



Ministry
of Defence



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EXPLORING A BALISTIC PROBLEM WITH COMPUTATONAL MODELING

References. See footnotes and references section 9.

Abstract

The intent of this report is to demonstrate that the student has fully explored a ballistic impact scenario and developed an understanding of the Abaqus Toolset. To this effect it details a credible scenario on a bullet impacting a target plate, exploring when and how the plate fails as well as different aspects of modelling techniques.

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2. Introduction and Background

This report will explore a ballistic impact model via Finite Element Analysis (FEA) using Abaqus. The aim of this report is to demonstrate how a particular type of bullet penetrates a target plate in relation to principle and shear stress.

xxx

7.62mm x 39mm is a popular calibre in ex-soviet states as the availability of AK-47's and ammunition is widespread. For a cruise missile low flying following through ex-soviet states this is a likely event that could pose a threat to the weapon system.

The chosen problem that this report will consider is the impact of a subsonic 7.62mm x 39mm round on a low flying cruise missile. This will be modelled with a representative round impacting an aluminium plate. The aluminium plate is assumed to be representative of a cruise missile external structure as data surrounding these missiles is sensitive. The data achieved from models such as the ones in this report can be used to evaluate the effectiveness of a missiles protective structure at low altitude against ground threats.

4. Model 1

4.1. Model 1: Geometry

The model provided by the lecturer as an example is a basic example to clearly demonstrate the principles of modelling.

The plate is a 0.30m x 0.30m x 0.035m square Plate. The projectile is a basic 'Bullet' shape with a diameter of 0.07m (70mm) and a length of 0.096m (96mm). This geometry is similar to that of a CRV 7 Rocket Tip.

4.2. Model 1: Mesh

Plate: The original example provided has a basic 0.005m global mesh size with a Hex mesh. This mesh is suitable for the simplicity of the model and is a comparable size to the projectile.

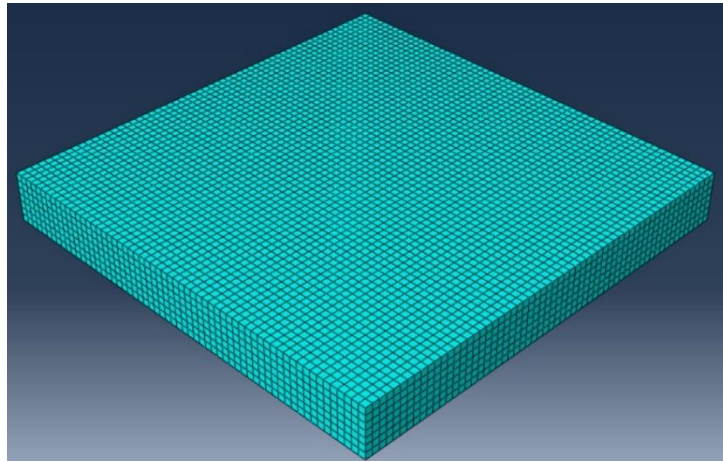


Figure 1 - Model 1 Plate Mesh

Projectile: Like the plate the projectile has a 0.01m Global Mesh size with a Tet Mesh. A Tet mesh was used here due to a Hex Mesh not being able to conform to the shape.

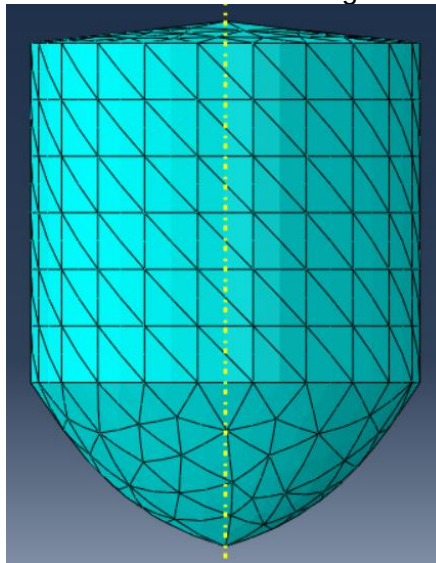


Figure 2 - Model 1 Projectile Mesh

4.4. Model 1 – Materials

Below are the material properties that have been used in the lecturer's example model. This details a simple model for the steel projectile and a more accurate model for aluminium. It is assumed that this is to reduce the computing time and likelihood of errors in the model.

