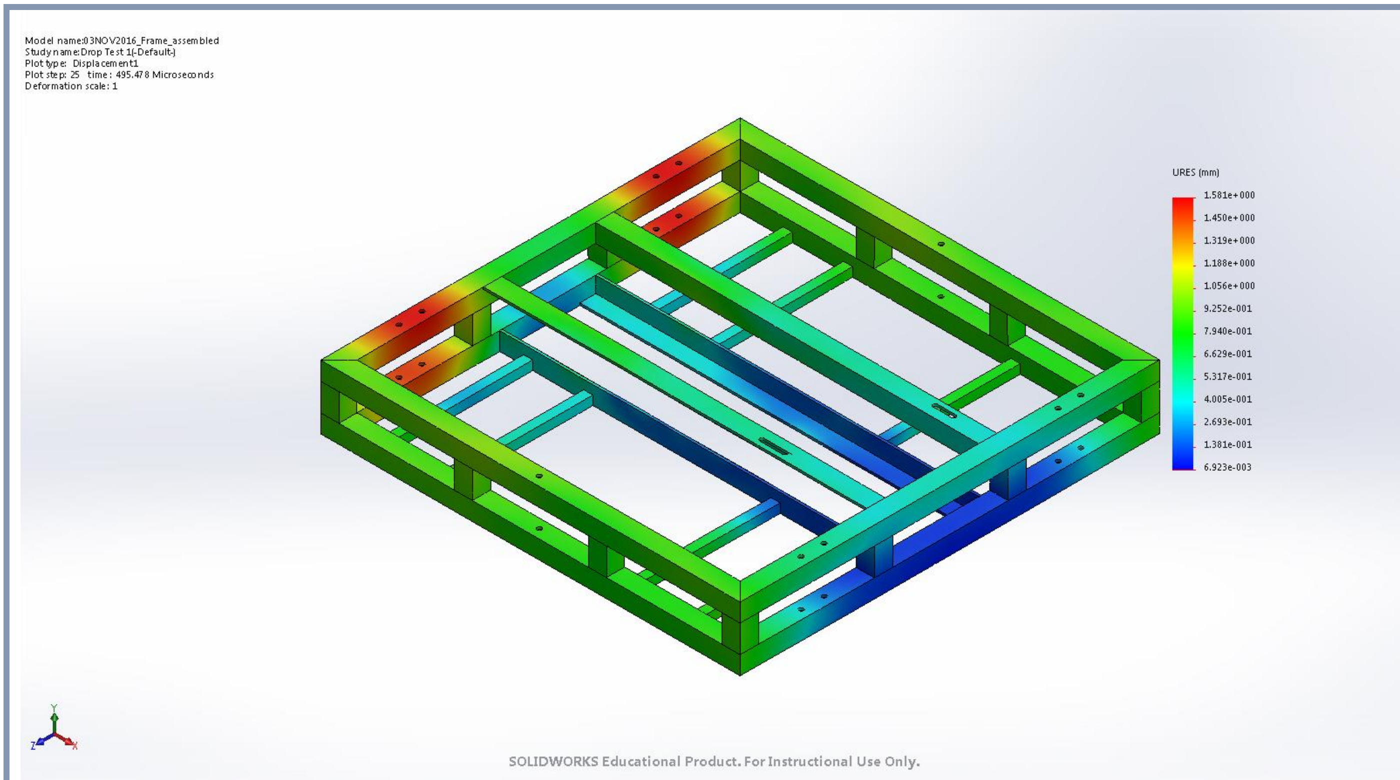
Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	1.92827e+006 N/m^2 Node: 69353	2.68269e+008 N/m^2 Node: 63468



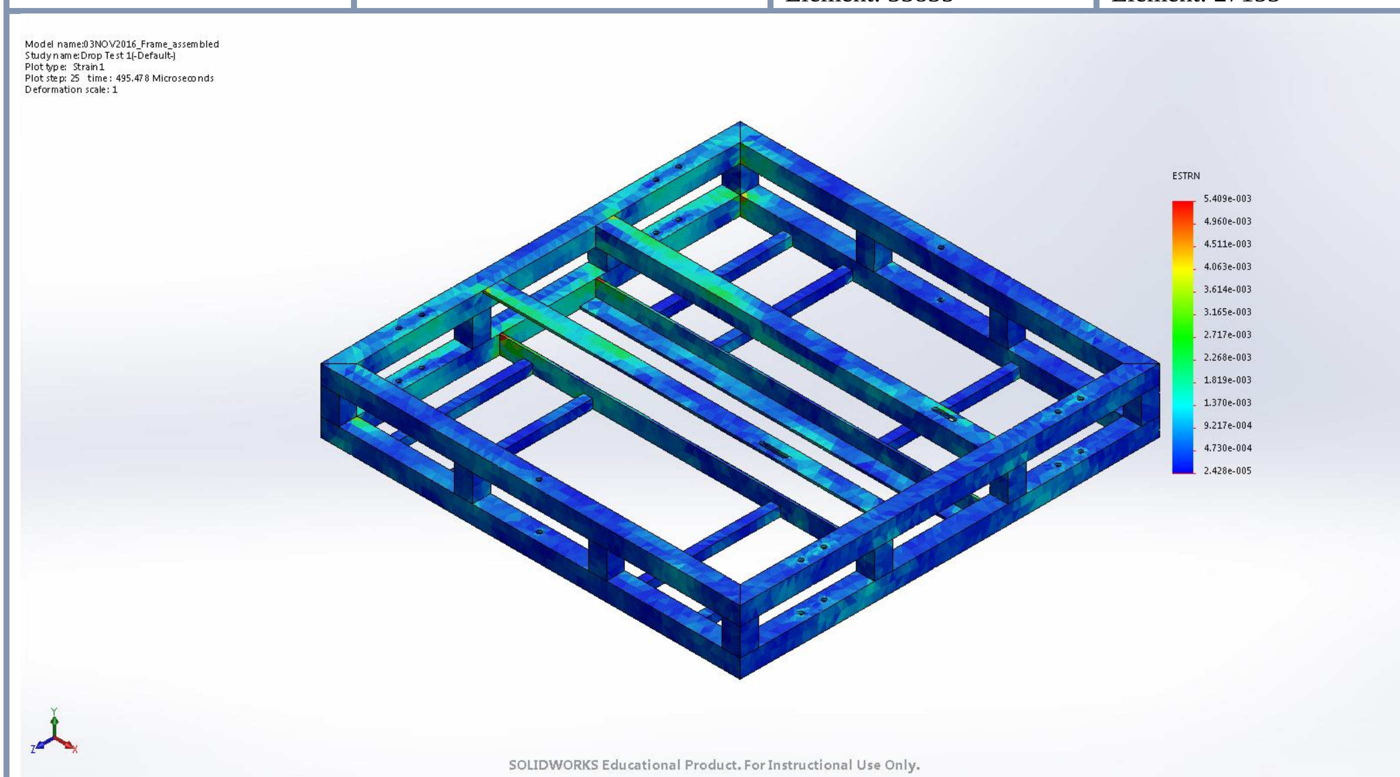
03NOV2016_Frame_assembled-Drop Test 1-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.00692295 mm Node: 7598	1.58115 mm Node: 24450

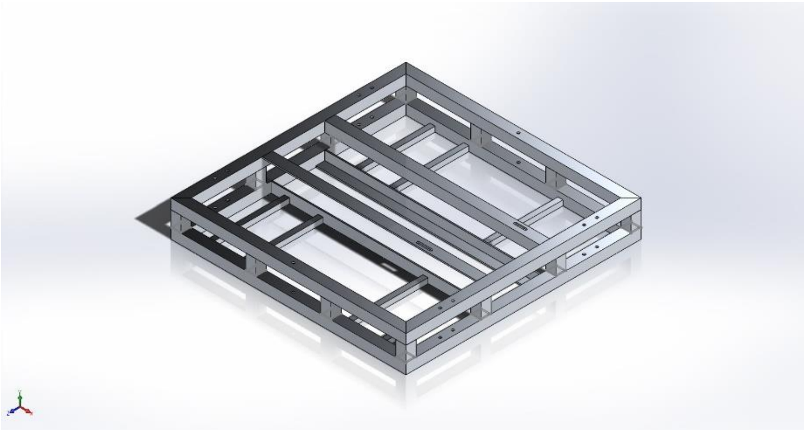


03NOV2016_Frame_assembled-Drop Test 1-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	2.42847e-005 Element: 33835	0.00540879 Element: 27153



03NOV2016_Frame_assembled-Drop Test 1-Strain-Strain1



Simulation of 4ft Drop: Front

Date: Friday, April 21, 2017
Designer: Solidworks
Study name: Drop Test 2
Analysis type: Drop Test

Table of Contents

Study Properties

Study name	Drop Test 2
Analysis type	Drop Test
Mesh type	Solid Mesh
Large displacement	On
Result folder	SOLIDWORKS document (\\clusterfsnew.ceas1.uc.edu\students\riordamv\desktop\final frame-20170421T184351Z-001\final frame)

Setup Information

Type	Drop height
Drop height from lowest point	12.838 ft.
Gravity	9.81 m/s^2
Gravity Reference	Edge<1>
Friction Coefficient	0
Target Stiffness	Rigid target
Critical Damping Ratio	0

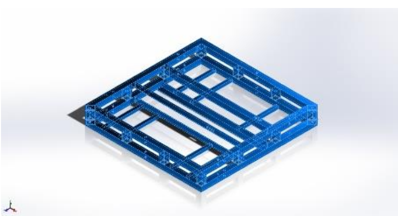
Result Options

Solution Time After Impact	495.5 microsec
Save Results Starting From	0 microsec
No. of Plots	25
No. of Graph Steps Per Plot	20
Number of vertex	0

Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

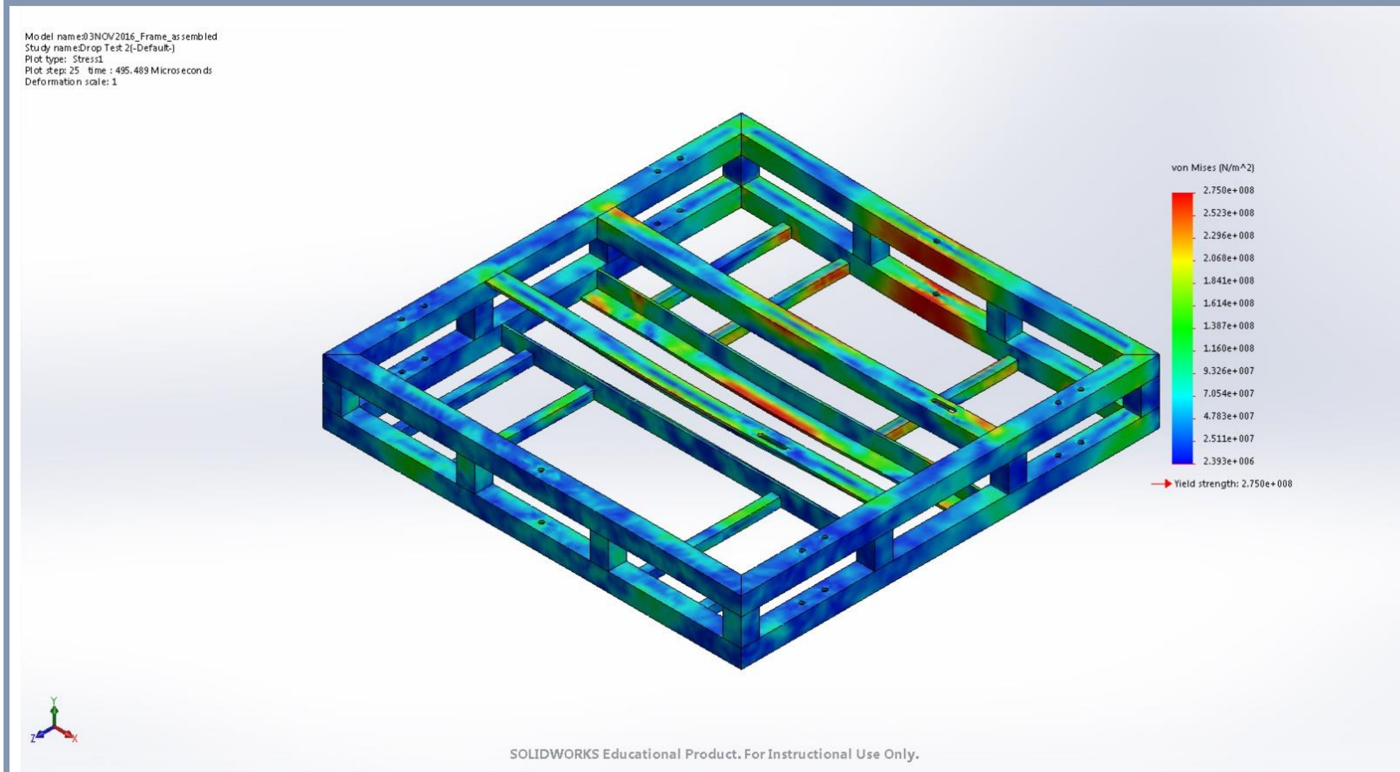
Material Properties

Model Reference	Properties	Components
	Name: **6061-T6 (SS)** Model type: **Plasticity - von Mises** Default failure criterion: **Unknown** Yield strength: **2.75e+008 N/m^2** Hardening factor (0.0-1.0; 0.0=isotropic; 1.0=kinematic): **0.85** Elastic modulus: **6.9e+010 N/m^2** Poisson's ratio: **0.33** Mass density: **2700 kg/m^3**	**SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-3), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-5), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-6), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_2-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_3-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_4-1), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-1), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-10), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-11), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-12), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-2), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-3), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-4), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-5), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-6),**

		SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-7), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-8), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-9), SolidBody 1(Boss-Extrude1)(27OCT2016_Angle_Weapon_Support-1), SolidBody 1(Boss-Extrude1)(27OCT2016_Angle_Weapon_Support-2), SolidBody 1(Cut-Extrude1)(27OCT2016_Angle_Weapon_Support_Top-1), SolidBody 1(Cut-Extrude1)(27OCT2016_Angle_Weapon_Support_top2-1), SolidBody 1(Boss-Extrude1)(wheel assembly support-1), SolidBody 1(Boss-Extrude1)(wheel assembly support-2), SolidBody 1(Boss-Extrude1)(wheel assembly support-3), SolidBody 1(Boss-Extrude1)(wheel assembly support-4), SolidBody 1(Boss-Extrude1)(wheel assembly support-5), SolidBody 1(Boss-Extrude1)(wheel assembly support-6), SolidBody 1(Boss-Extrude1)(wheel assembly support-7), SolidBody 1(Boss-Extrude1)(wheel assembly support-8)
Curve Data:N/A		

