Dilatant Failure

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ME 661 Finite Elements Analysis

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Abstract:

In this project, we did a preliminary stress analysis on select components of a base plate designed to utilize newly developed RATs (Rate attenuating decelerate straps), which have the purpose of reducing G-forces on pilots during intense maneuvering. Two parts were selected for the analysis, a ball joint which attaches the RATs to the rest of the base plate and the cylinder which contains the ball joint, as these components were thought to be the weakest links in the overall base plate system and most likely components to fail. Finite element analysis was used to estimate the stress concentration factor of the components in a static loading condition through Nastran. Based on the stress concentration factors, the Cylinder appears to be the weakest link of the entire assembly, but the ball joint needs more work done in order to get the results to converge into an accurate value. The conclusion section includes recommendations on verifying the cylinder results and changing the mesh of the ball joint to get a more accurate, converged result, and recommendations on future analyses involving the baseplate system.

Introduction:

Pilots experience a wide range of strong G-forces while in flight, so it is very important that every precaution possible is taken to make sure their head and neck are safely protected. A privately held company, Dilatant LLC, located out of Kansas City, Missouri, has made a goal to provide a new level of pilot head safety and protection. To do this, their company has created rate attenuating decelerate straps (RATs) to help reduce the violent head and body motion that occurs during any acceleration, deceleration, impact, or ejection.

Figure 1 Pilot with Helmet and RATs

The RATs incorporate a Shear Thickening Fluid which is a Non -Newtonian fluid where the shear viscosity increases with applied shear stress. The RATs provide head and neck support against severe G-forces. This means that the straps stretch easily at low speeds, but at high speeds they resist the stretching to help reduce the violent head movement. The RATs are secured to a base plate attached to the back of the helmet, which restricts the rotation of the head. However, one problem is that the original base plate restricts the pilot's head mobility.

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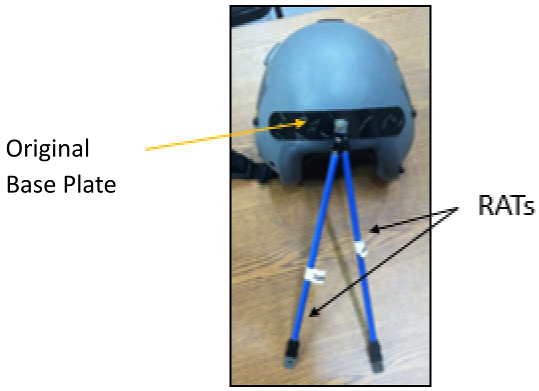

Figure 2 Original Base Plate with RATs

In order to optimize the design, a KU team has developed a new base plate for the helmet that meets the needed criteria.

With the design made, the KU team has presented and delivered the final product to the president of Dilatant LLC. However, part of the team decided to take the design and run a FEA to see if it can actually withstand a 15 G impulse force that may arise during flight. Other applications of the new base plate design could also be integrated into NASCAR or Formula One. In order to get some results, two of the five components that made up the base plate were isolated and analyzed. One part is a hollow cylinder with one side having a smaller diameter to create a lip. That lip is to ensure the other analyzed part, a joint piece, to be in place so it will not fall out of the cylinder. The joint piece is to be inserted into the bottom of the cylinder and all the way to the lips, where the piece can act as a ball joint, allowing a swivel motion.

Modeling:

Each part of the base plate was made through SolidWorks 2018. The base plate is made up of a base frame, a frame bottom cover, a tab, a cylinder, and a ball joint. For the analysis, the ball was saved as a .x_t file to be used in Patran/Nastran2018. The cylinder was made on Patran/Nastran2018. The cylinder plays a vital role of connecting

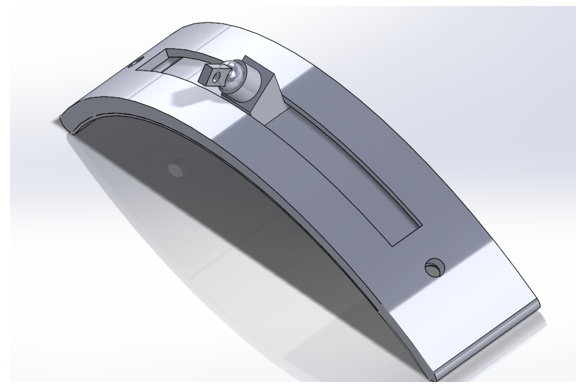

Figure 3 Assembled Base Plate

the ball joint part to the base plate and preventing the ball joint socket from falling out of the cylinder. The length of the cylinder is measured to be 1cm with an outer diameter of 1.12cm.

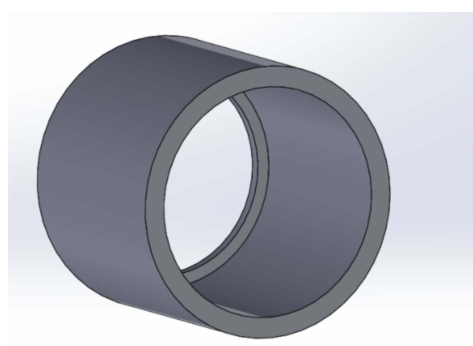

Figure 4 Cylinder Part

The ball joint is made with a sphere and a rectangular prism with a circular hole towards the top. The ball joint has a total length of 1.93cm with the sphere's diameter

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toe be 0.91cm. The ball joint is inserted into the cylinder, acting as a ball socket joint mechanism, allowing the sphere to freely rotate without the ball joint falling out.

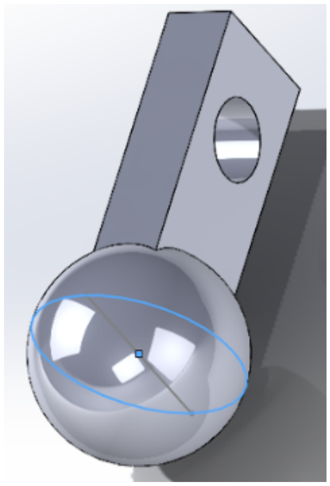

Figure 5 Ball Joint Part

Procedure:

The design has the ball joint inserted into the cylinder with the rectangular prism in front on the side that does not have a lip. The design is then supposed to have the ball joint pulling on the lip. So in order to make an approximate model on Patran/Nastran 2018, two different meshes were made on the cylinder and two on the ball joint:

Cylinder: Quad4/Hex8
Quad8/Hex20
Ball Joint: Tet4
Tet10

A Quad mesh with a Paver automesh was applied to a surface and was extruded out 360° to make the cylinder shape, resulting in a Hex mesh. The cylinder had the force applied to each intersecting node on the bottom edge of the lip. The inner lower edge of the lip of the cylinder was selected to be where the force was applied since the spherical part of the ball joint will be pulling mainly on the edge. Initially, a total load was considered, but since that will work on a flat surface, a point load was applied along the circumference. Since the bottom of the cylinder will be attached to another part, securing the cylinder in place, the bottom of the cylinder had a constraint with zero translation and rotation in all directions. The ball joint had a constraint along the circumference, ¾ way up from the bottom of the sphere, to replicate where the lip of the cylinder would touch. MPCs were made from the top of the hollowed out circular hole on the ball joint and MPCs were made along the top half of the hole, connecting to the center top of the hole, to represent where the force will be applied. Titanium was used to model the part.