Material	Steel [1]	Aluminium
Density (kgm^{-3})	7860	2699
Young's Modulus (Pa)	210000000000	680000000000
Poisson's Ratio	0.3	0.36
Johnson Cook		
A (Pa)	Not Used	324100000
B (Pa)		113800000
N		0.42
M		1.34
Melting Temp (°C)		900
Transition Temp (°C)		293
C		
$\epsilon_0 (s^{-1})$		
D1		-0.77
D2		1.45
D3		0.47
D4		0
D5		1.6
Reference Strain Rate		1
Damage Evolution		
Fracture Energy		0

Table 1 - Model 1 Materials

4.5. Model 1 Simulation Results¹

At the initial impact step, the bullet has already caused a significant amount of damage to the plate with a large depression being visible in Figure 7. In the next few steps, the stress wave is visible as the colours show a tensile stress along the edges of the plate and on the back side of the impact location. This is common with such a large projectile as the transferred kinetic energy wants to 'scab' off material from the back side of the plate, this phenomenon is known as spalling. As the steps of this model progress in Annex A the compressive stress can be seen to develop in front of the projectile with a large tensile stress on the back surface in a ring pattern. Once the ultimate tensile stress of the material is breached, we observe slight fragmentation on the back of the target and a release of stress in the material.

This simple model demonstrates how a basic ballistic impact can be modelled and is what the next two models are based upon. This model has a large quantity of nodes within the target plate that are not affected by the projectile, this wastes computing time for no material gain. The size of the projectile is large compared to the chosen scenario.

¹ The full results for this model can be found at Annex A

5. Model 2

5.1. Model 2: Geometry

The projectile in this model was designed to imitate the basic geometric characteristics of a standard 7.62mm x 39 mm Bullet [2]. See Figure 3 below. This model has no delineation between the inner and outer parts of the standard round and has been created in the Abaqus tool.

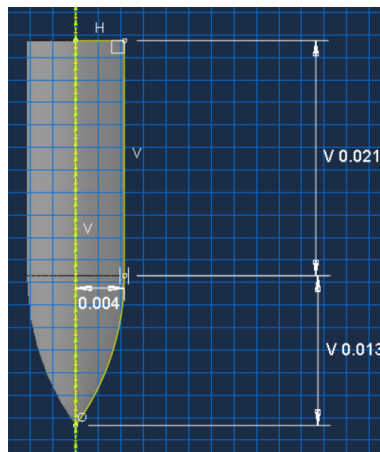


Figure 3 - Model 2 Projectile Dimensions

As the dimensions of the projectile were greatly reduced it was also appropriate to resize the target plate to 0.1m x 0.1m x 0.02m which is subdivided into quarters to allow biased meshing.

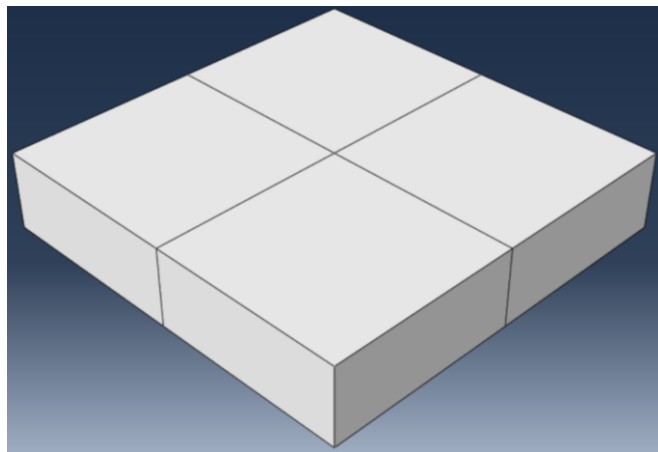


Figure 4 - Model 2 Plate

5.2. Model 2: Mesh

Projectile: As the shape of the projectile narrows down to a point it forces a Tet mesh to become finer towards the point hence it was determined that a bias on the projectile was not needed. Instead a simple 0.005m Global Seeded mesh was used.

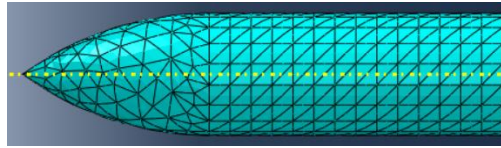


Figure 5 - Model 2 Projectile Mesh

Target Plate: Using the partitions created in the target plate model a biased seed was created that graduated towards the centre on both the top and bottom surfaces. This seed was biased from 0.007m on the edge to 0.001m in the centre. The remaining edges were globally seeded to 0.005m. The resultant is the mesh below in Figure 6. This mesh greatly improves on the one used in model 1 as it provides a finer density where the projectile will impact leading to a more efficiently used computing time.