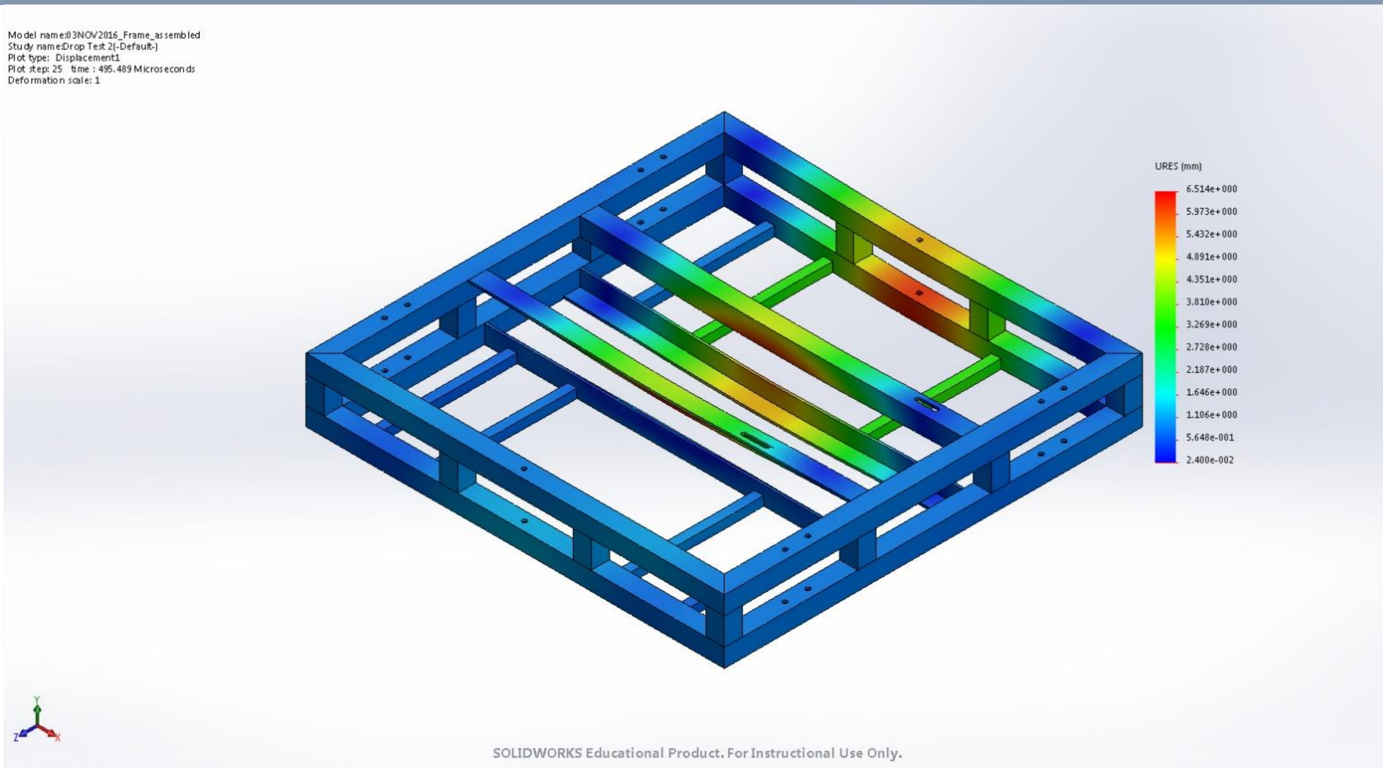
Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	2.39339e+006 N/m^2 Node: 67083	2.74984e+008 N/m^2 Node: 48908



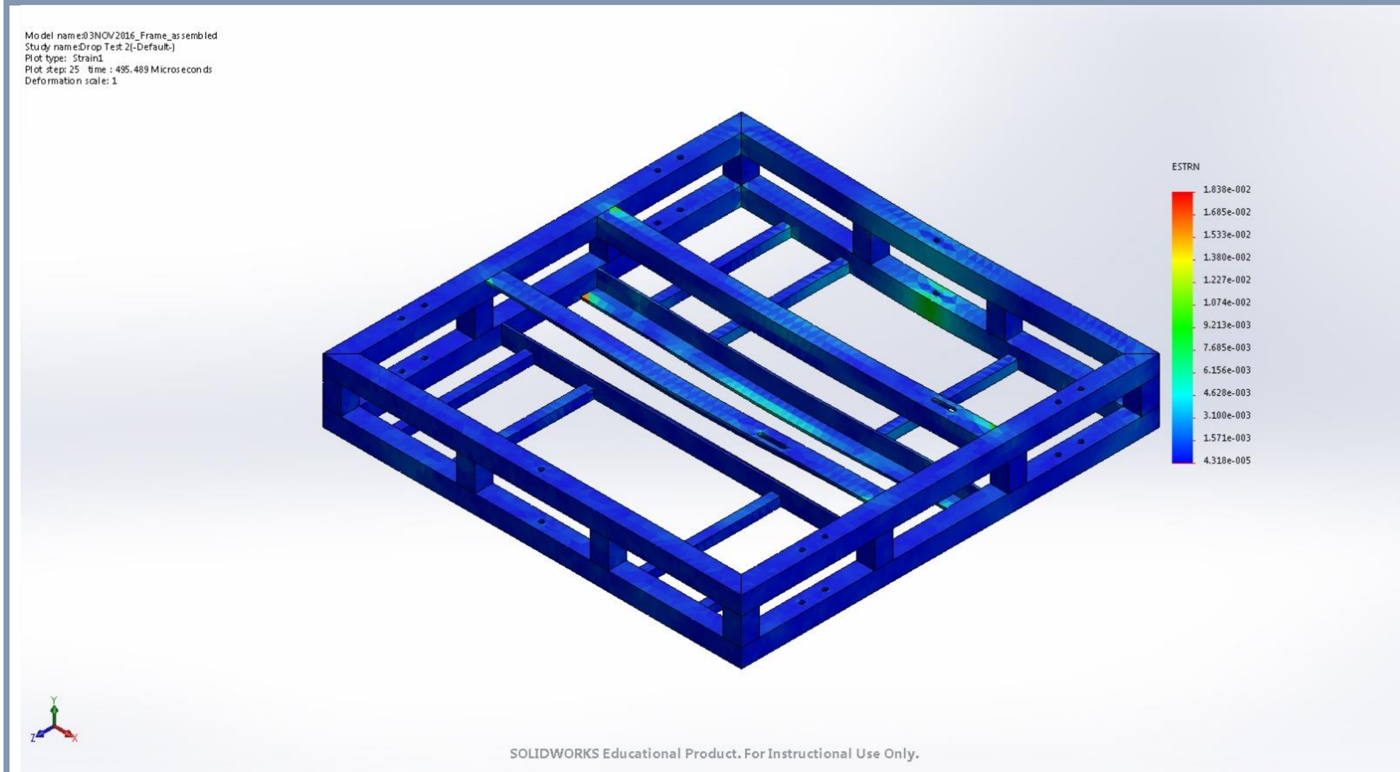
03NOV2016_Frame_assembled-Drop Test 2-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.0239991 mm Node: 55728	6.51398 mm Node: 60683



03NOV2016_Frame_assembled-Drop Test 2-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	4.31753e-005 Element: 32834	0.0183827 Element: 27164



03NOV2016_Frame_assembled-Drop Test 2-Strain-Strain1

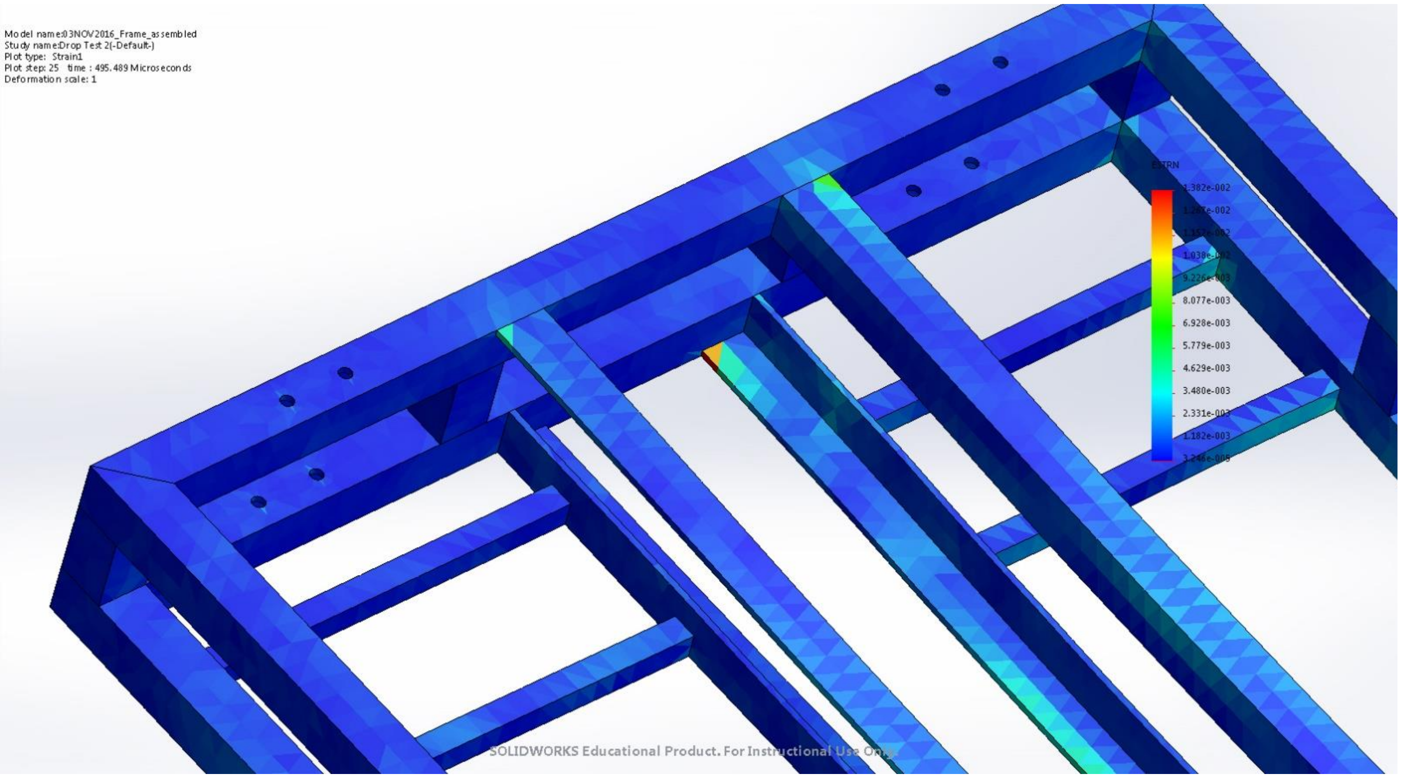


Image-1

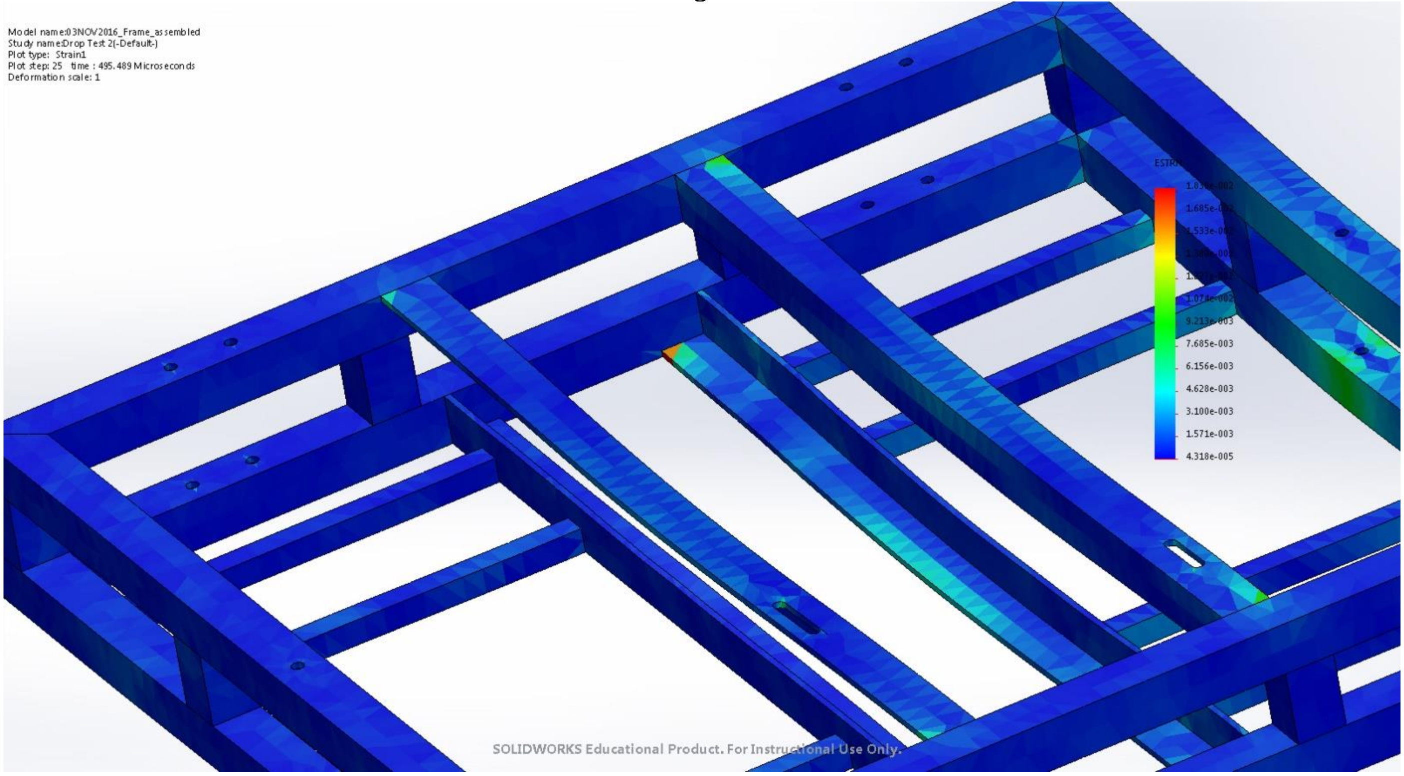
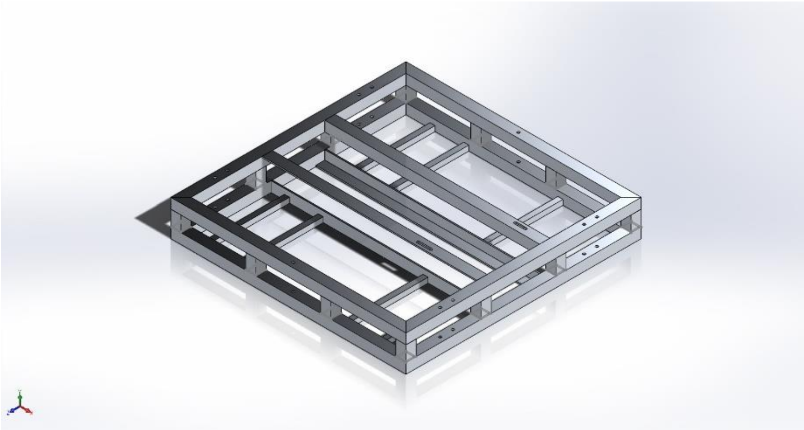


Image-2



Simulation 4ft Drop: Corner

Date: Friday, April 21, 2017
Designer: Solidworks
Study name: Drop Test 3
Analysis type: Drop Test

Table of Contents

Study Properties

Study name	Drop Test 3
Analysis type	Drop Test
Mesh type	Solid Mesh
Large displacement	On
Result folder	SOLIDWORKS document (\\clusterfsnew.ceas1.uc.edu\students\riordamv\desktop\final frame-20170421T184351Z-001\final frame)