Titanium Properties	
Density	$0.163\ lb/in^3$
Modulus of Elasticity	$1.68\ x\ 10^4$ ksi
Yield Strength	128 ksi
Ultimate Strength	138 ksi
Poisson's Ratio	0.340

Figure 6: Titanium Properties

While the part can theoretically be made of all sorts of materials, Titanium was picked as a representative material due to good strength (both under static conditions and fatigue) and being a reasonable elastic material. Cost is tertiary; material costs for the baseplate is unlikely to be dominant compared to the RATs, the helmet itself, or the airframe.

Results & Discussion:

The effective stress concentration factors are shown below.

The cylindrical part was analyzed by varying both the number of elements and the order of the elements. Under second-order elements (Cylinder Cases 2-4), increasing the number of elements resulted in the cases being close to convergence around a stress concentration factor of 25-30. The highest stress along the part was at the edge of contact.

The ball joint was analyzed by varying only the number of elements, due to the difficulty and time required to manually enter every MPC and displacement condition upon changing the number of elements. The maximum stress of the part occurs at the sides of the hole.

Unfortunately, the program had issues implementing anything higher than a 2nd-order element for the mesh, so only a 1st order and 2nd order element case was analyzed here. The two cases had drastically different concentration factors and did not converge, which requires another analysis including either changing the number of mesh elements or re-thinking the entire FEA model for the ball joint.

Load Case	**Stress Concentration Factor**
Cylinder 1	13
Cylinder 2	27
Cylinder 3	30
Cylinder 4	18
Ball Joint 1	1.18
Ball Joint 2	4.49

Figure 7: Stress Concentration Factor of Different Element Sizes

Conclusion & Future work:

The location of the maximum stress along each part was satisfactorily determined. The ball joint's maximum stress occurs at the edge of the center hole, and the cylinder's occurs at the contact edge with the ball joint.

The actual, numerical value for the stress concentration factor of the cylinder and, especially, the ball joint were not adequately determined. The cylinder part may have converged around a stress concentration factor of 30, but more iterations are needed with increasing number of elements to show this conclusively. The ball joint case did not converge and needs more analysis with varying the number of mesh elements or possibly a change to how the joint is modeled. It is recommended that future work models the flat plate portion of the ball joint with an extruded quad element (Hexahedral) and the spherical portion with tetrahedral elements instead of modeling the entire part with tetrahedral elements, since hexahedral elements are more accurate and the simple flat plate is more critical to model with high accuracy than the spherical region which has minimal stress.

Other work to be done includes studying design modifications to reduce these stress concentrations, especially for the cylindrical part. This should be aided by knowledge gathered in the general shape of the part stress and the location of their maximums. In the case of the cylindrical part, this could be reduced by adjusting the geometry of the part to put the entire bottom surface in contact with the ball joint instead of just the edge. Reducing the ball joint's stress concentrations should focus on the hole region.

Material selection for the ball joint and cylinder, as well as the rest of the backplate assembly, should be finalized. Though the KU backplate design team picked Titanium for the analysis and recommends it for the first prototype, a more comprehensive material analysis should still be done on the feasibility of each material and their various alloys based on desired material properties, cost, manufacturing constraints, and other considerations.

A method of estimating and modeling the magnitude of the forces acting on the part is necessary for modeling whether the part will fail under its loading conditions.

Perhaps most importantly, future work must include a dynamic analysis. The nature of the part is such that it will undergo short "spikes" of force as the pilot undergoes heavy accelerations in sharp turns, so a static analysis is insufficient to model a realistic condition and fatigue will be an issue, if not the most important factor controlling the design. Such an analysis is necessary to estimate if a part will fail after a number of high-G cycles, and if so, how many cycles.

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References:

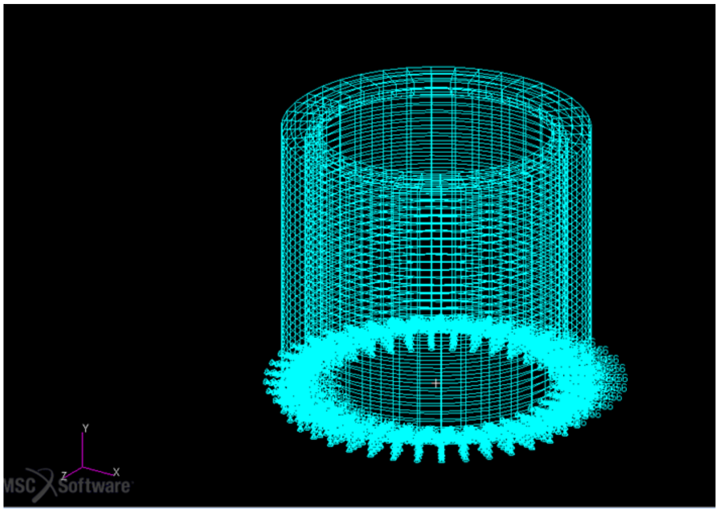
Figure 1: Decelerate System Fighter Pilot; Dilatant LLC

Figure 2: Decelerate System Fighter Pilot; Dilatant LLC

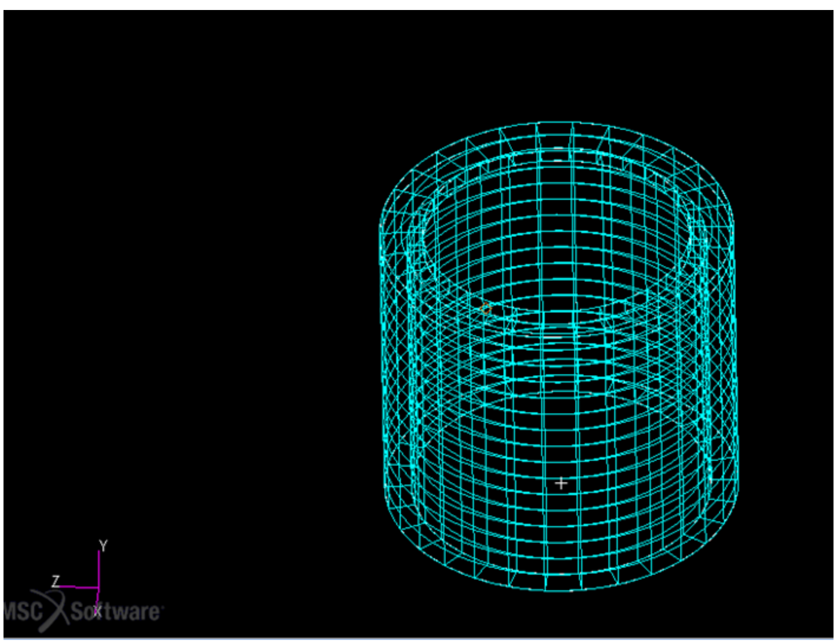
Figure 6: " Titanium (Ti) - The Different Properties and Applications."
" AZoM™ - The A to Z of Materials and AZojomo - The "AZo Journal of Materials Online". N.p., n.d. Web. 20 July 2019.