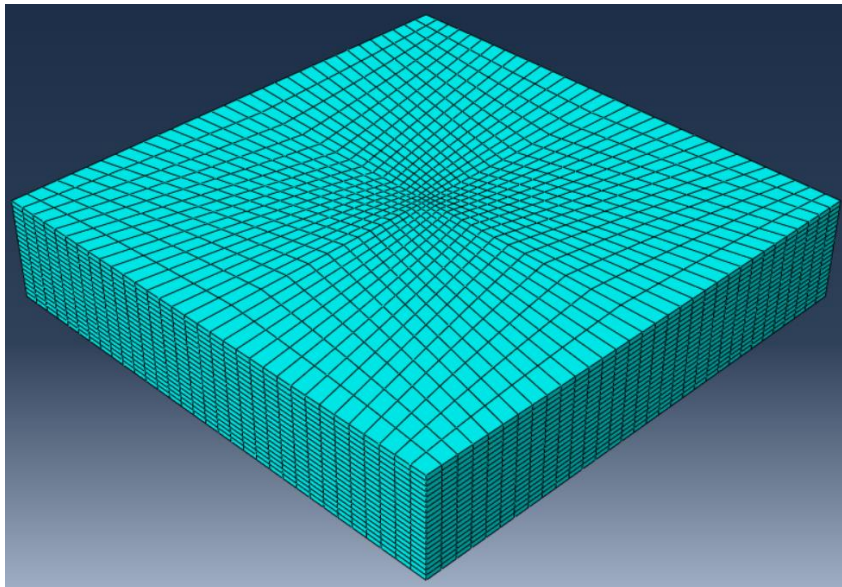


Figure 6 - Model 2 Target Plate Mesh

5.3. Model 2 and 3 Materials

From the initial material model new material properties were introduced one at a time to. This allowed the creation of bespoke geometry and modification of the models with the assurance that the material models were likely functional and correct.

The materials chosen for this model were 7075 Aluminium for the target plate and an alloy steel for the projectile.

7075 Aluminium is commonly used in the aviation industry as it is a high strength material that can be used in structural parts. This material is often also used in Missile bodies and hence is applicable to defensive capabilities in this capacity. [3]

In addition to this a solid steel projectile was determined to be the most appropriate material as although a solid steel 7.62mm projectile is an unlikely threat it presents the worst-case scenario for credible threats to a low flying missile. In addition to this a solid steel projectile was determined to be suitable for the capability of modelling at this stage.

Below is the material model used for both Model 2 and 3.

Material	Steel [1]	AA 7075 [4]
Density (kgm^{-3})	7860	2700
Young's Modulus (Pa)	210000000000	700000000000
Poisson's Ratio	0.3	0.30
Johnson Cook		
A (Pa)	304330000	520000000
B (Pa)	422007000	477000000
N	0.345	0.52
M	0.87	1.00
Melting Temp ($^{\circ}k$)	1800	893
Transition Temp ($^{\circ}k$)	293	293
C	0.0156	
ϵ_0 (s^{-1})	0.0001	
D1	0.1152	-0.77
D2	1.0116	1.45
D3	-1.7684	0.47
D4	0	0
D5	0.5262	1.6
Reference Strain Rate	1	1
Damage Evolution	0	
Fracture Energy	0	0

Table 2 – Model 2 and 3 Materials

5.4. Model 2 Simulation Results²

To best evaluate a few different simulation scenarios varying velocities were chosen with two different impacting angles to understand how the plate might fail.

300 mps³

The initial model that was run was a perpendicular central impact at 300 mps. Initially a tension wave can be observed in front of the projectile as it impacts. As the projectile penetrates further, energy transfer is observed in Figure 15 where significant compression around the projectile is visible. The tension wave can also be seen impacting the back side of the plate causing stretching and deformation. After this last step the round stops and starts bouncing back out leaving the crater in its place. The round does not penetrate the target.

400 mps³

Must like the 300 mps impact, initially compression can be seen at the tip of the projectile with a corresponding tension wave in front. This is best demonstrated in Figure 19 – Model 2, 400mps, Step 2Figure 19. The start of the max tension can also be seen on the back surface of the plate. As the projectile moves forward it overcomes the UTS of around 500 MPa of the plate and breaks the surface. The projectile penetrates the plate.

350 mps at a 45 degree central impact element deletion

As an exactly perpendicular impact is unlikely, a 45-degree impact was modelled. In these two simulations the difference between element deletion and non-deletion is demonstrated. From Figure 23 to Figure 43 this impact demonstrates how the stress develops under the round causing it to begin to penetrate and then deflect due to the shape of the bullet. In addition to this a large shear stress can be observed initially within the bullet and then within the plate. This indicates that the bullet is likely to deform before penetrating further in reality.

350 mps at a 45 degree central impact mass conservation

This simulation is the same as the previous simulation apart from element deletion being turned off, this allows for the conservation of mass. Figure 44 to Figure 64 show the bullet impacting and the aluminium deforming around the projectile as it impacts. These results show that with the conservation of mass the bullet impacts and stops faster than without mass conservation. Providing further evidence to the efficacy of the aluminium plate.

6. Model 3

A third model and simulation were successfully conducted building upon the developments of model 1 and 2. Unfortunately due to the limitations of the report and task the details of this model can be found at Annex C

² The full results for this model can be found at Annex B.

³ Element Deletion is active, and conservation of mass is ignored.