Setup Information

Type	Drop height
Drop height from lowest point	12.838 ft.
Gravity	9.81 m/s^2
Gravity Reference	Edge<1>
Friction Coefficient	0
Target Stiffness	Rigid target
Critical Damping Ratio	0

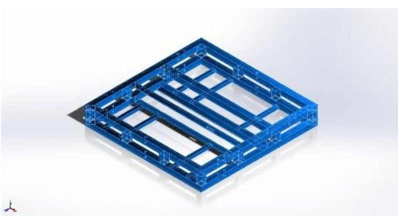
Result Options

Solution Time After Impact	495.5 microsec
Save Results Starting From	0 microsec
No. of Plots	25
No. of Graph Steps Per Plot	20
Number of vertex	0

Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

Material Properties

<table>
<tr><th>Model Reference</th><th>Properties</th><th>Components</th></tr>
<tr><td></td><td>Name: **6061-T6 (SS)**
Model type: **Plasticity - von Mises**
Default failure criterion: **Unknown**
Yield strength: **2.75e+008 N/m^2**
Hardening factor (0.0-1.0; 0.0=isotropic; 1.0=kinematic): **0.85**
Elastic modulus: **6.9e+010 N/m^2**
Poisson's ratio: **0.33**
Mass density: **2700 kg/m^3**</td><td>**SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-1),
SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-3),
SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-5),
SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-6),
SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole-1),
SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_2-1),
SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_3-1),
SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_4-1),
SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-1),
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SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-11),
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SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-2),
SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-3),
SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-4),
SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-5),
SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-6),**</td></tr>
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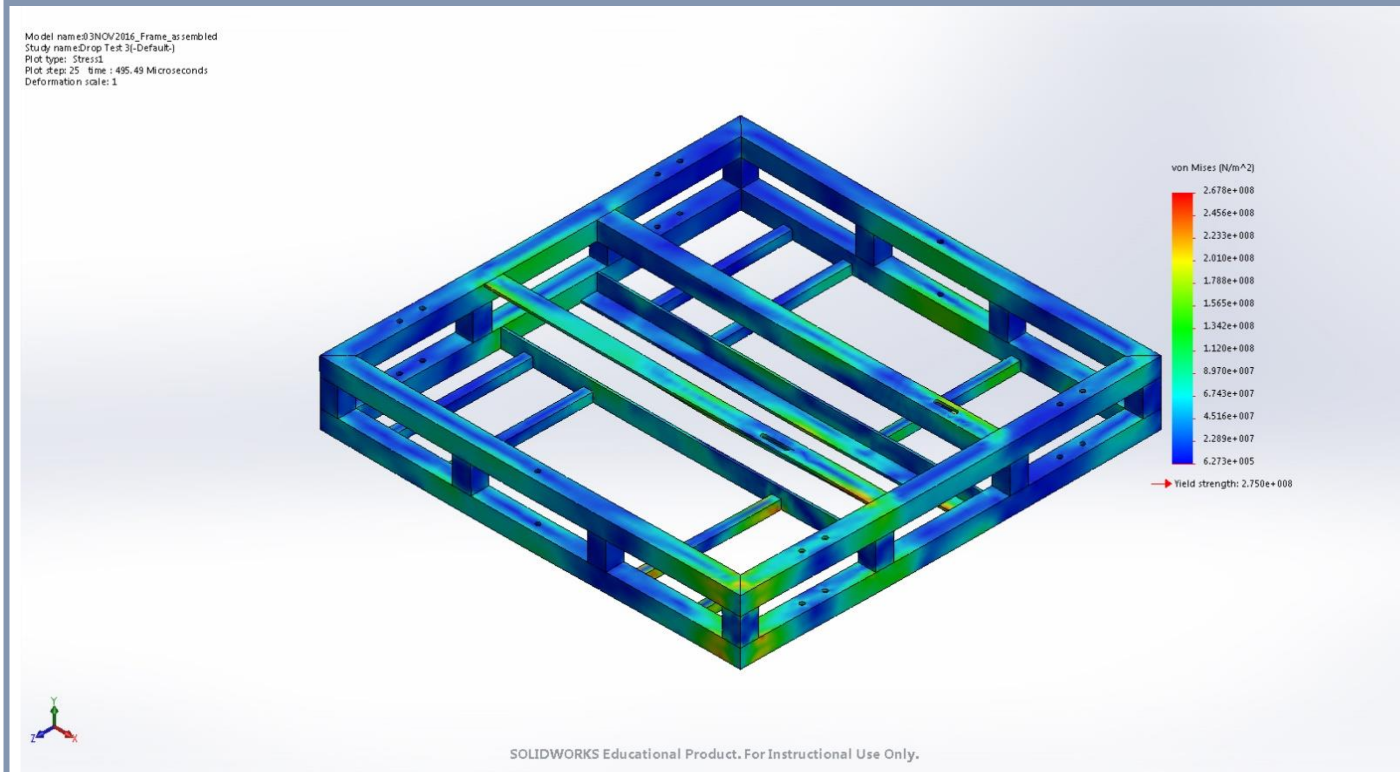
		SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-7), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-8), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-9), SolidBody 1(Boss-Extrude1)(27OCT2016_Angle_Weapon_Support-1), SolidBody 1(Boss-Extrude1)(27OCT2016_Angle_Weapon_Support-2), SolidBody 1(Cut-Extrude1)(27OCT2016_Angle_Weapon_Support_Top-1), SolidBody 1(Cut-Extrude1)(27OCT2016_Angle_Weapon_Support_top2-1), SolidBody 1(Boss-Extrude1)(wheel assembly support-1), SolidBody 1(Boss-Extrude1)(wheel assembly support-2), SolidBody 1(Boss-Extrude1)(wheel assembly support-3), SolidBody 1(Boss-Extrude1)(wheel assembly support-4), SolidBody 1(Boss-Extrude1)(wheel assembly support-5), SolidBody 1(Boss-Extrude1)(wheel assembly support-6), SolidBody 1(Boss-Extrude1)(wheel assembly support-7), SolidBody 1(Boss-Extrude1)(wheel assembly support-8)
Curve Data:N/A		

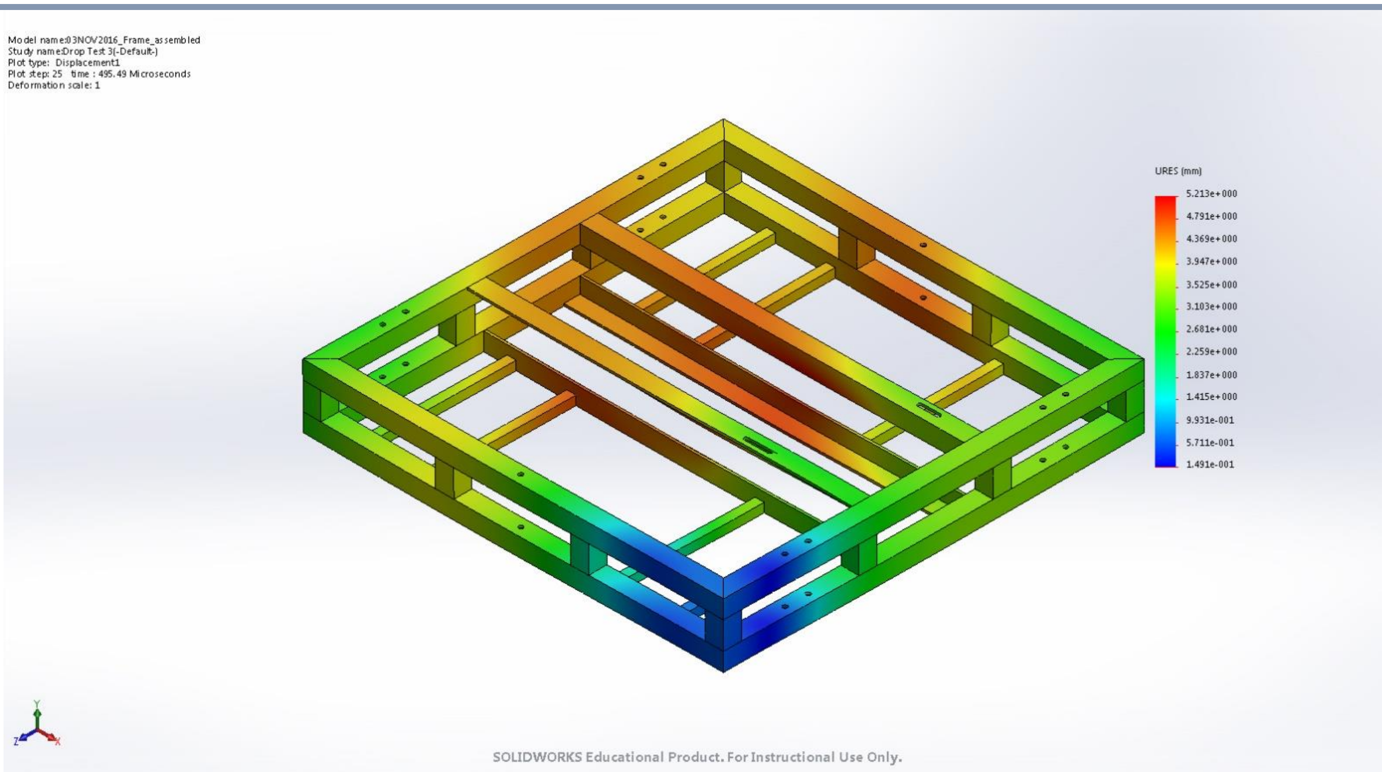
Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	627311 N/m^2 Node: 544	2.67833e+008 N/m^2 Node: 58437



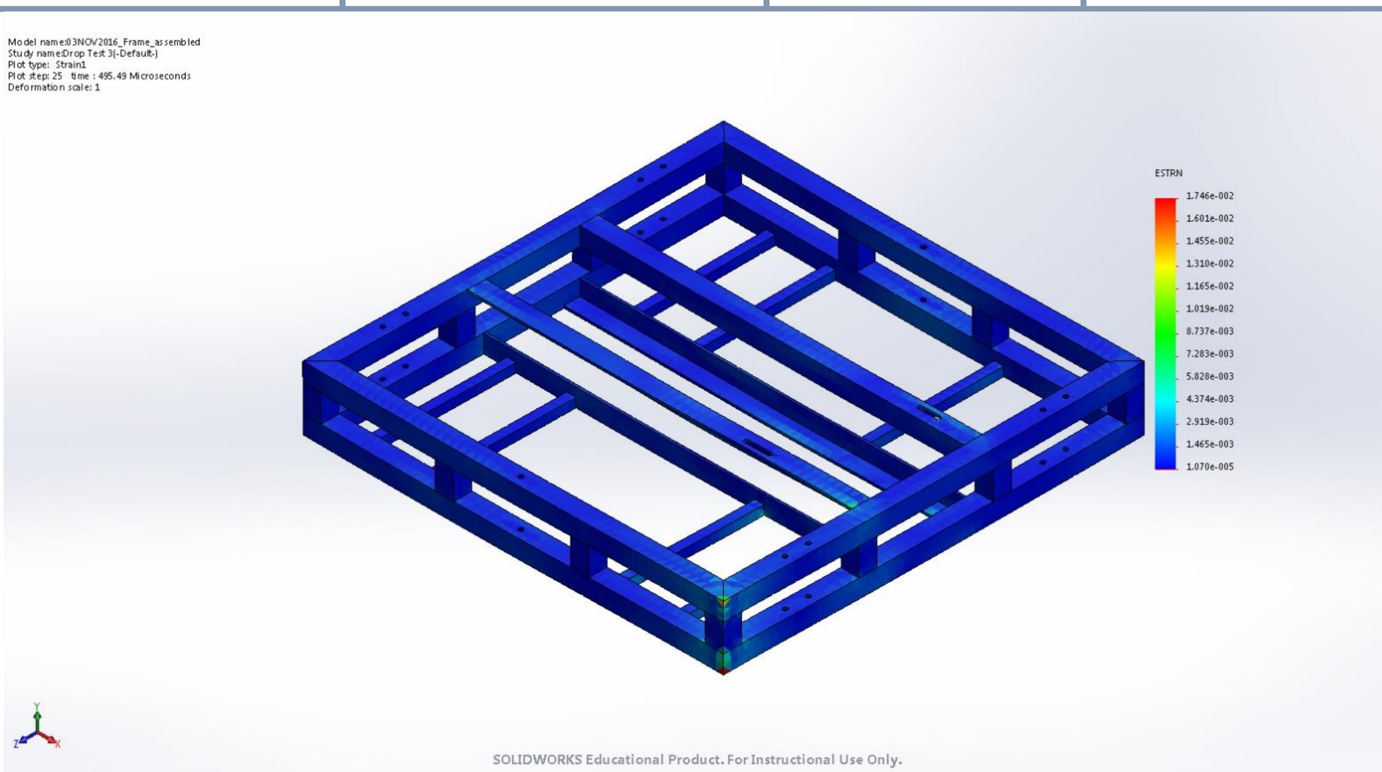
03NOV2016_Frame_assembled-Drop Test 3-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.149106 mm Node: 19565	5.21298 mm Node: 63325



03NOV2016_Frame_assembled-Drop Test 3-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	1.06969e-005 Element: 7481	0.0174635 Element: 18348