Appendix:

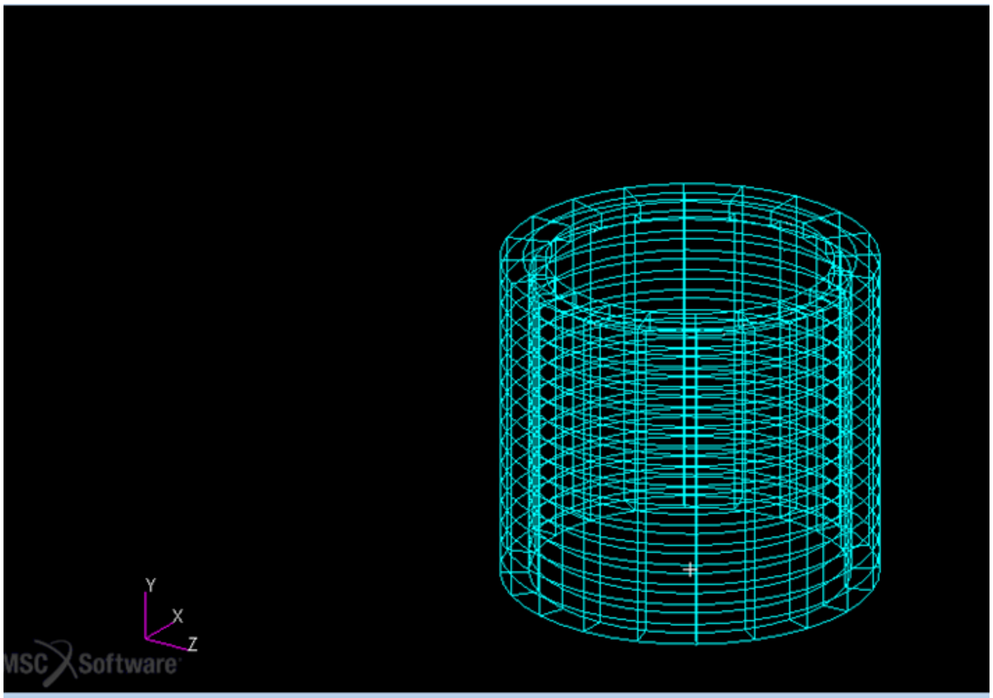
A-1: Meshing



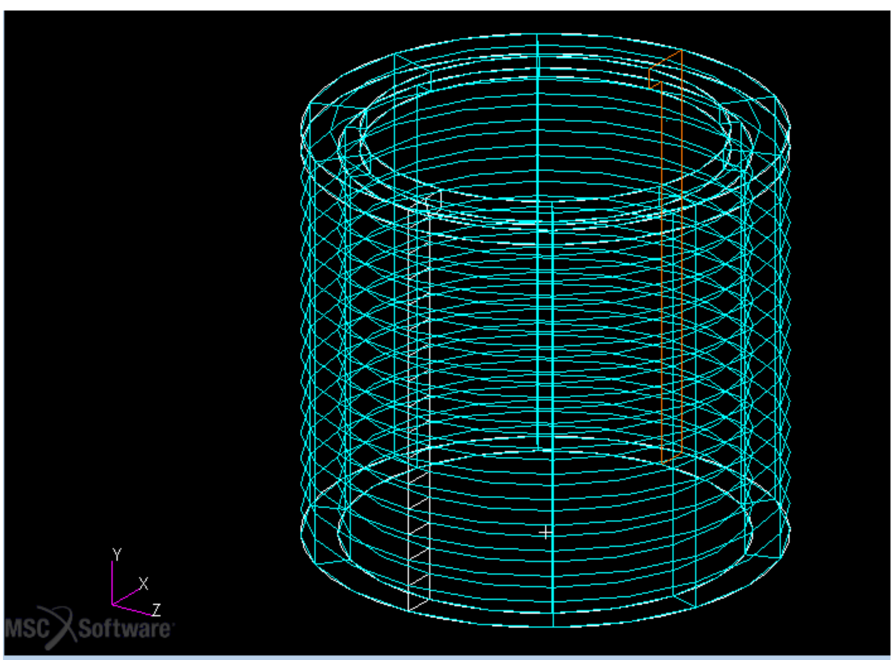
Cylinder (Hex8, 4223 elements)



Cylinder (Hex20, 510 elements)



Cylinder (Hex20, 340 elements)



Cylinder (Hex20, 178 elements)

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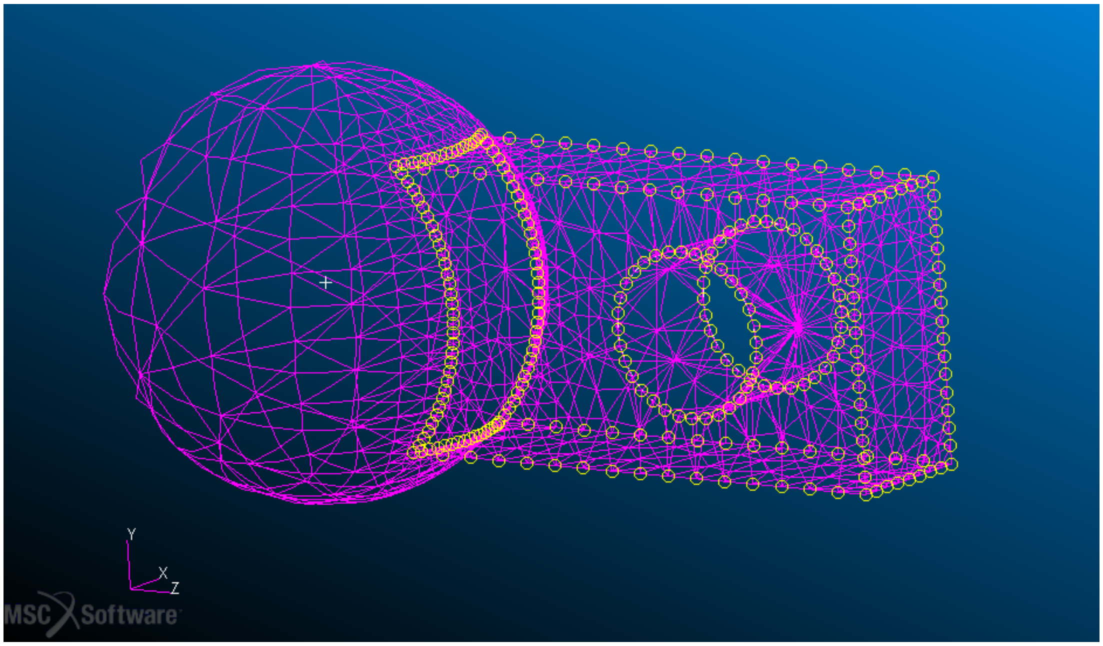