8. Conclusion

In conclusion the models developed clearly demonstrate a ballistic problem and begin to explore the efficacy of aluminium plate against a likely threat of a 7.62mm x 39mm for the given scenario. In all simulations the results show how the bullet impacts the plate and how the stress within the plate and projectile develops. These simulations also show the limitations of computational modelling as decisions and assumptions must be made to allow for efficiency and workflow. This demonstrates the importance of physical trials alongside the simulations. The 3rd model takes the lessons of the first two and develops a more accurate scenario with the intent of a realistic impact showing the classic results of the copper jacket being shed and a steel core penetrating through. Unfortunately, due to time limitations this was not chosen to be developed further.

9. References

- [1] D. E. T. a. R. Trebinski, "ON THE INFLUENCE OF FRACTURE CRITERION ON PERFORATION OF HIGH-STRENGTH STEEL PLATES SUBJECTED TO ARMOUR PIERCING PROJECTILE," *Archive of Mechanical Engineering*, vol. LXII, no. 2, pp. 157 - 179, 2015.
- [2] J. K. Holmen and T. Borvik, "Ballistic impact of layered and case-hardened steel plates," *International Journal of Impact Engineering*, no. 1, 2017.
- [3] MatWeb, "Aluminium 7075-T6;7075-T651," MatWeb, [Online]. Available: <https://www.matweb.com/search/DataSheet.aspx?MatGUID=4f19a42be94546b686bbf43f79c51b7d>. [Accessed 29 04 2023].
- [4] E. Flores-Johnson, L. Shen, I. Guimatsia and G. Nguyen, "Numerical investigation of the impact behaviour of bioinspired nacre-like aluminium composite plates," *Composites Science and Technology*, vol. 96, no. 1, pp. 13-22, 2014/05/01.