03NOV2016_Frame_assembled-Drop Test 3-Strain-Strain1

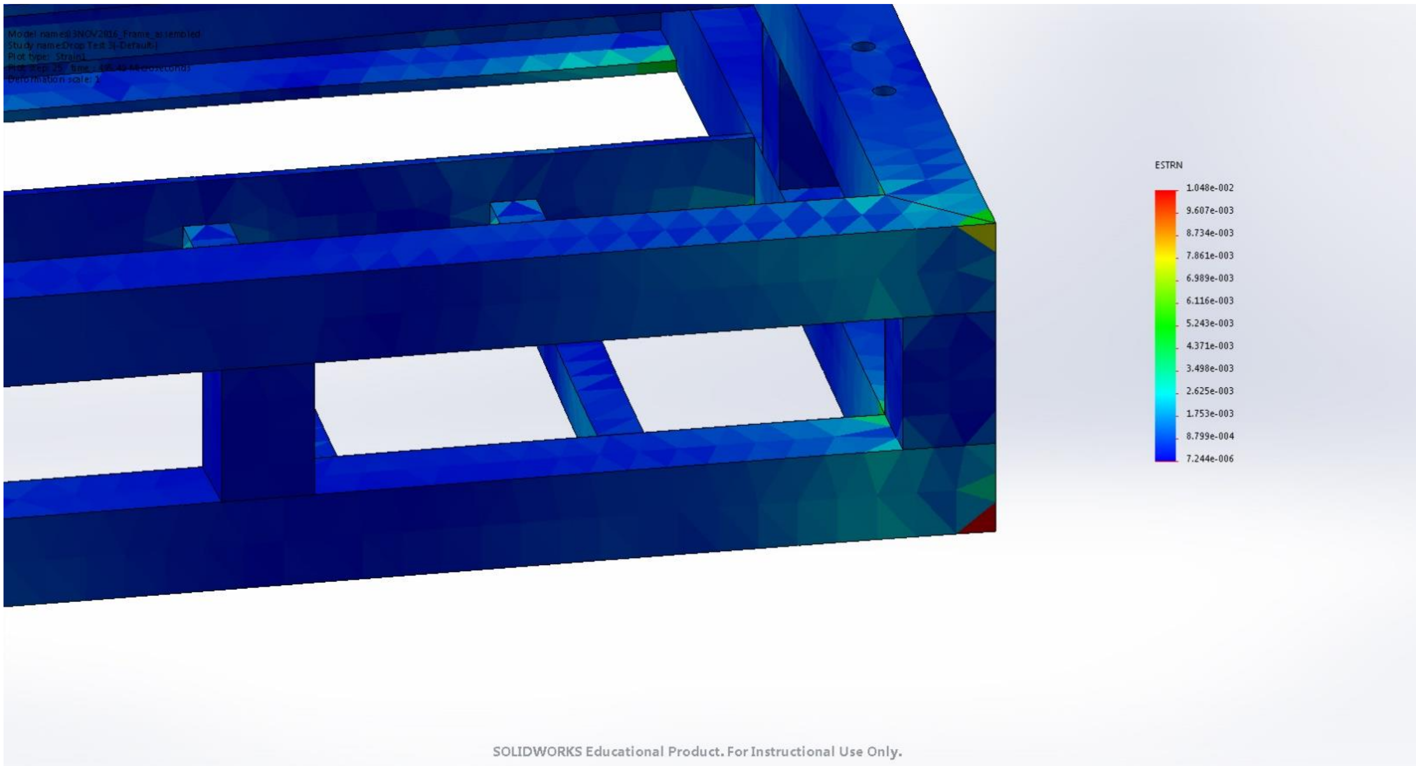


Image-1

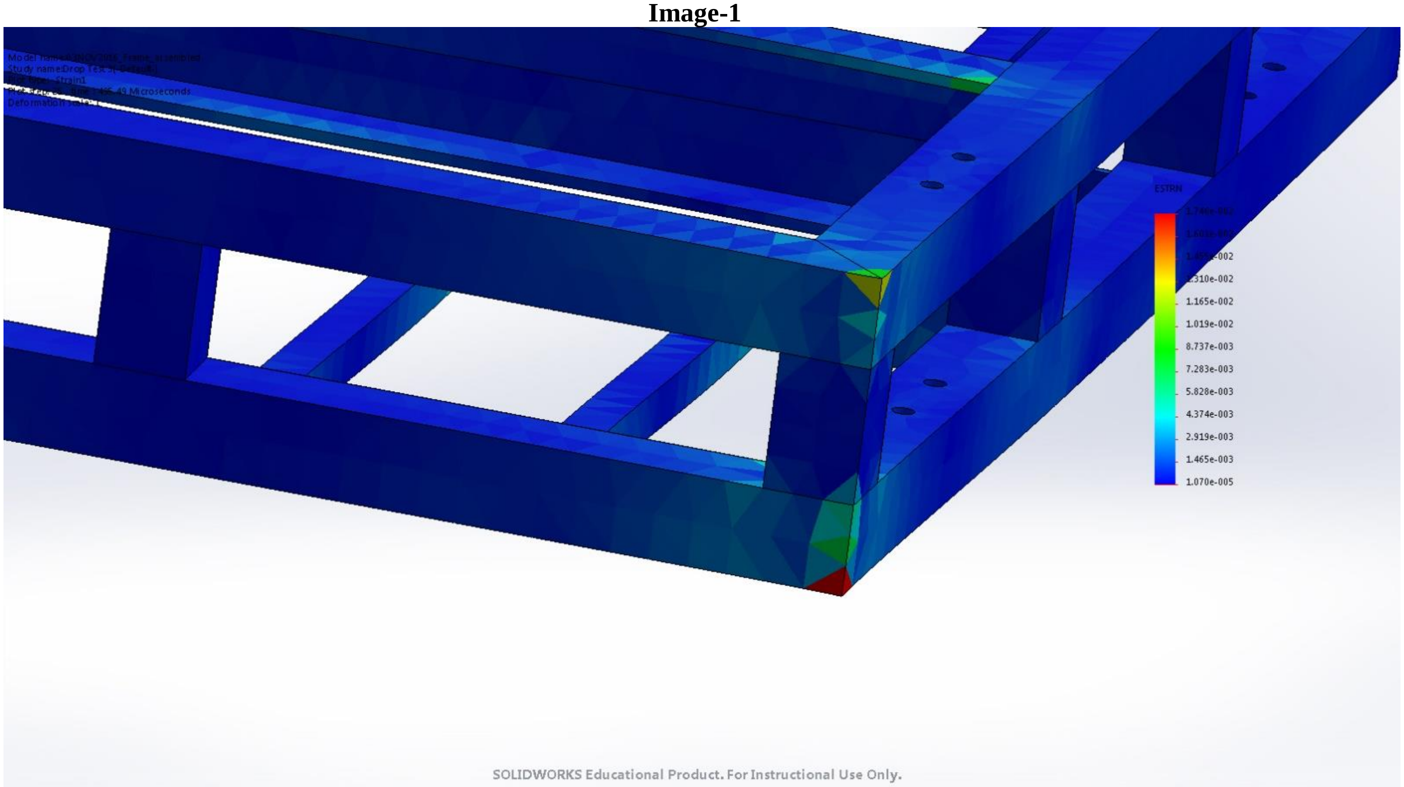
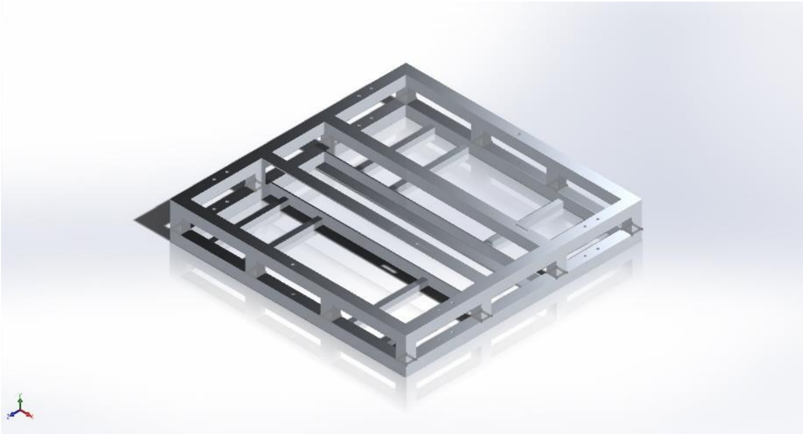


Image-2

Simulation 10-5ft Drop: Side



Simulation of 5ft Drop: Side

Date: Wednesday, April 26, 2017
Designer: Solidworks
Study name: Drop Test 1
Analysis type: Drop Test

Table of Contents

Study Properties

Study name	Drop Test 1
Analysis type	Drop Test
Mesh type	Solid Mesh
Large displacement	On
Result folder	SOLIDWORKS document (\\clusterfsnew.ceas1.uc.edu\students\riordamv\desktop\Final Report\Solidworks Simulations\final frame)

Setup Information

Type	Drop height
Drop height from lowest point	16.0471 ft.
Gravity	9.81 m/s^2
Gravity Reference	Edge<1>
Friction Coefficient	0
Target Stiffness	Rigid target
Critical Damping Ratio	0

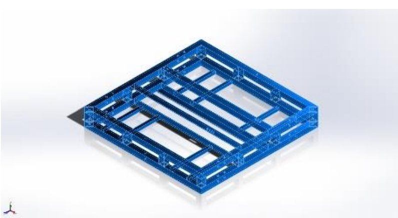
Result Options

Solution Time After Impact	495.5 microsec
Save Results Starting From	0 microsec
No. of Plots	25
No. of Graph Steps Per Plot	20
Number of vertex	0

Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

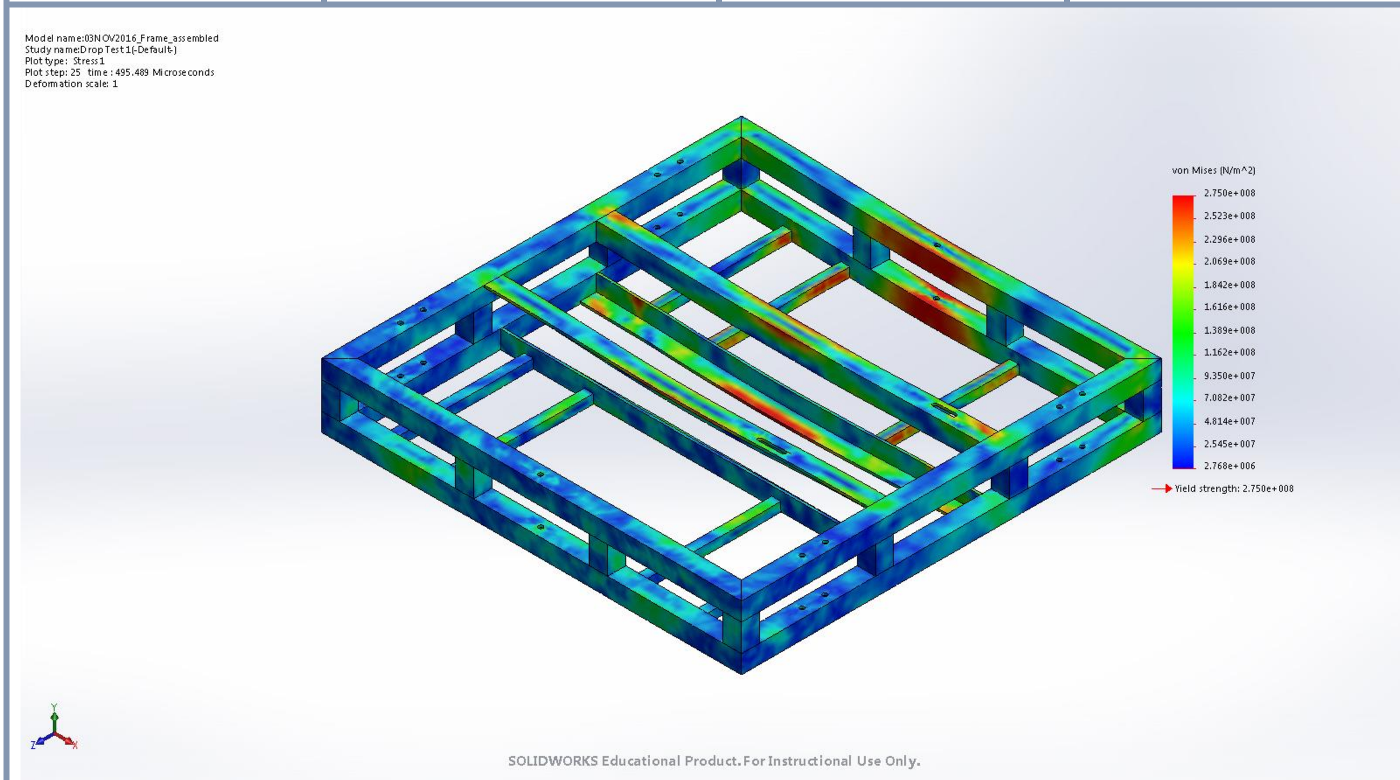
Material Properties

Model Reference	Properties	Components
	Name: **6061-T6 (SS)** Model type: **Plasticity - von Mises** Default failure criterion: **Unknown** Yield strength: **2.75e+008 N/m^2** Hardening factor (0.0-1.0; 0.0=isotropic; 1.0=kinematic): **0.85** Elastic modulus: **6.9e+010 N/m^2** Poisson's ratio: **0.33** Mass density: **2700 kg/m^3**	**SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-3), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-5), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal-6), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_2-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_3-1), SolidBody 1(Cut-Extrude2)(18OCT2016_Frame_Horizontal_1_hole_4-1), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-1), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-10), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-11), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-12), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-2), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-3), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-4), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-5), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-6),**

		SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-7), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-8), SolidBody 1(Boss-Extrude1)(18OCT2016_Frame_Vertical-9), SolidBody 1(Boss-Extrude1)(27OCT2016_Angle_Weapon_Support-1), SolidBody 1(Boss-Extrude1)(27OCT2016_Angle_Weapon_Support-2), SolidBody 1(Cut-Extrude1)(27OCT2016_Angle_Weapon_Support_Top-1), SolidBody 1(Cut-Extrude1)(27OCT2016_Angle_Weapon_Support_top2-1), SolidBody 1(Boss-Extrude1)(wheel assembly support-1), SolidBody 1(Boss-Extrude1)(wheel assembly support-2), SolidBody 1(Boss-Extrude1)(wheel assembly support-3), SolidBody 1(Boss-Extrude1)(wheel assembly support-4), SolidBody 1(Boss-Extrude1)(wheel assembly support-5), SolidBody 1(Boss-Extrude1)(wheel assembly support-6), SolidBody 1(Boss-Extrude1)(wheel assembly support-7), SolidBody 1(Boss-Extrude1)(wheel assembly support-8)
Curve Data:N/A		

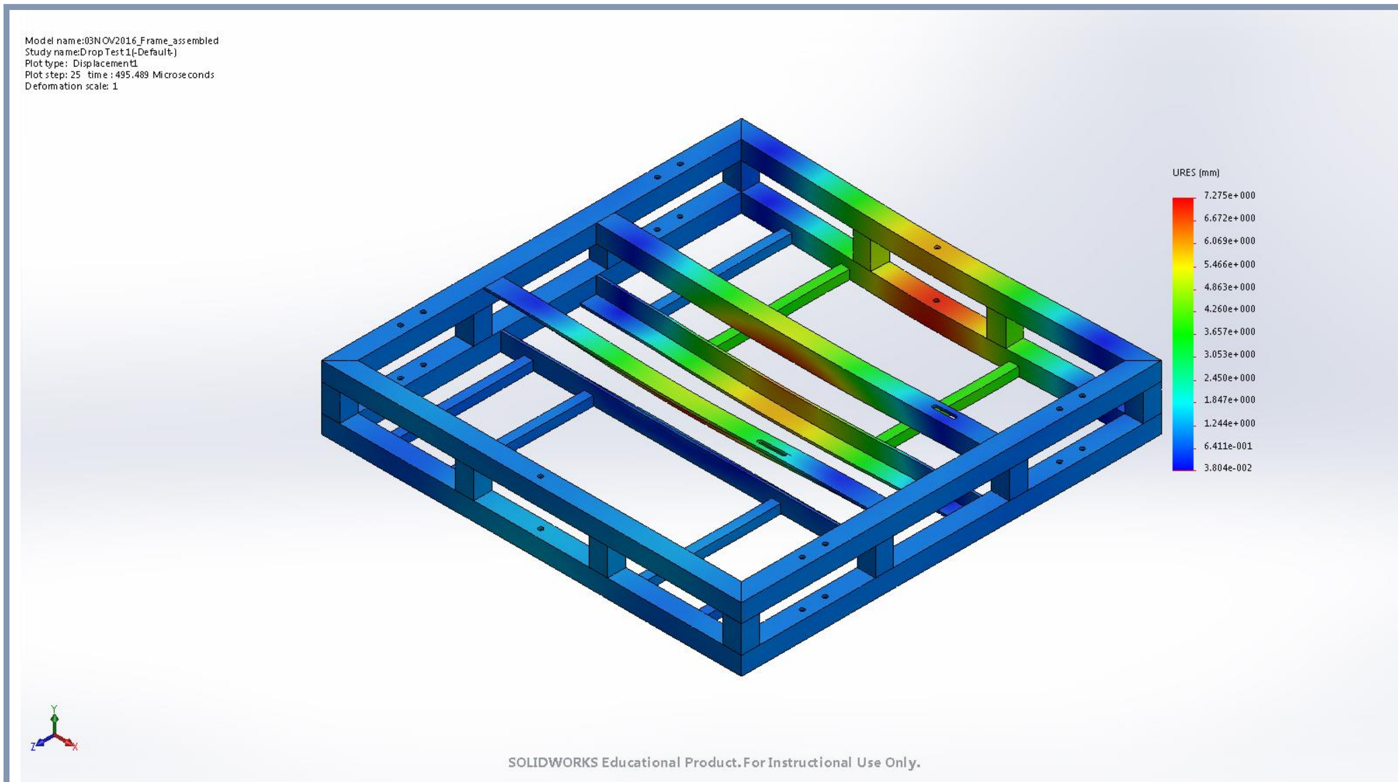
Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	2.76786e+006 N/m^2 Node: 67083	2.74979e+008 N/m^2 Node: 66552