Ball Joint Mesh

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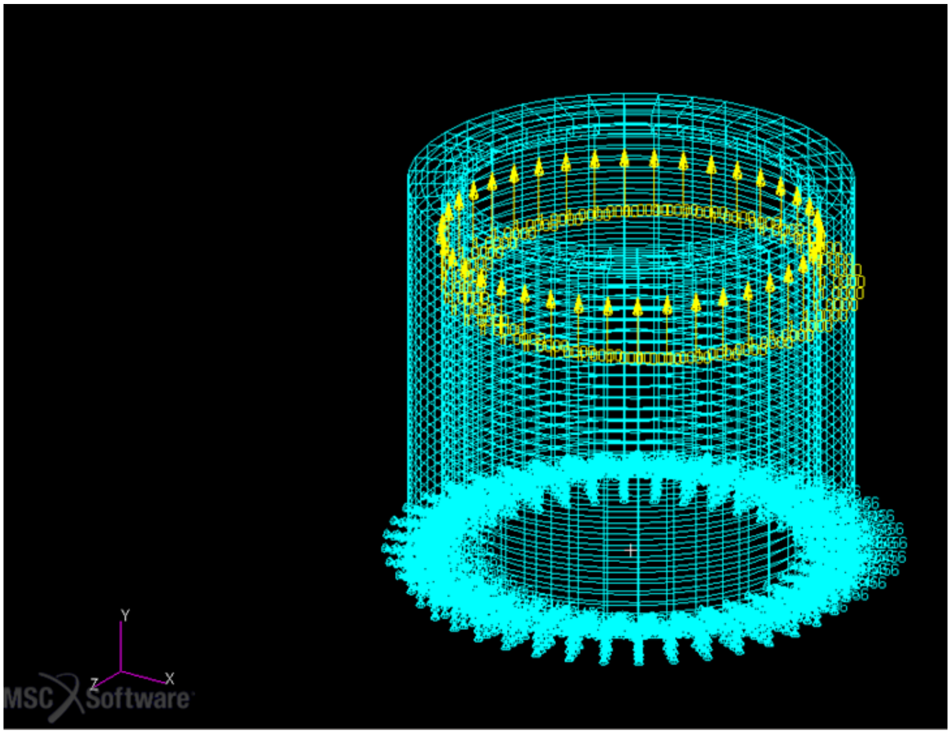
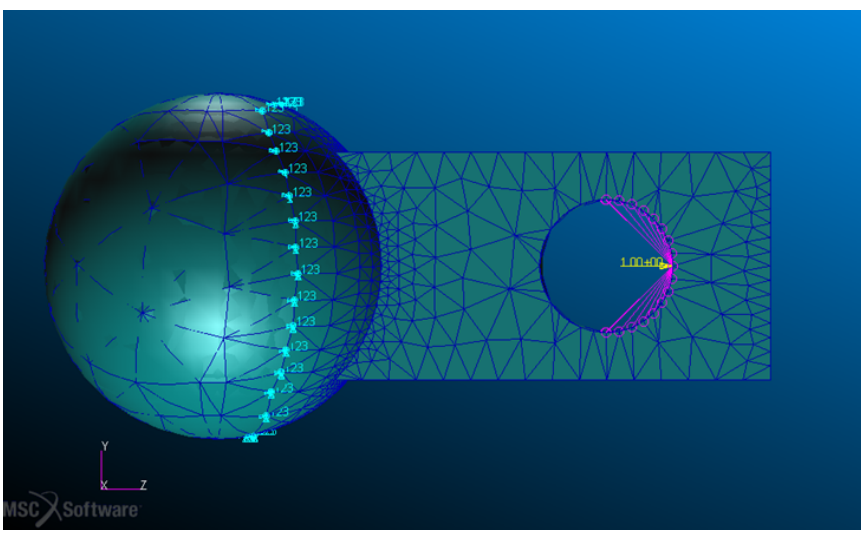
A-2: Loads & Restraints