10. Annex A: Model 1 Results⁴

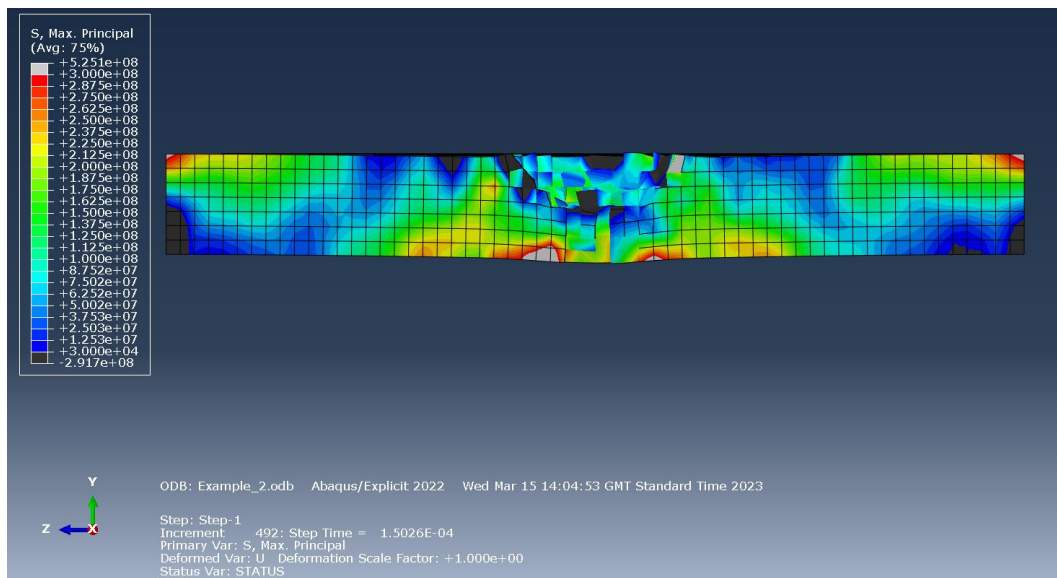


Figure 7 – Model 1, Step 1

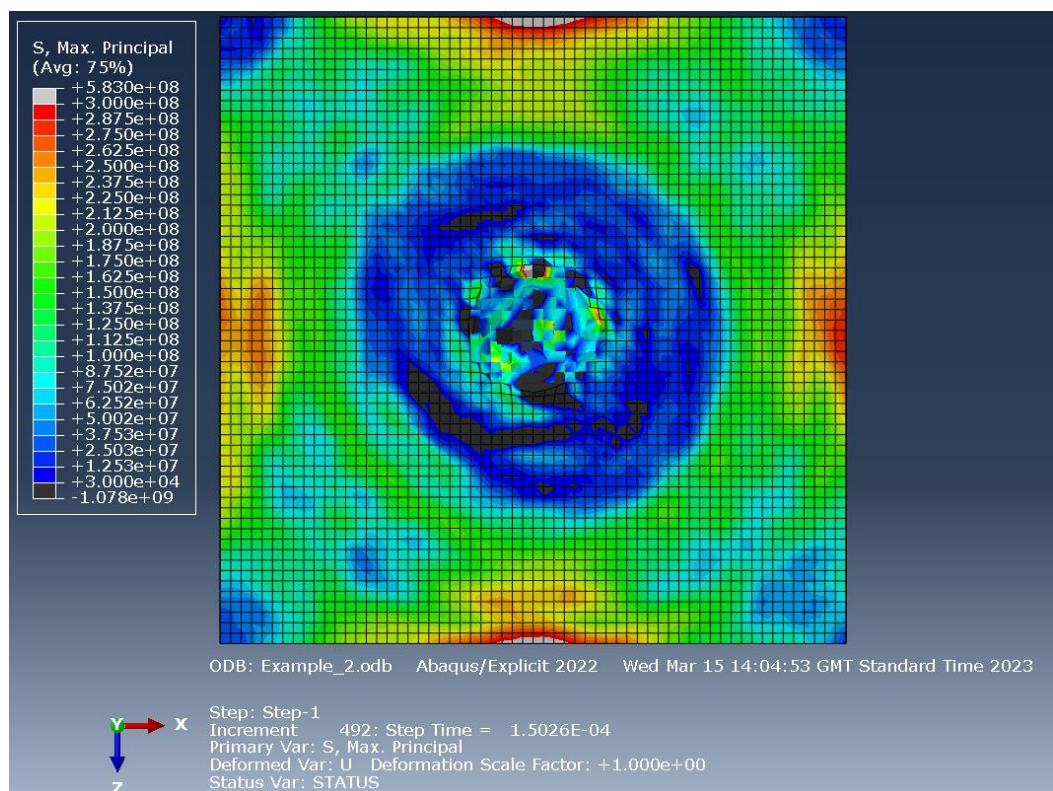


Figure 8 – Model 1, Step 2

⁴ Note; Projectile is hidden.