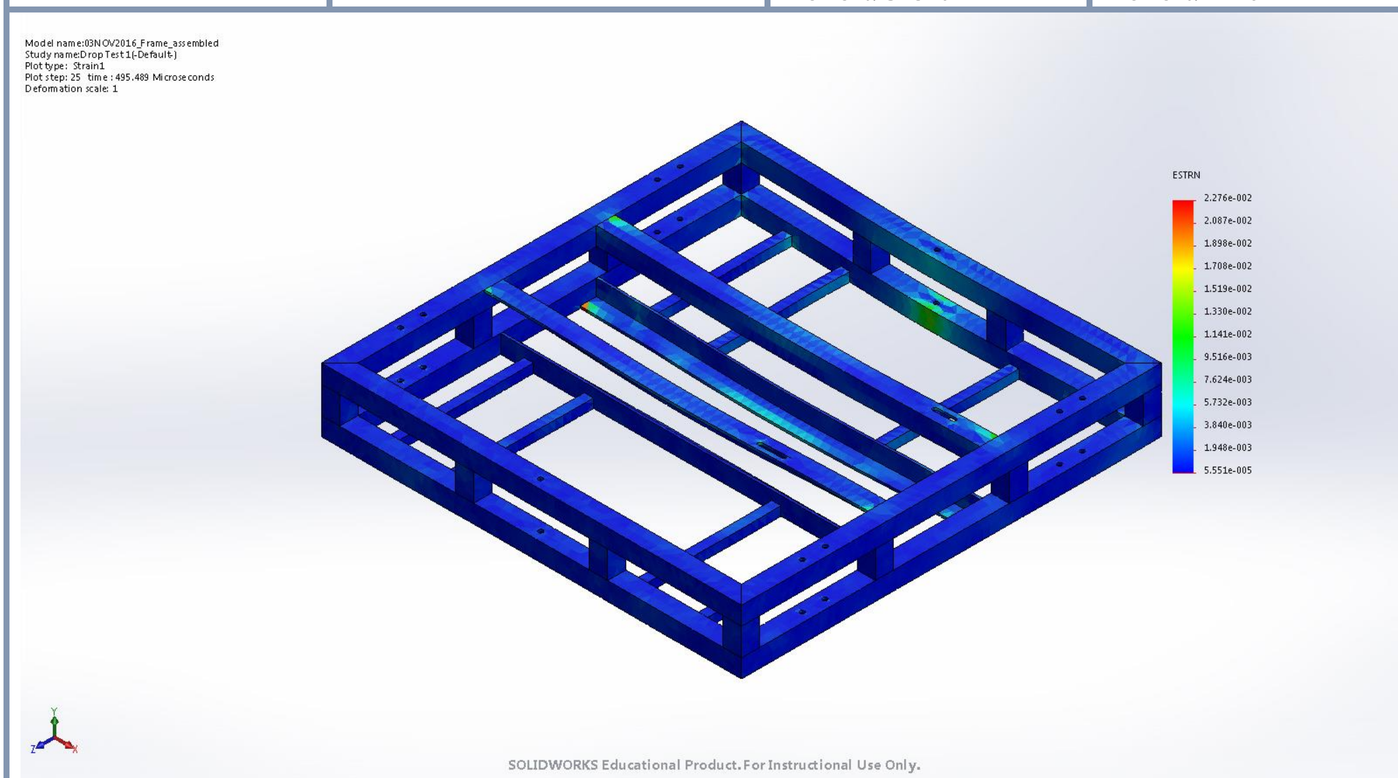
03NOV2016_Frame_assembled-Drop Test 1-Stress-Stress1

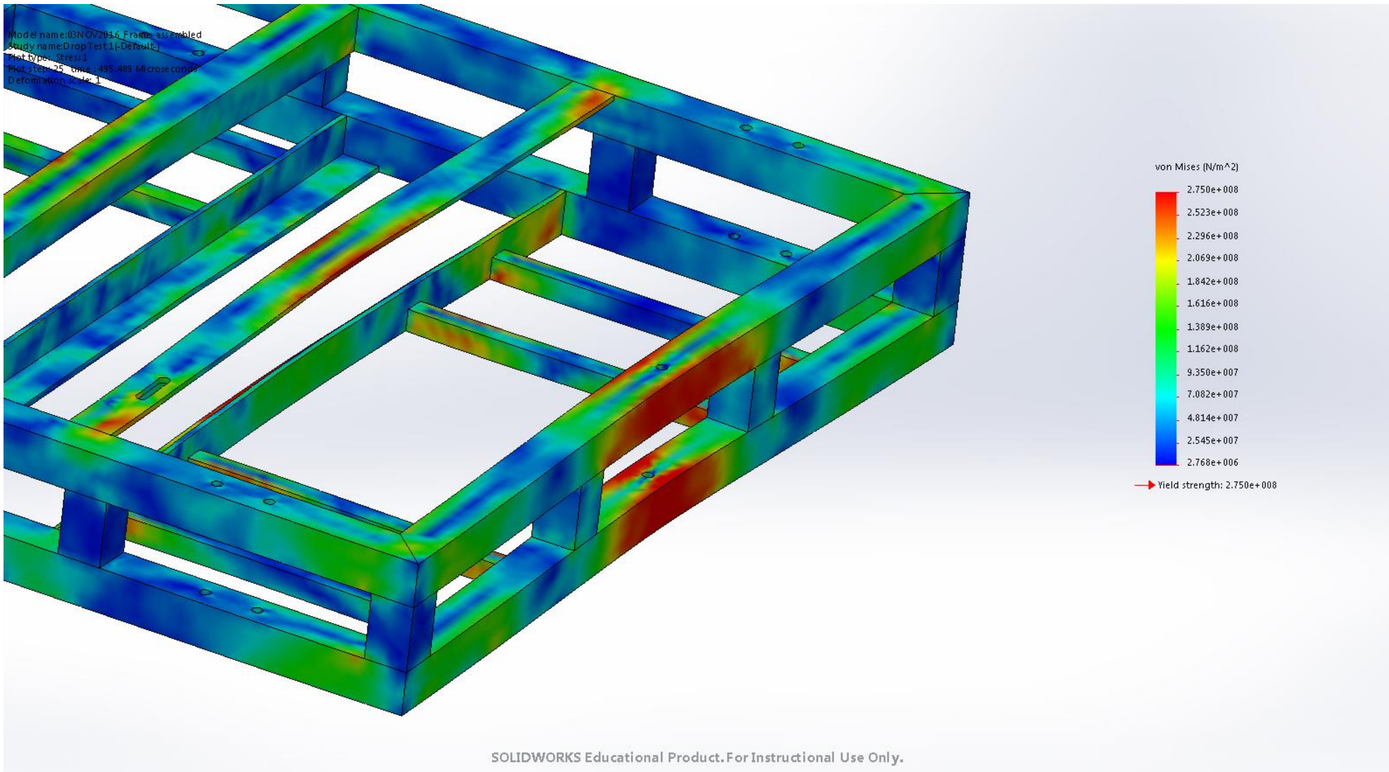
Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.038044 mm Node: 55728	7.27507 mm Node: 60473



03NOV2016_Frame_assembled-Drop Test 1-Displacement-Displacement1

Name	**Type**	**Min**	**Max**
Strain1	ESTRN: Equivalent Strain	5.55106e-005 Element: 32840	0.0227601 Element: 27164





Model name:03NOV2016_Frame_assembled
Study name:Drop Test 1(-Default-)
Plot type: Stress1
Plot step: 25 time : 495.489 Microseconds
Deformation scale: 1
von Mises (N/m^2)
2.750e+008
2.523e+008
2.296e+008
2.069e+008
1.842e+008
1.616e+008
1.389e+008
1.162e+008
9.350e+007
7.082e+007
4.814e+007
2.545e+007
2.768e+006
Yield strength: 2.750e+008
SOLIDWORKS Educational Product. For Instructional Use Only.

Image-1

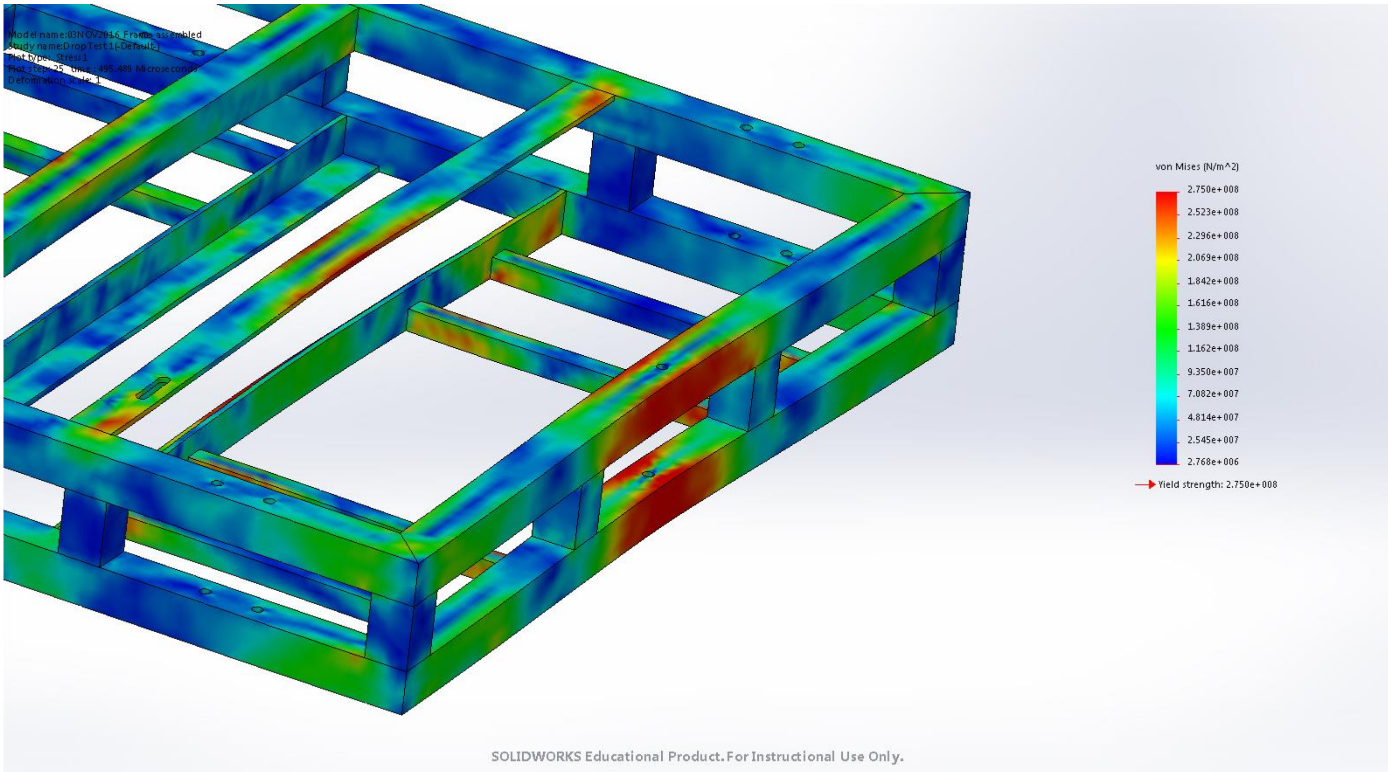


Image-2

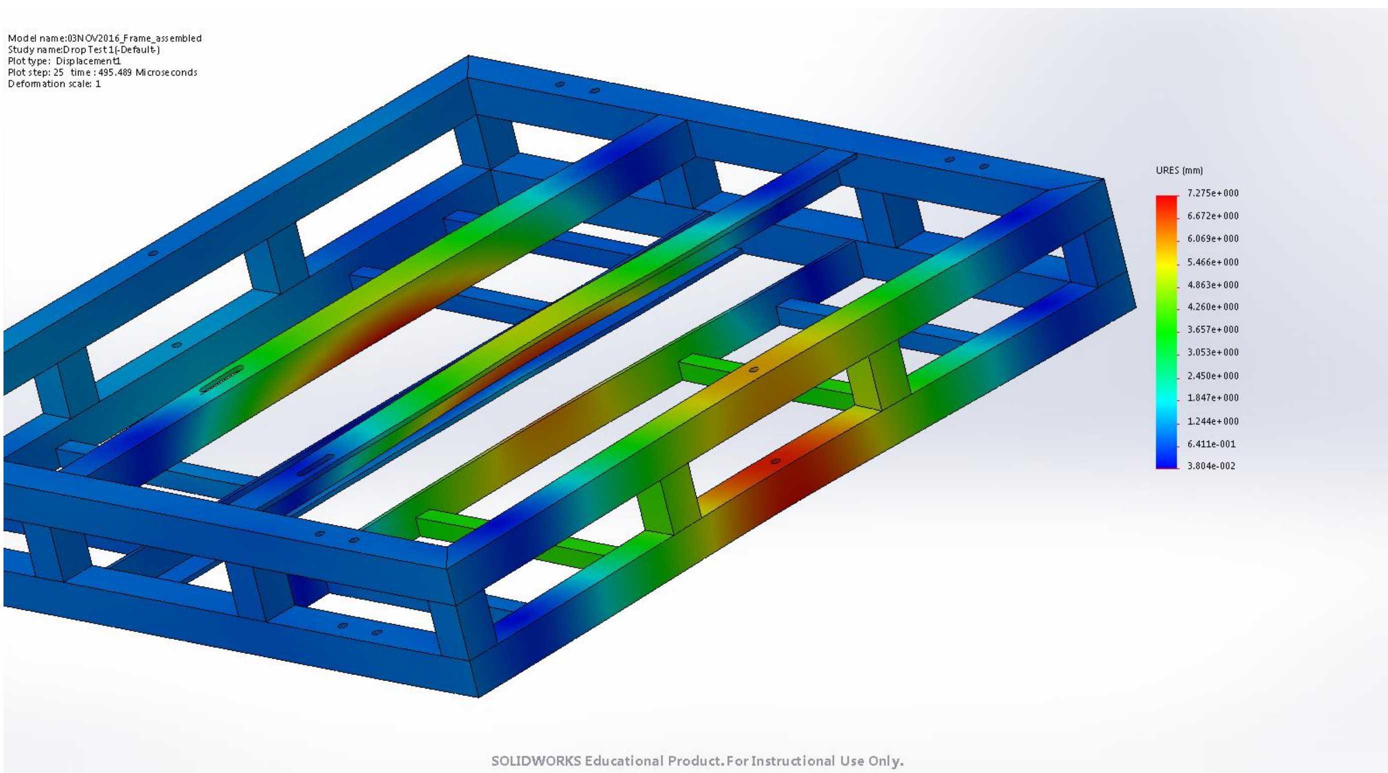


Image-3

Simulation 5ft Drop: Front

Date: Saturday, April 22, 2017
Designer: Solidworks
Study name: Drop Test 2
Analysis type: Drop Test