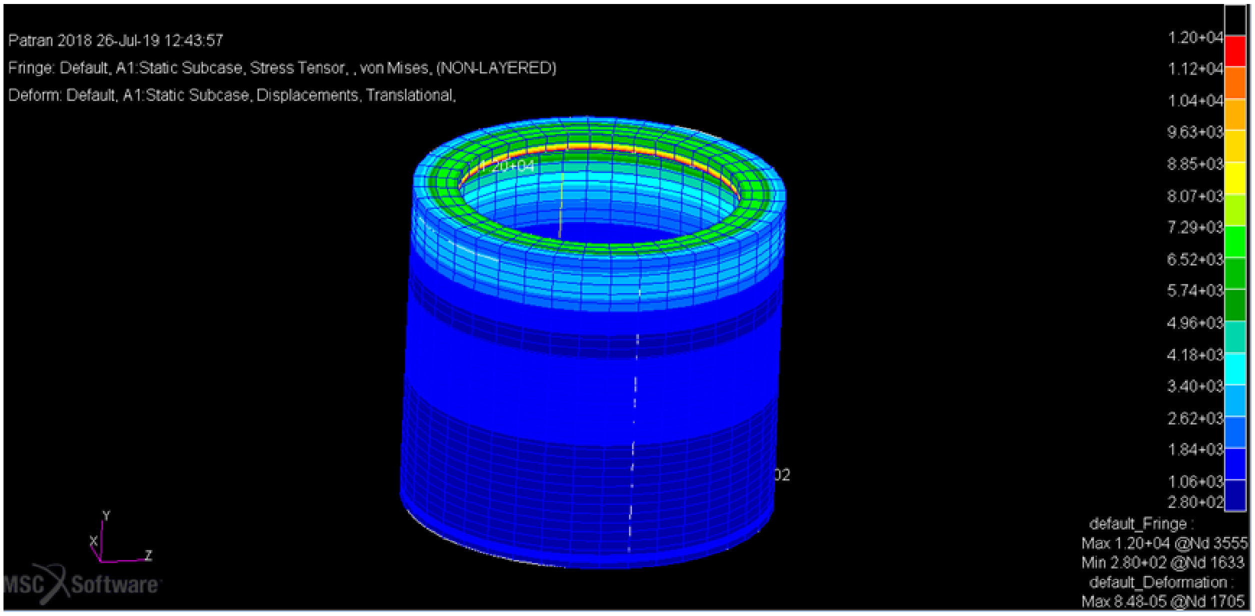
Cylinder Mesh with Loading



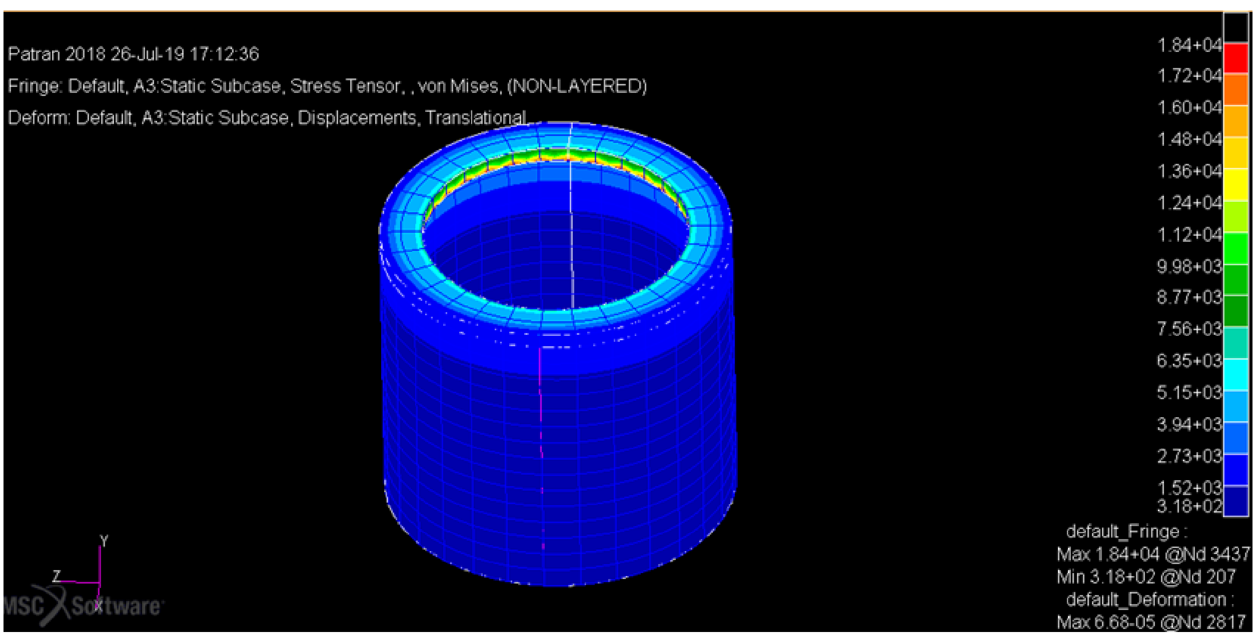
Ball Joint Mesh with Loading

A-3: Results

Von-Mises Stress



Cylinder (Hex8, 4223 elements)



Cylinder (Hex20, 510 elements)

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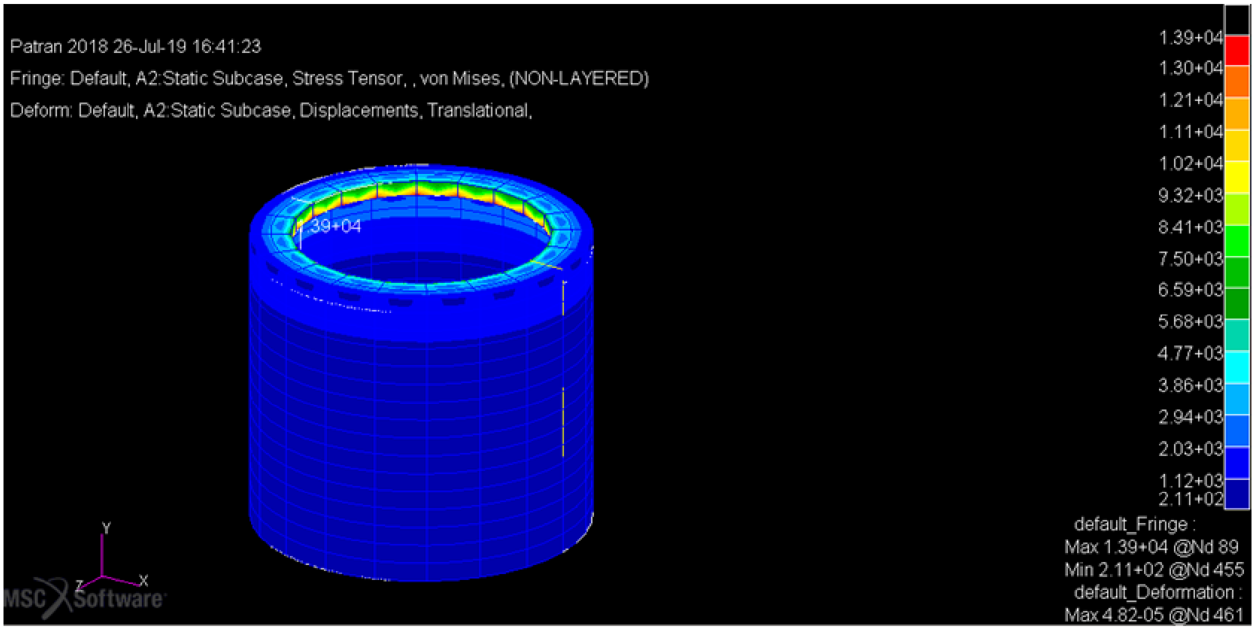
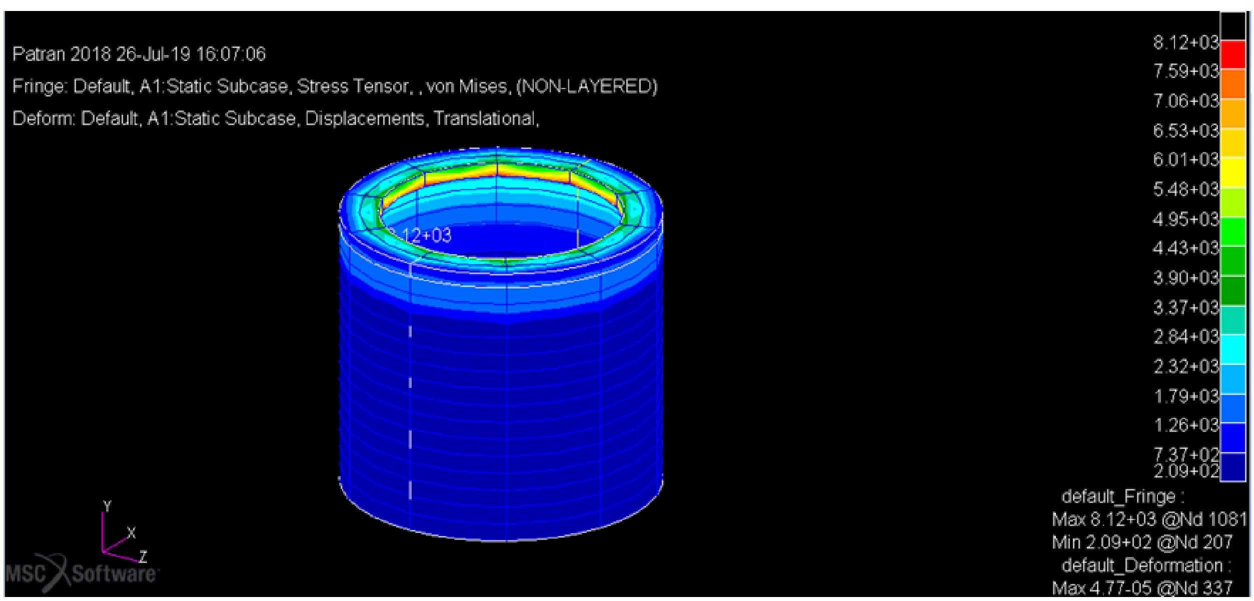