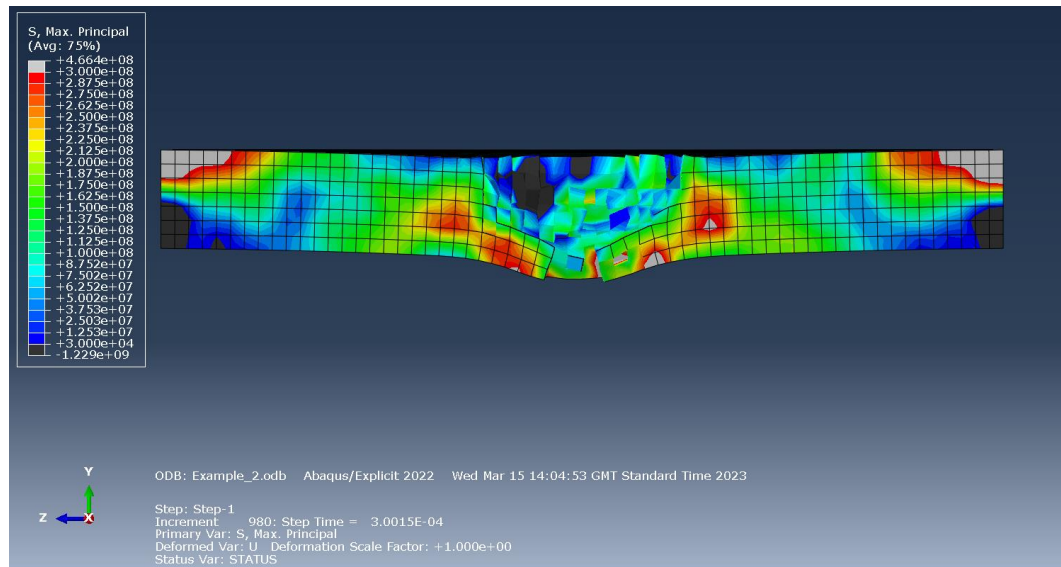


Figure 9 – Model 1, Step 3

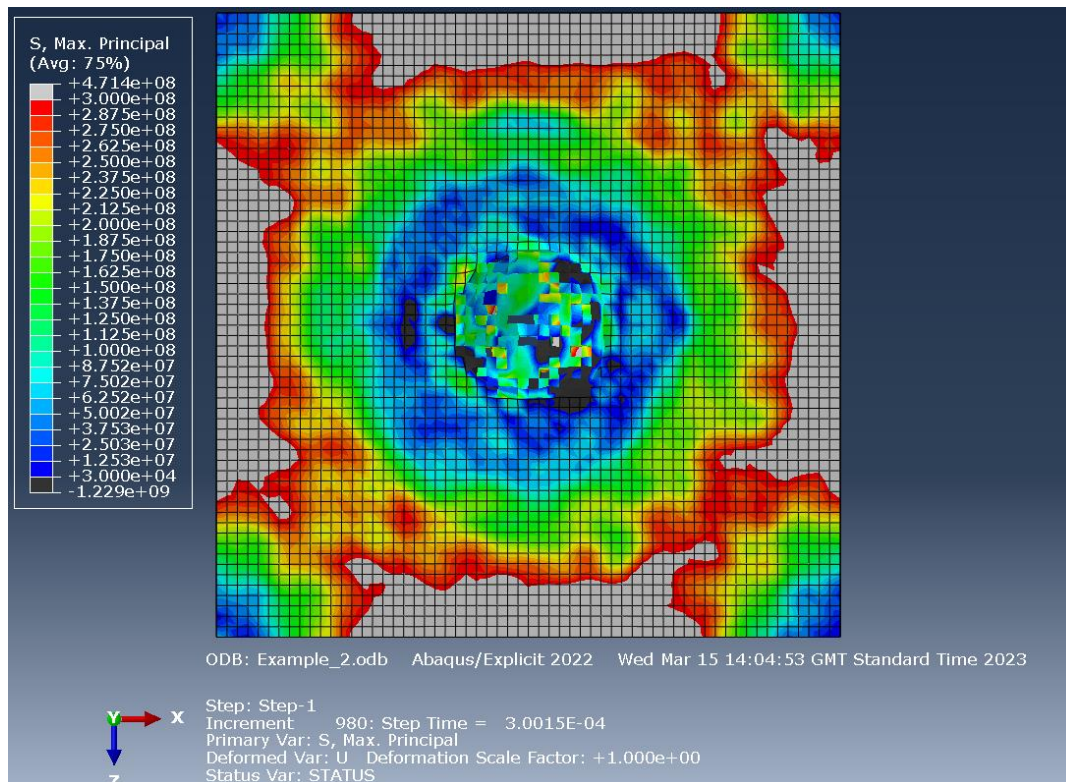


Figure 10 – Model 1, Step 3, Below

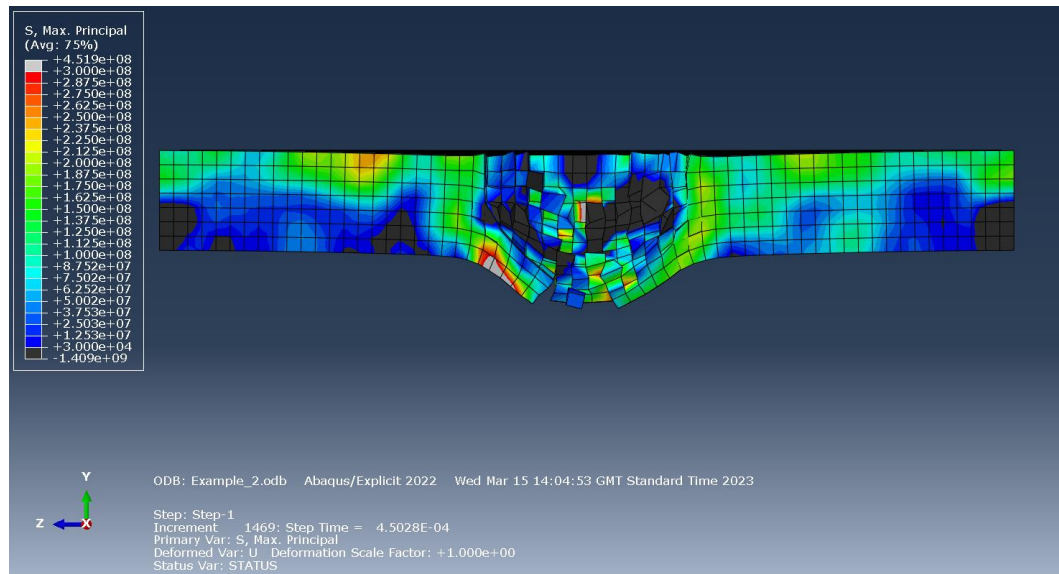