Table of Contents

Study Properties

Study name	Drop Test 2
Analysis type	Drop Test
Mesh type	Solid Mesh
Large displacement	On
Result folder	SOLIDWORKS document (\\clusterfsnew.ceas1.uc.edu\students\riordamv\desktop\final frame-20170421T184351Z-001\final frame)

Setup Information

Type	Drop height
Drop height from lowest point	16.047 ft.
Gravity	9.81 m/s^2
Gravity Reference	Edge<1>
Friction Coefficient	0
Target Stiffness	Rigid target
Critical Damping Ratio	0

Result Options

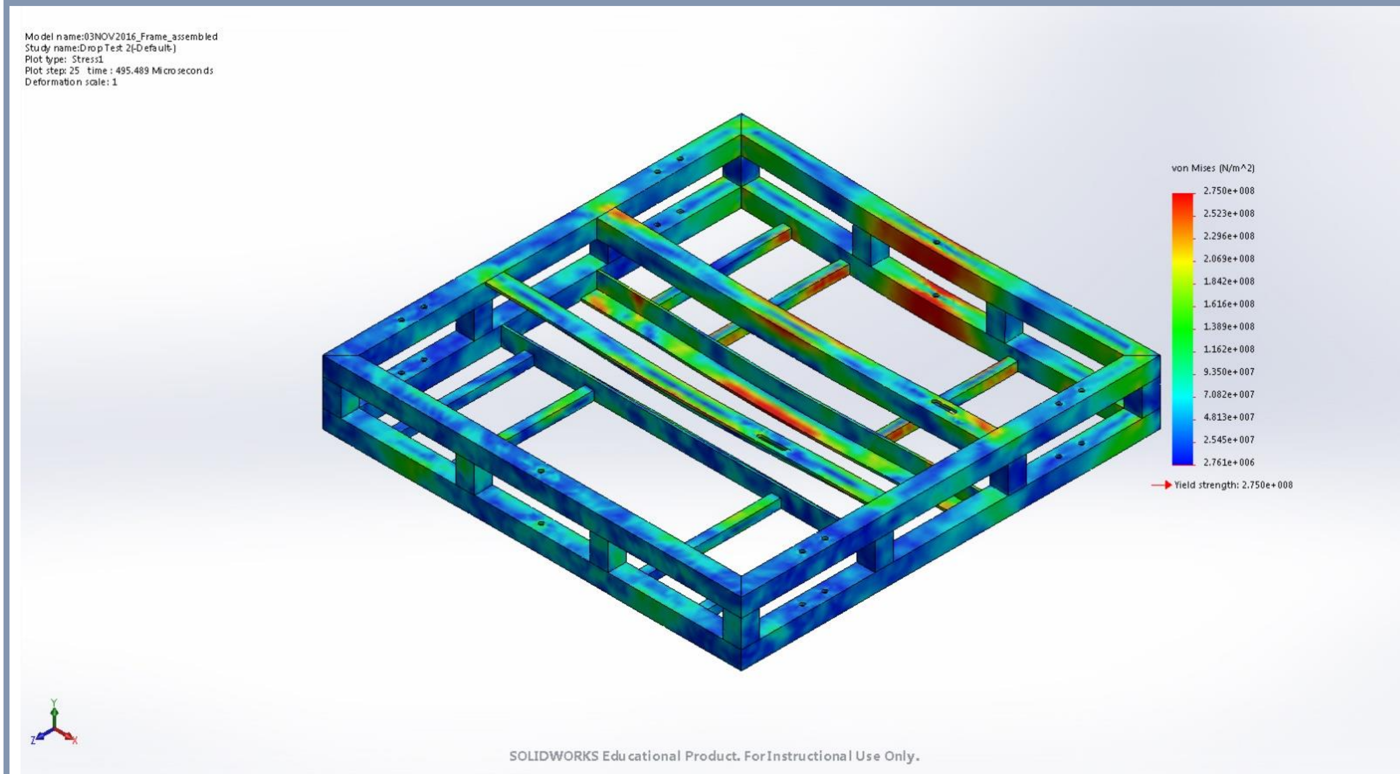
Solution Time After Impact	495.5 microsec
Save Results Starting From	0 microsec
No. of Plots	25
No. of Graph Steps Per Plot	20
Number of vertex	0

Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

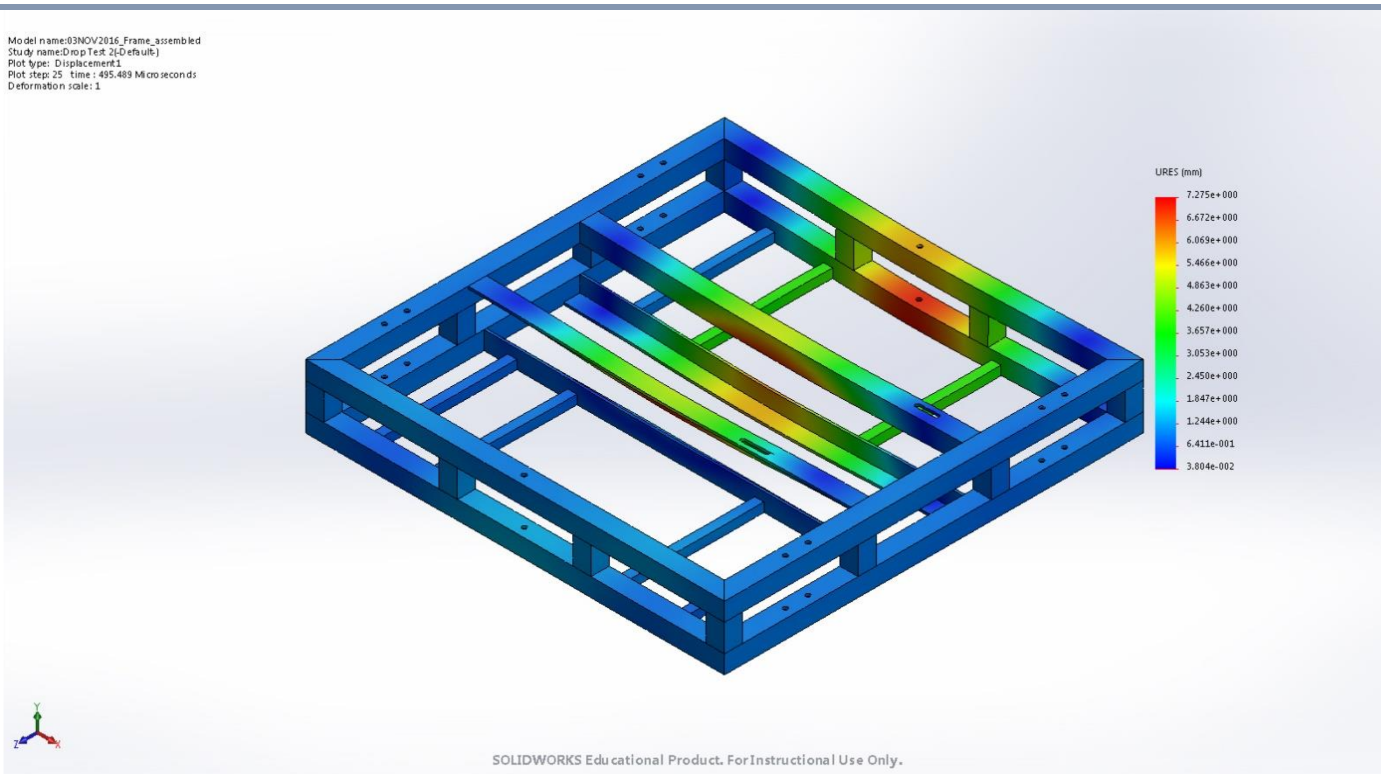
Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	2.76142e+006 N/m^2 Node: 67083	2.74979e+008 N/m^2 Node: 66552



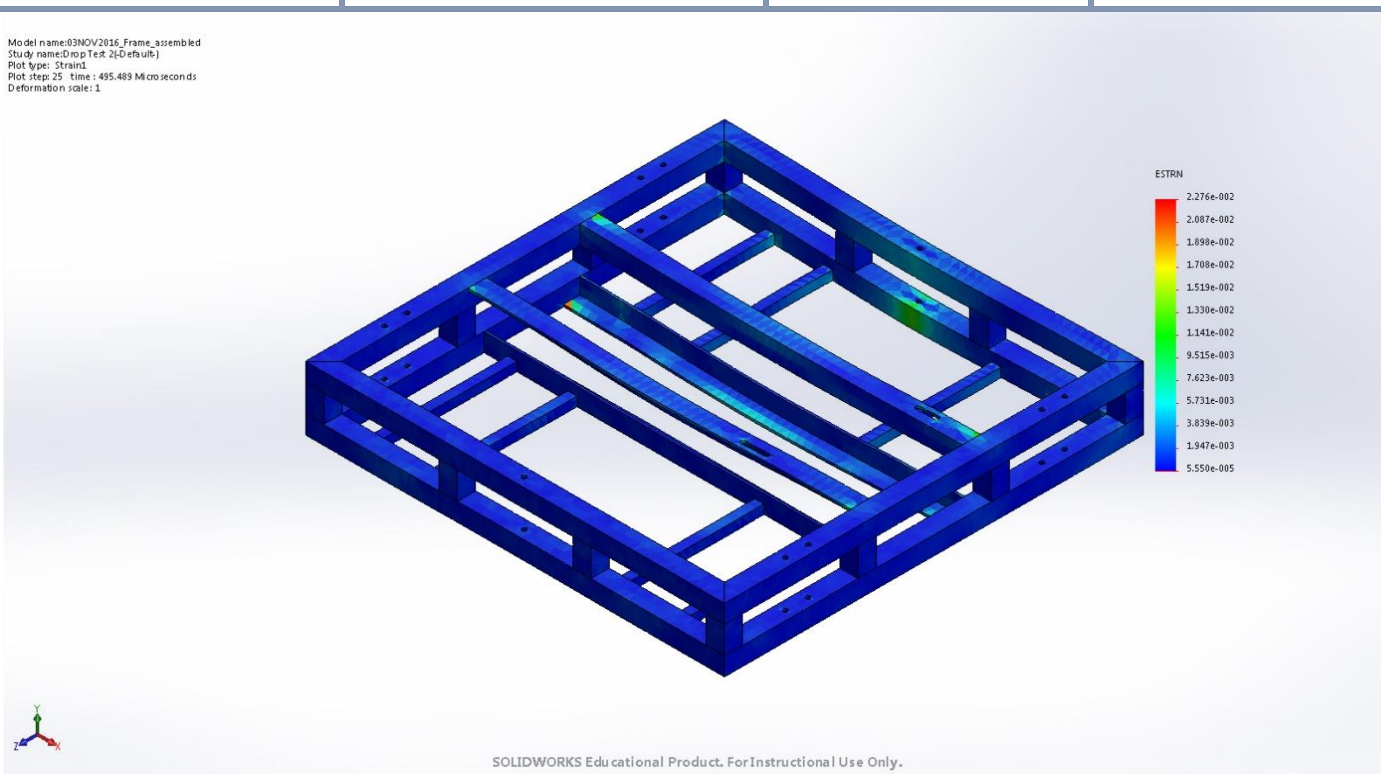
03NOV2016_Frame_assembled-Drop Test 2-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.0380352 mm Node: 55728	7.27504 mm Node: 60473



03NOV2016_Frame_assembled-Drop Test 2-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	5.55009e-005 Element: 32840	0.022759 Element: 27164