Cylinder (Hex20, 340 elements)



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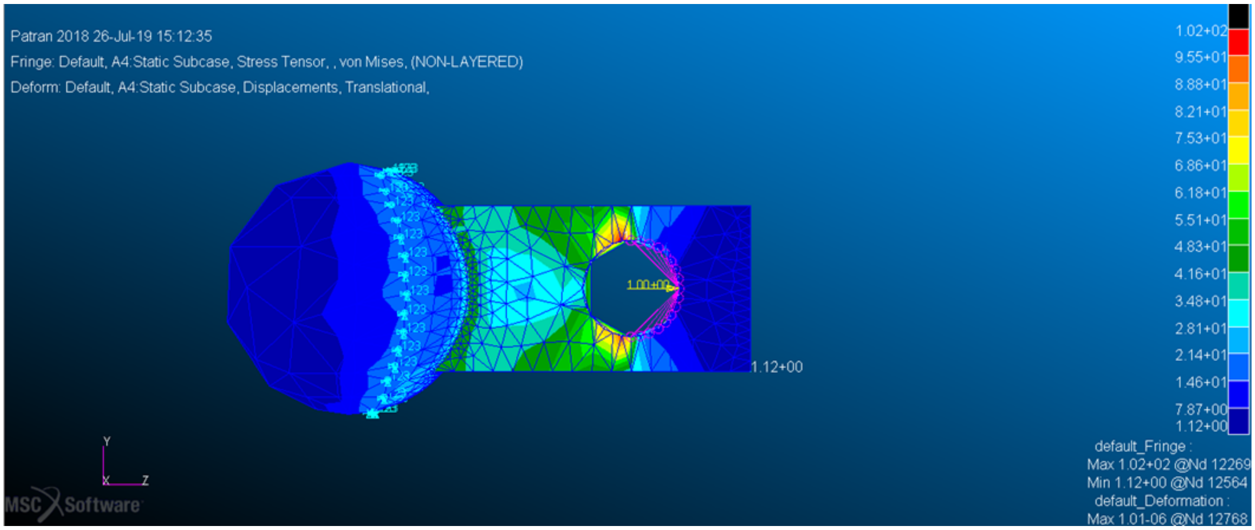
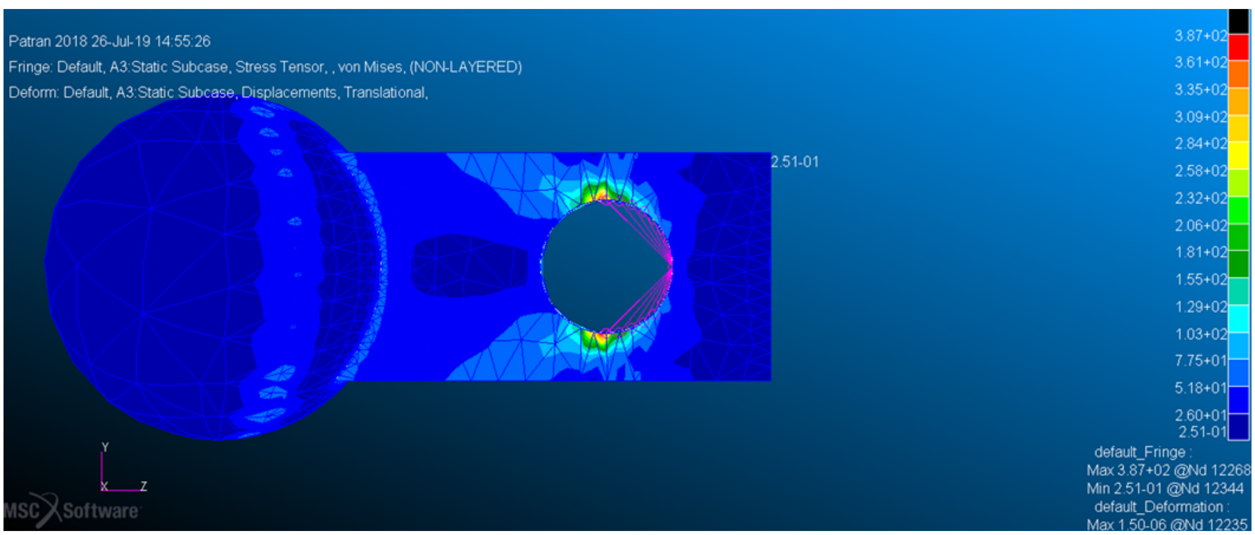


Ball Joint (Tet4)



Ball Joint (Tet10)