Figure 11 – Model 1, Step 4

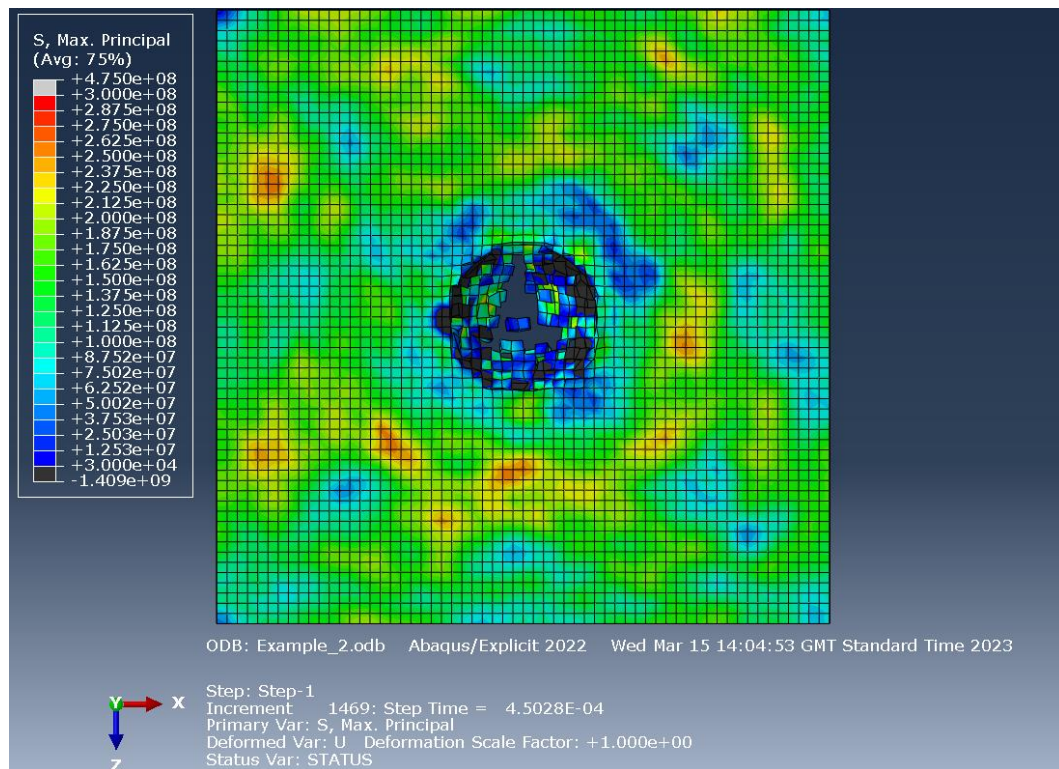


Figure 12 – Model 1, Step 4, Below

11. Annex B: Model 2 Results

11.1. 300mps Delete

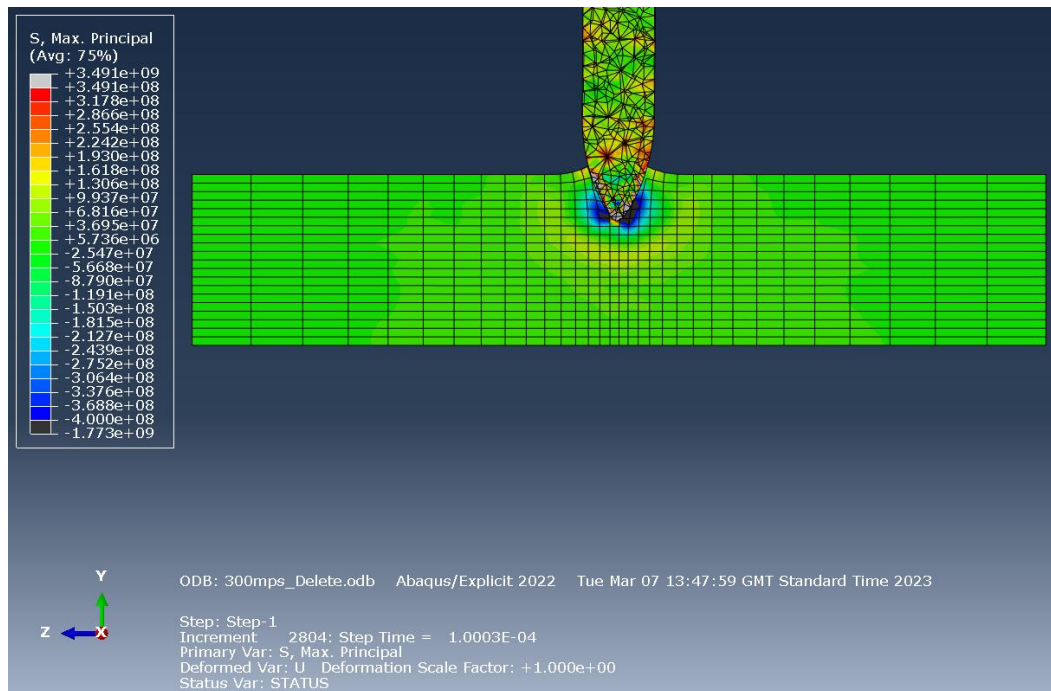