03NOV2016_Frame_assembled-Drop Test 2-Strain-Strain1

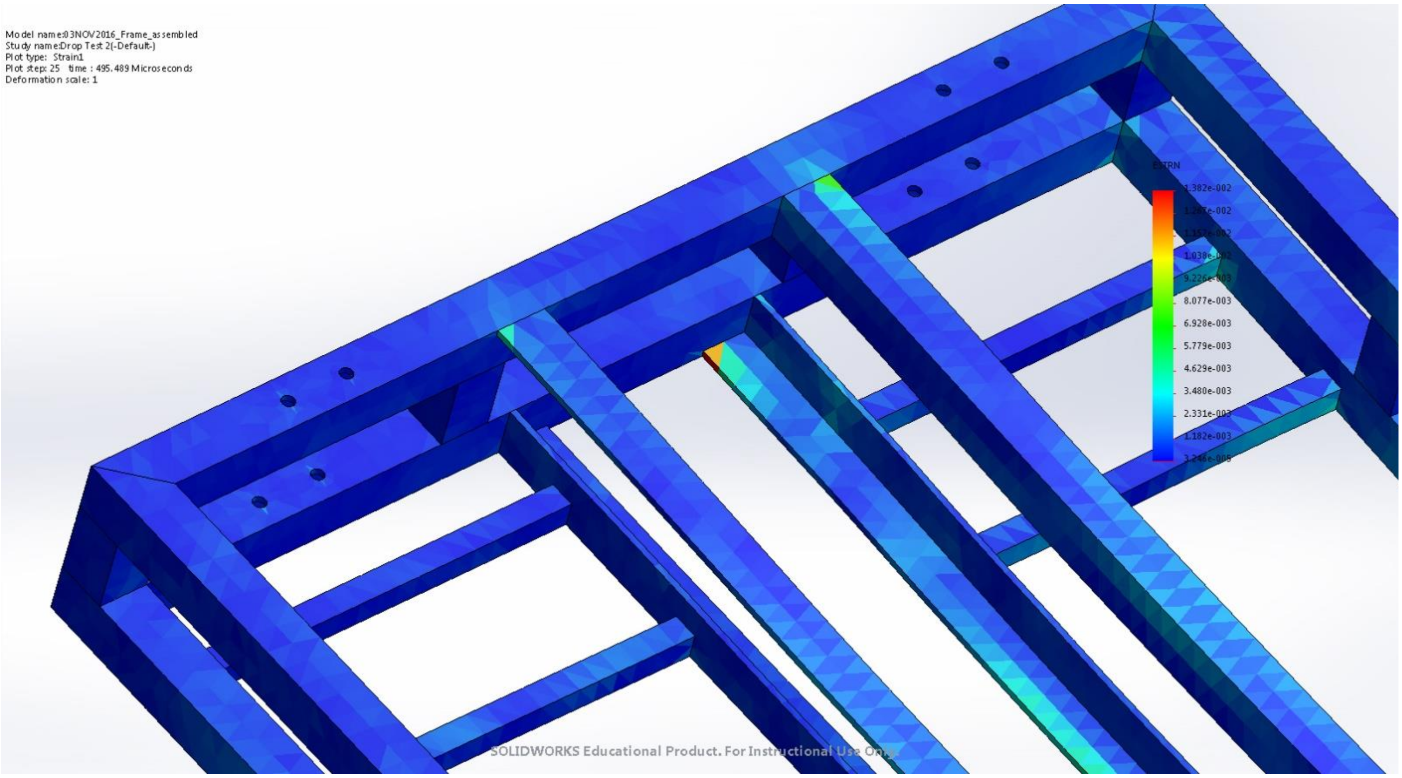


Image-1

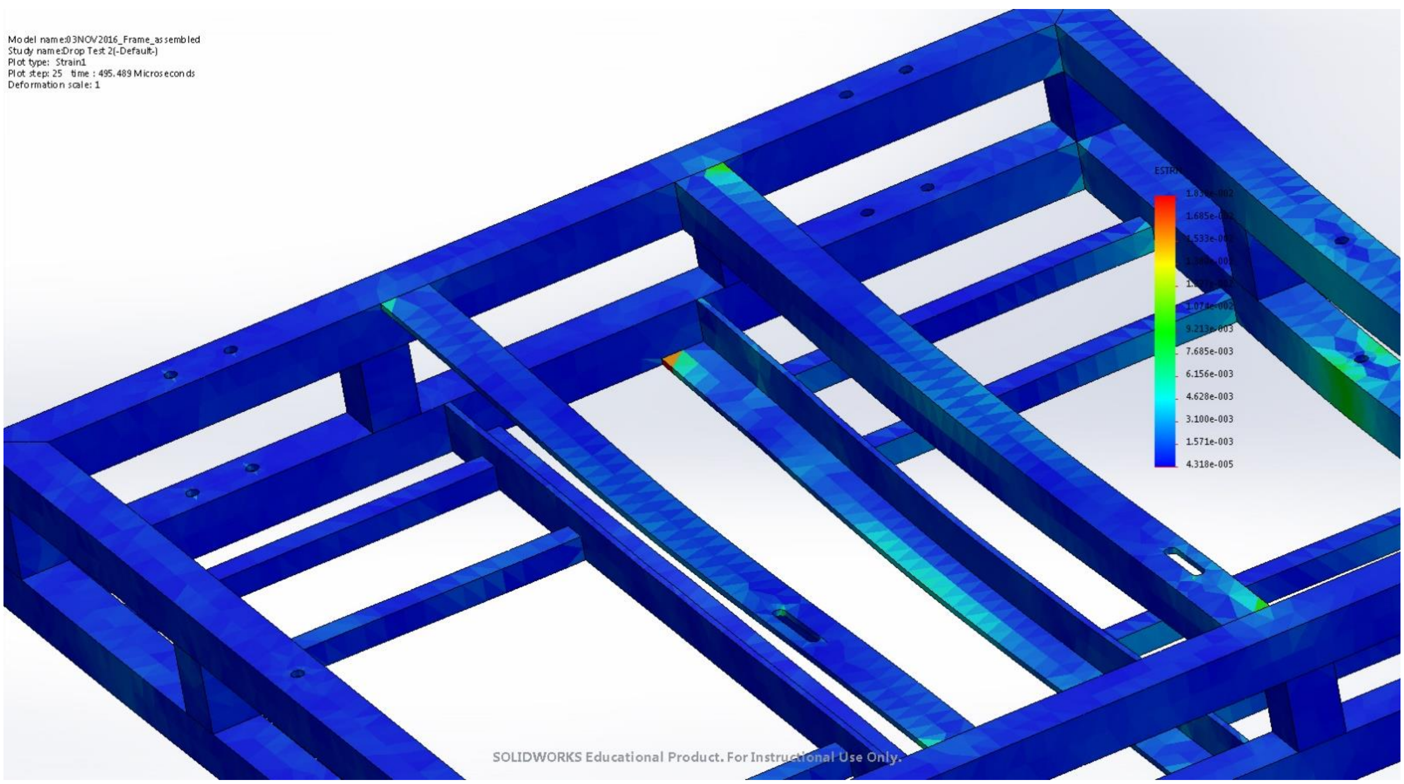


Image-2

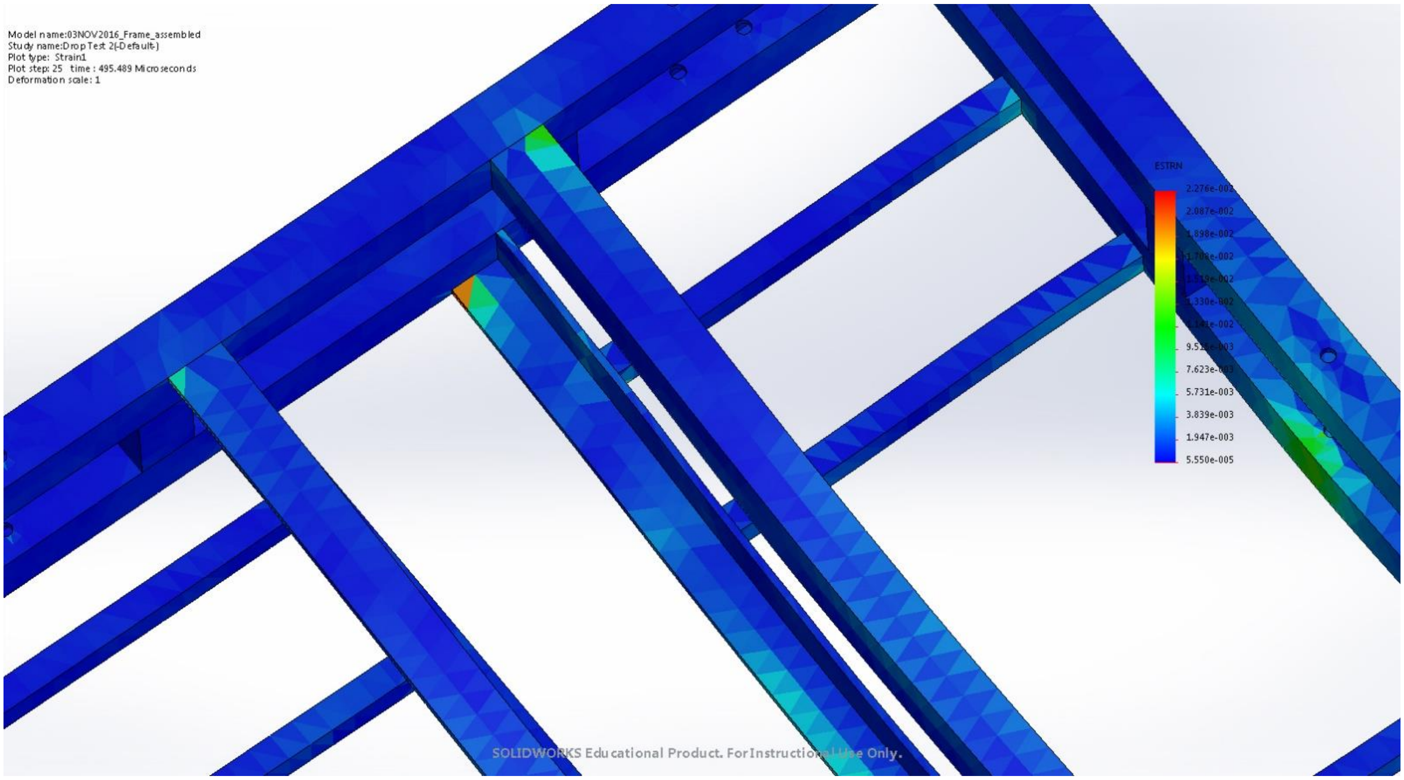
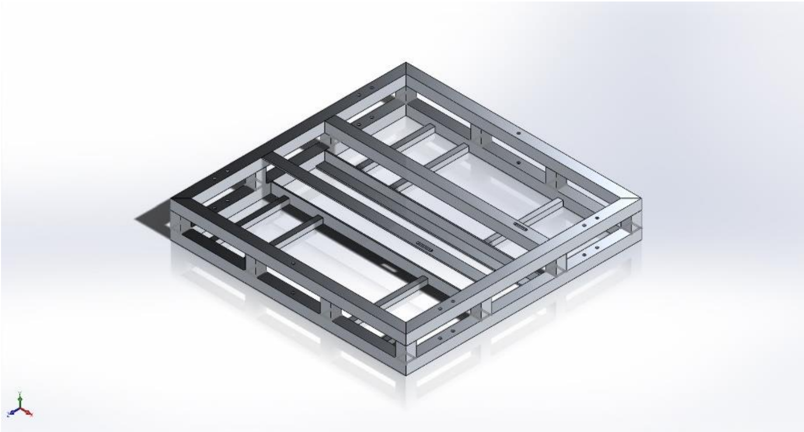

Model name:03NOV2016_Frame_assembled
Study name:Drop Test 2(-Default-)
Plot type: Strain1
Plot step: 25 time : 495.489 Microseconds
Deformation scale: 1
ESTRN
2.276e-002
2.087e-002
1.898e-002
5.731e-003
3.839e-003
1.947e-003
5.550e-005

Image-3



Simulation of 5ft Drop: Corner

Date: Saturday, April 22, 2017
Designer: Solidworks
Study name: Drop Test 3
Analysis type: Drop Test

Table of Contents

Study Properties

Study name	Drop Test 3
Analysis type	Drop Test
Mesh type	Solid Mesh
Large displacement	On
Result folder	SOLIDWORKS document (\\clusterfsnew.ceas1.uc.edu\students\riordamv\desktop\final frame-20170421T184351Z-001\final frame)

Setup Information

Type	Drop height
Drop height from lowest point	16.047 ft.
Gravity	9.81 m/s^2
Gravity Reference	Edge<1>
Friction Coefficient	0
Target Stiffness	Rigid target
Critical Damping Ratio	0

Result Options

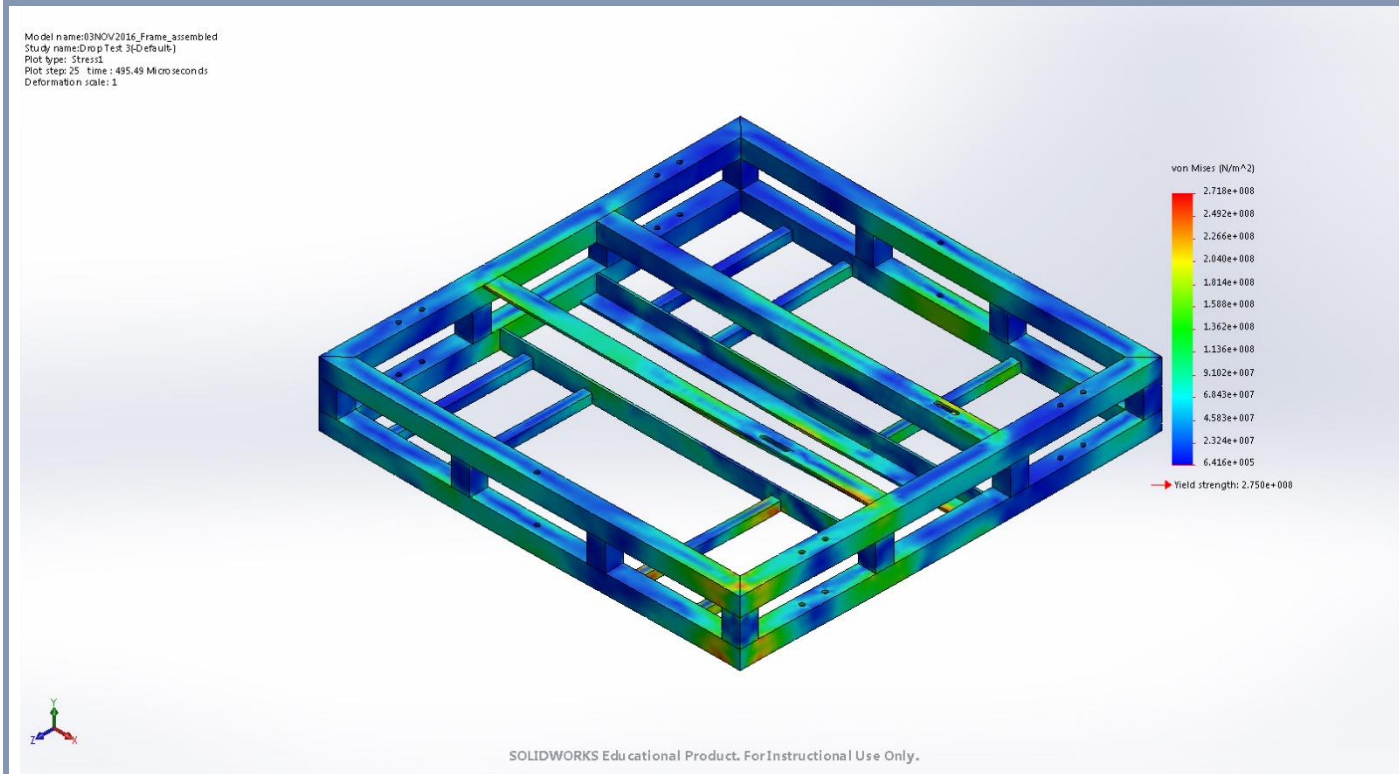
Solution Time After Impact	495.5 microsec
Save Results Starting From	0 microsec
No. of Plots	25
No. of Graph Steps Per Plot	20
Number of vertex	0

Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

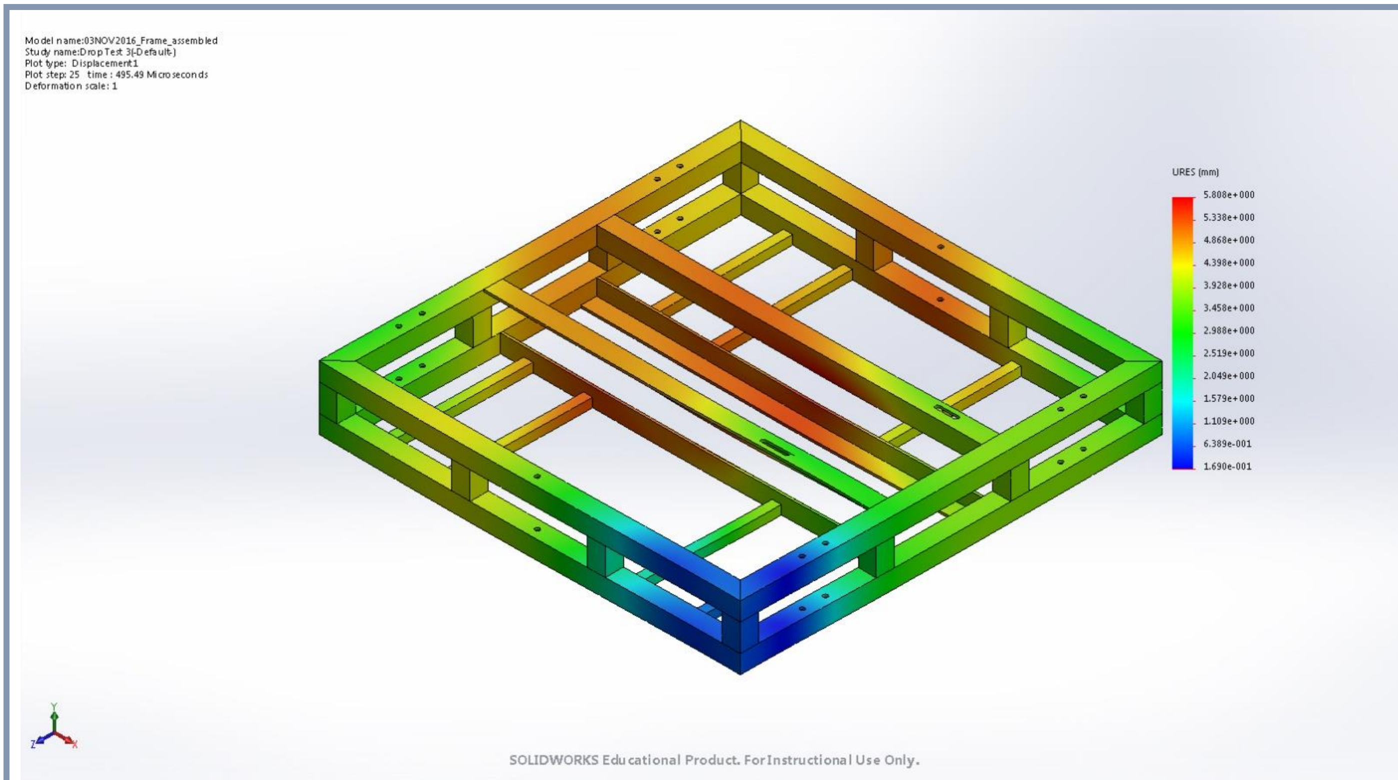
Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	641594 N/m^2 Node: 544	2.71791e+008 N/m^2 Node: 58437