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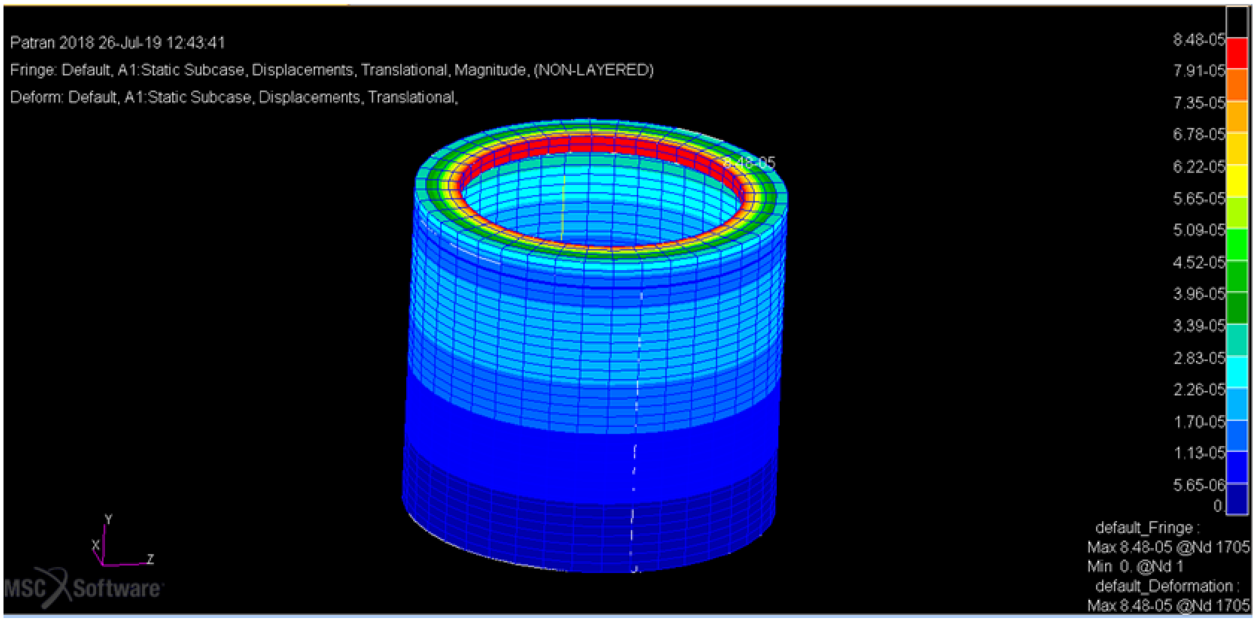
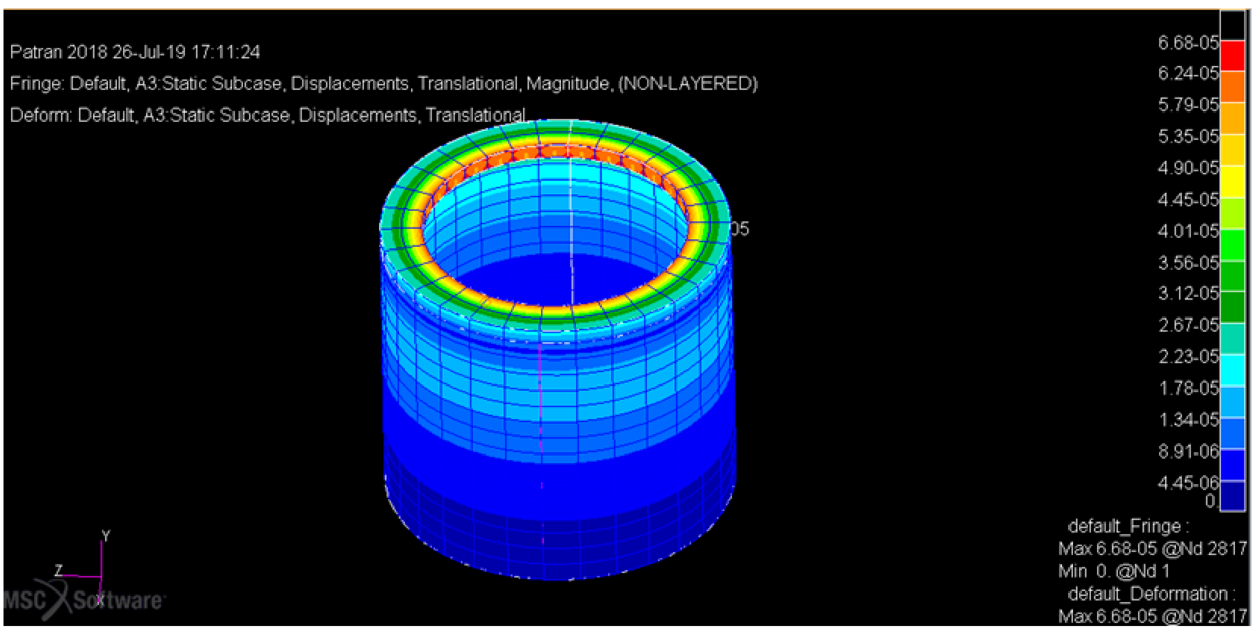
Displacements:



Cylinder (Hex8, 4223 elements)



Cylinder (Hex20, 510 elements)

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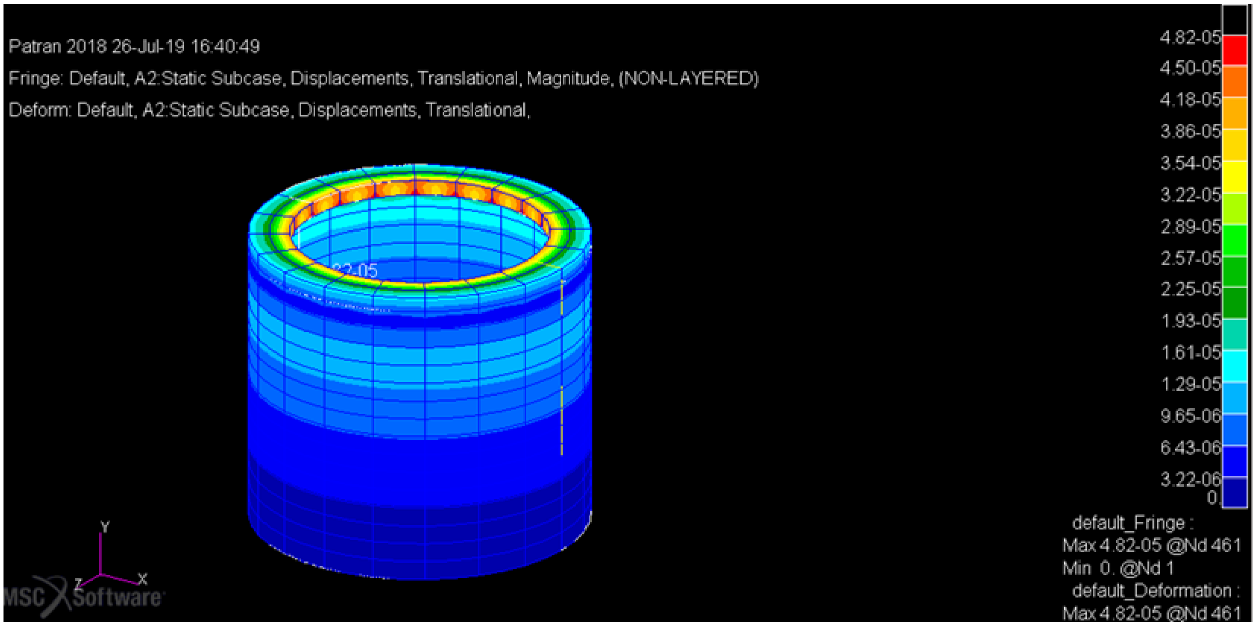
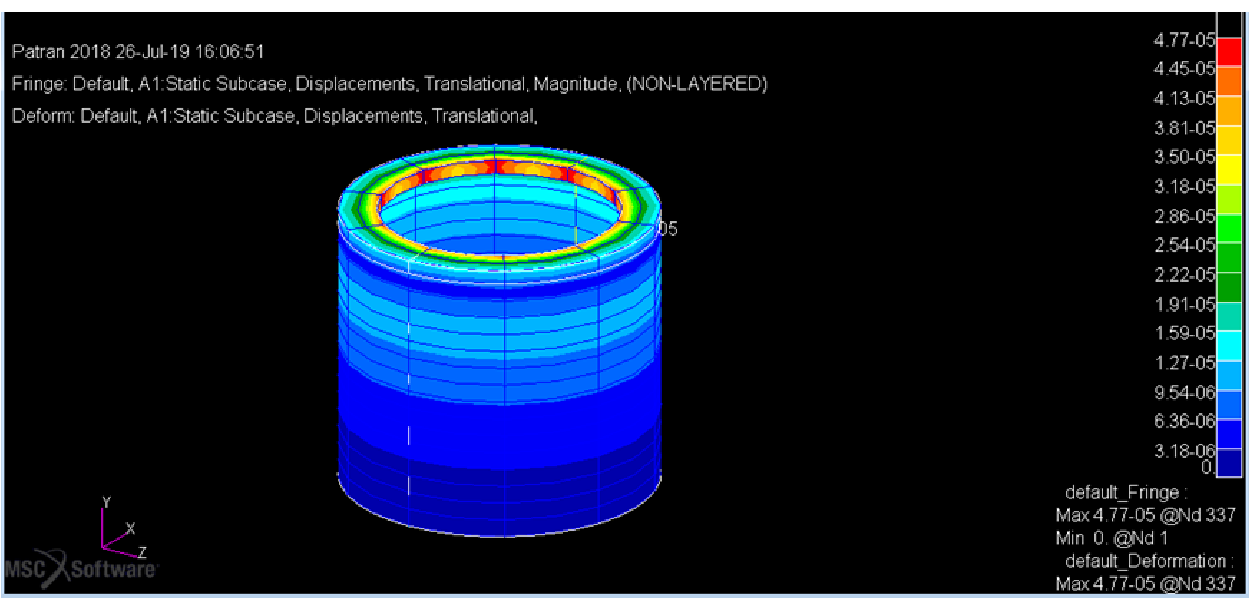


Cylinder (Hex20, 340 elements)



Cylinder (Hex20, 178 elements)

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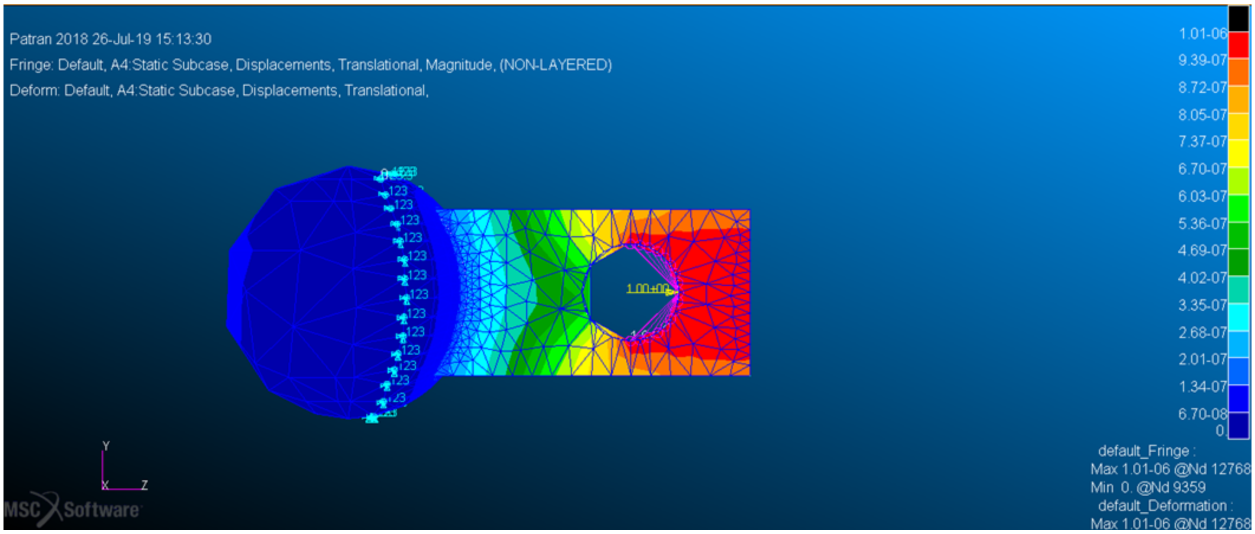
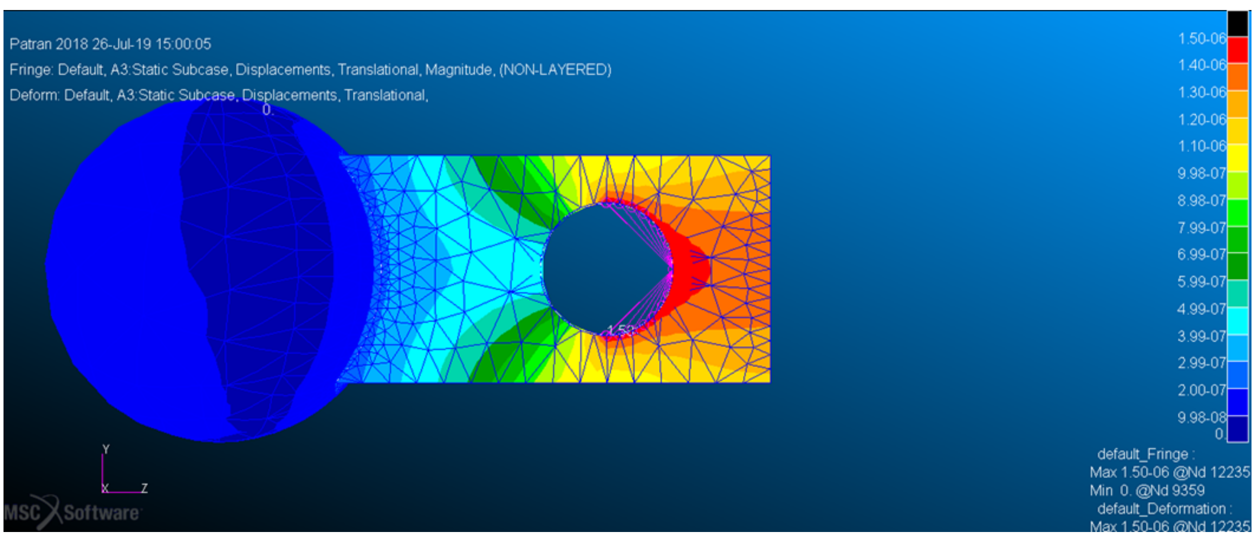


Ball Joint (Tet4)



Ball Joint (Tet10)

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A-4: Reference Area, Reference Stress, & Stress Concentration Factor

Case	Reference Area (A_{Ref}) (sq in)	Force (F) (lbs)	Reference Stress (σ_{Ref}=F/A_{Re}) (psi)	FEA Stress (σ_{Max}) (psi)	Concentration Factor (K=σ_{Max}/σ_{Ref})	Notes
Cylinder 1	.043	40	920	12000	13	Base of Cylinder chosen as reference area.
Cylinder 2	.043	30	690	18400	27	
Cylinder 3	.043	20	460	13900	30	
Cylinder 4	.043	20	460	8120	18	
Ball Joint 1	.0116	1	86.2	102	1.18	Cross Section across hole chosen as reference area.
Ball Joint 2	.0116	1	86.2	387	4.49	