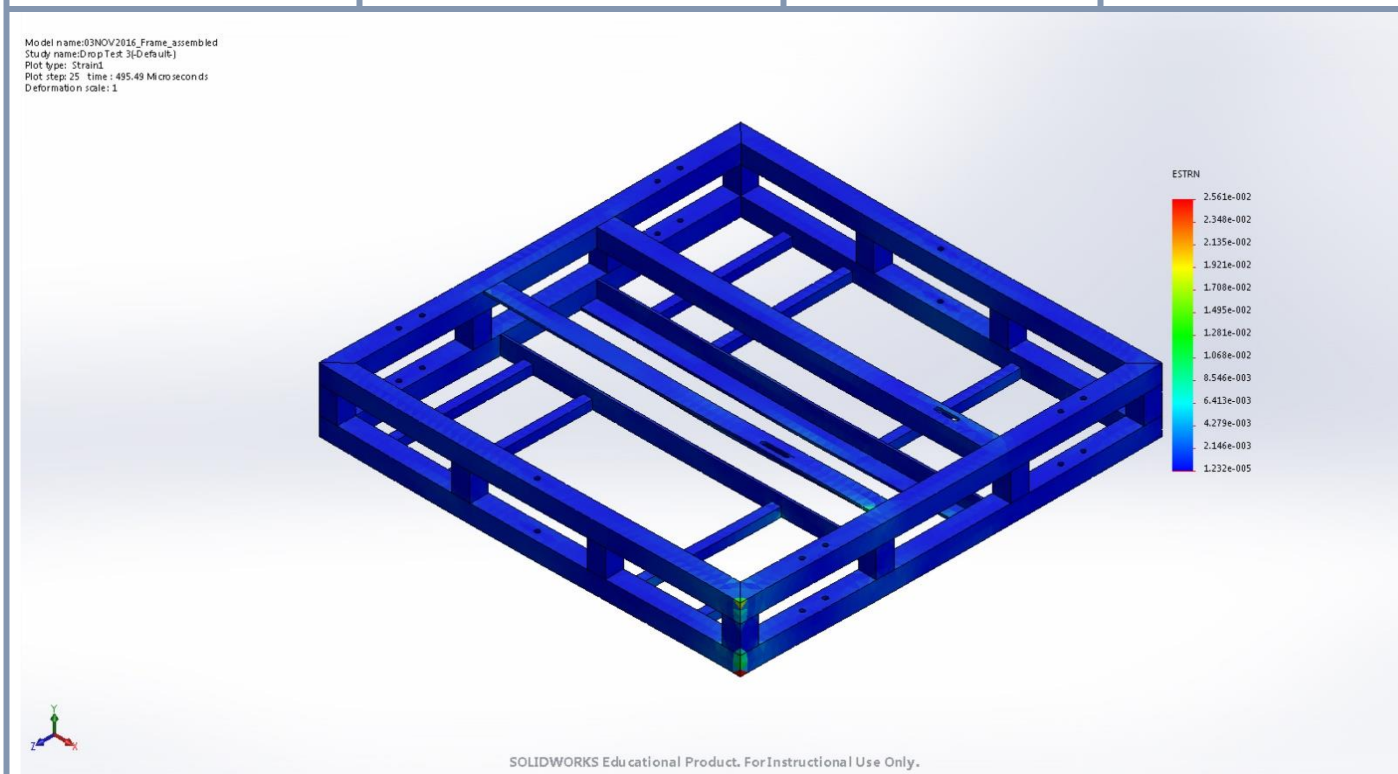
03NOV2016_Frame_assembled-Drop Test 3-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.169016 mm Node: 15846	5.80792 mm Node: 63325



03NOV2016_Frame_assembled-Drop Test 3-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	1.23234e-005 Element: 32764	0.0256137 Element: 18348



03NOV2016_Frame_assembled-Strain-Strain1

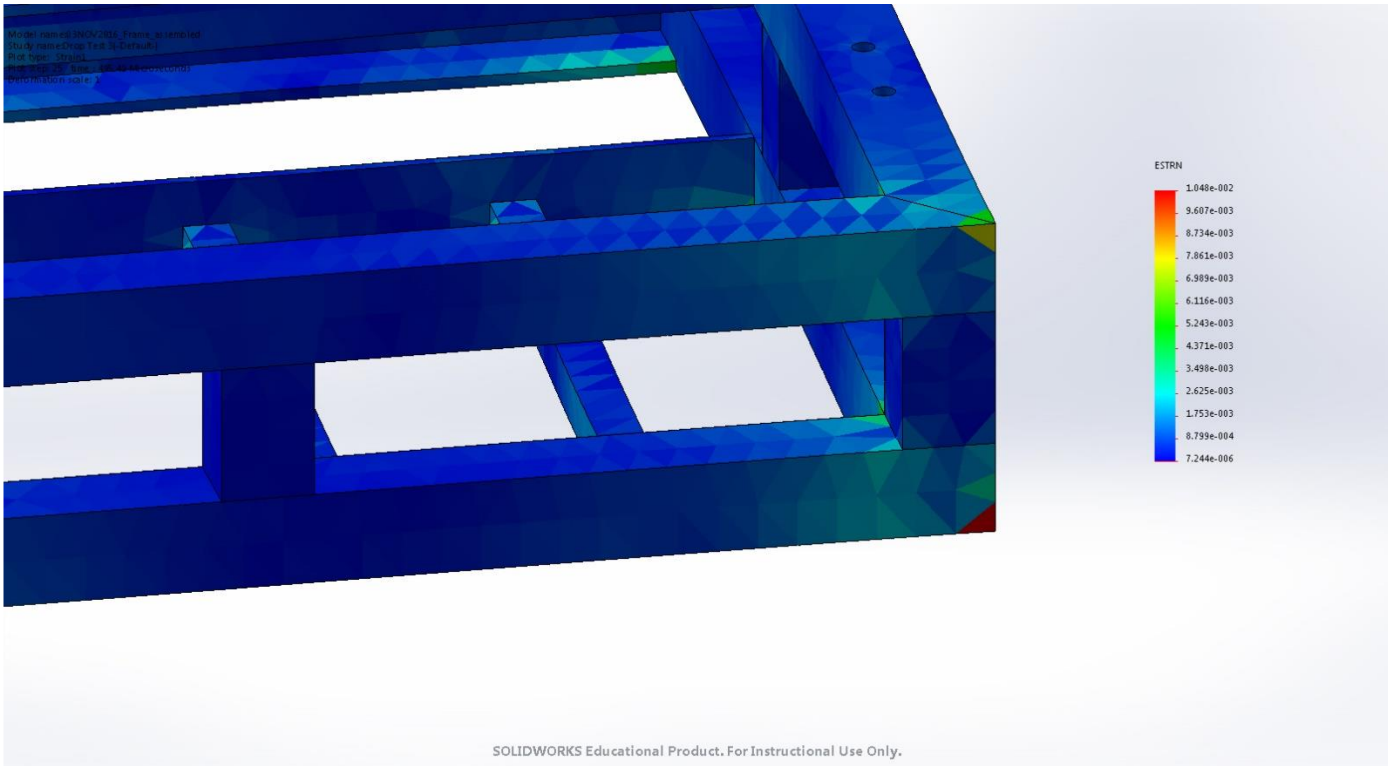


Image-1

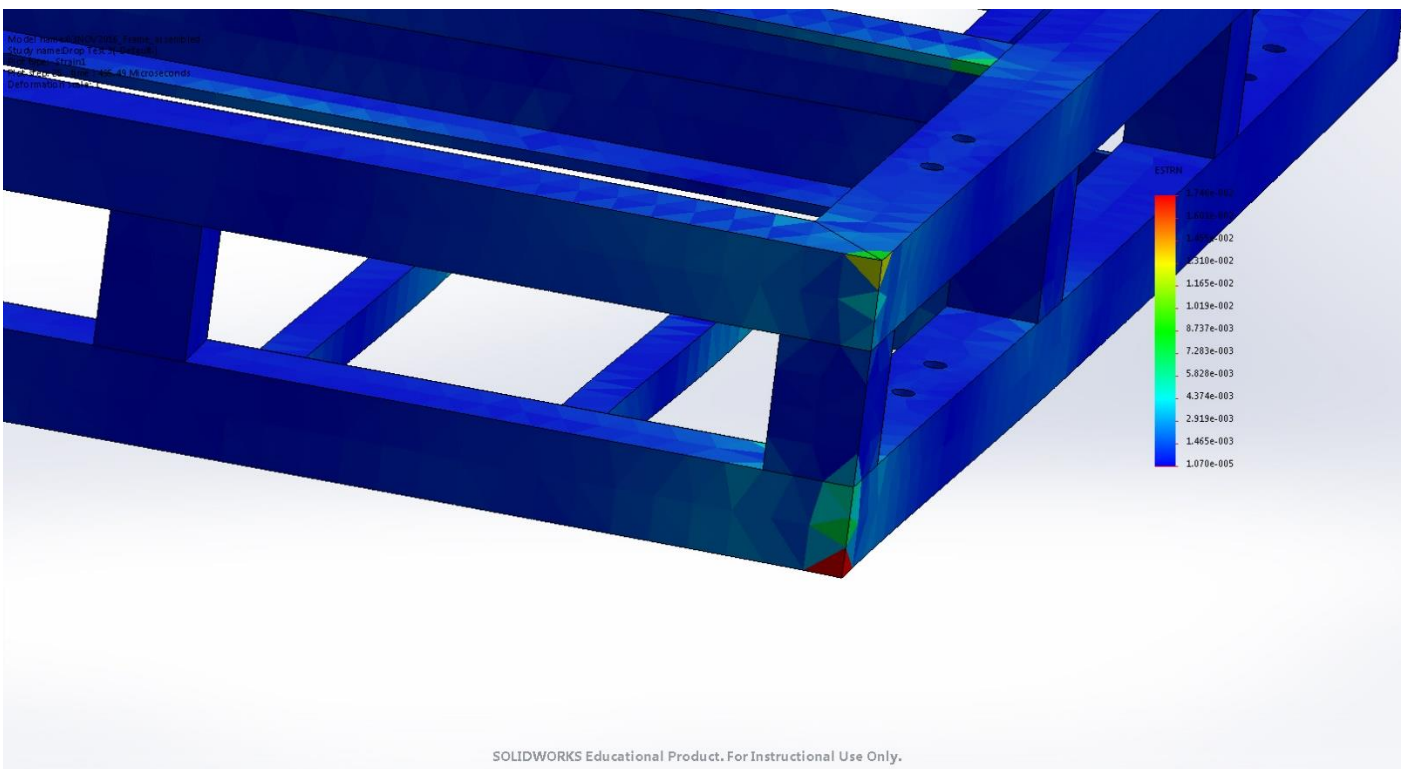


Image-2

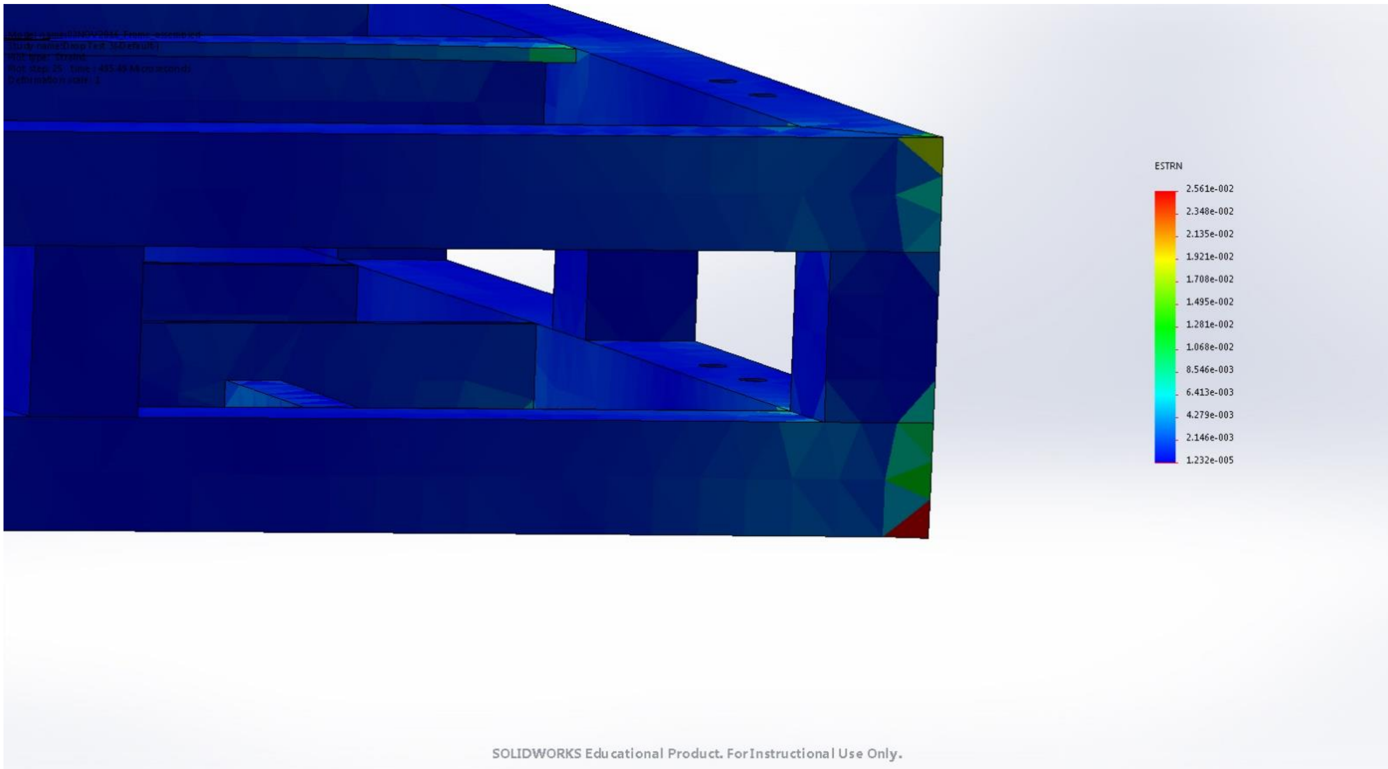

ESTRN
2.561e-002
2.348e-002
2.135e-002
1.921e-002
1.708e-002
1.495e-002
1.281e-002
1.068e-002
8.546e-003
6.413e-003
4.279e-003
2.146e-003
1.232e-005
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Image-3