Figure 13 – Model 2, 300mps, Step 1

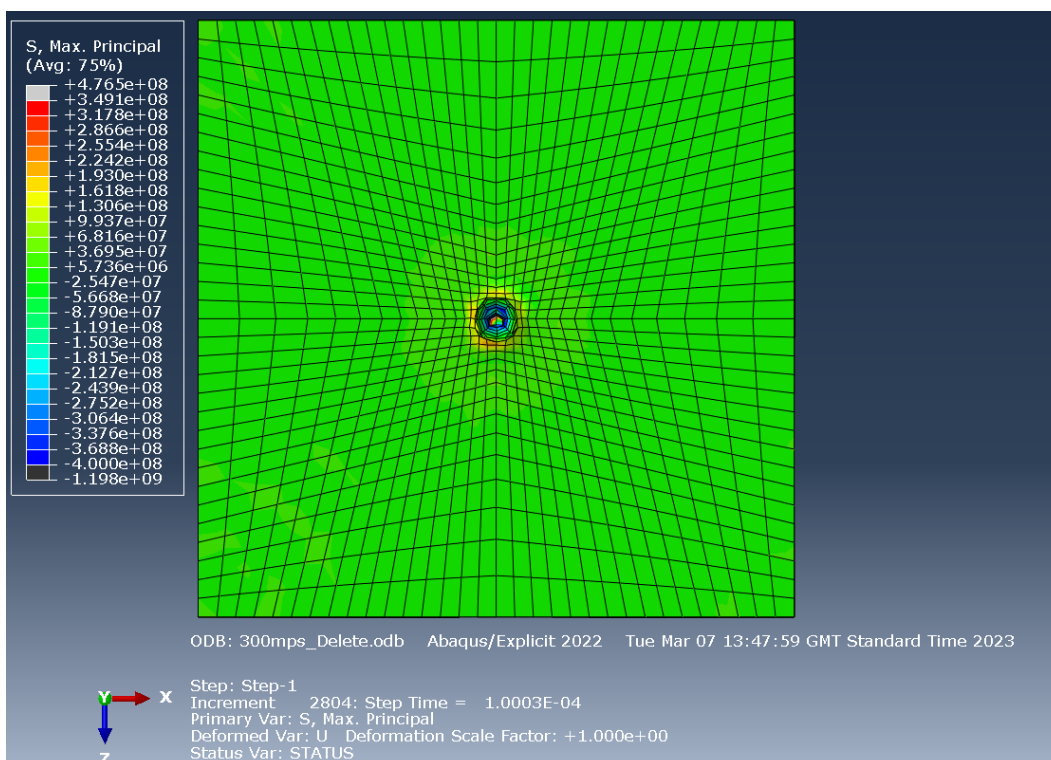


Figure 14 – Model 2, 300mps, Step 1, Top

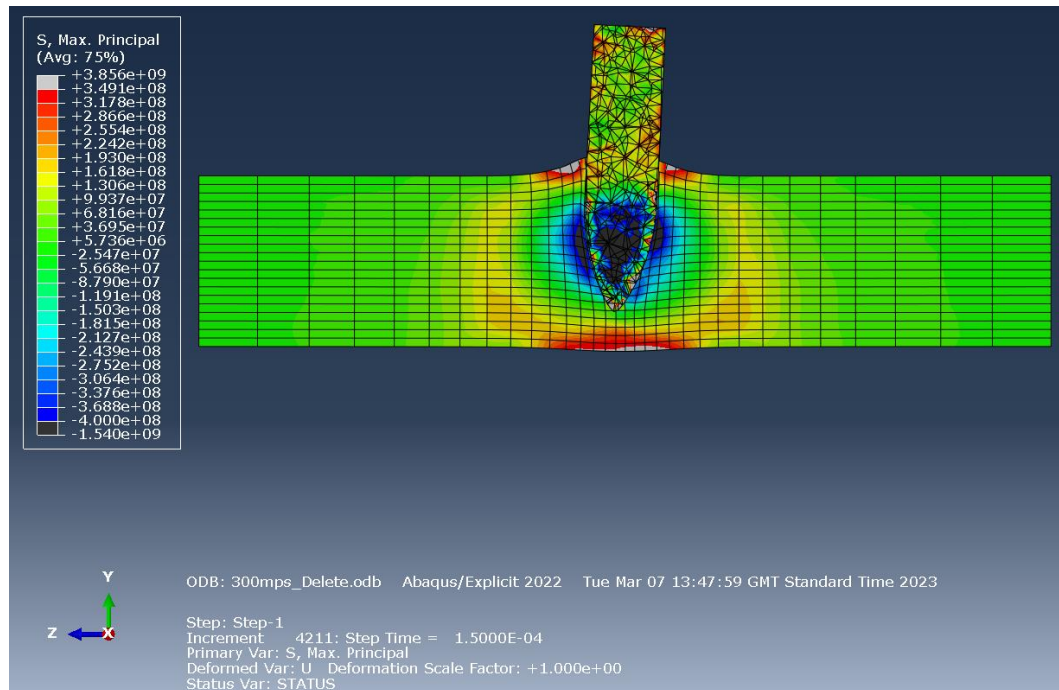


Figure 15 – Model 2, 300mps, Step 2

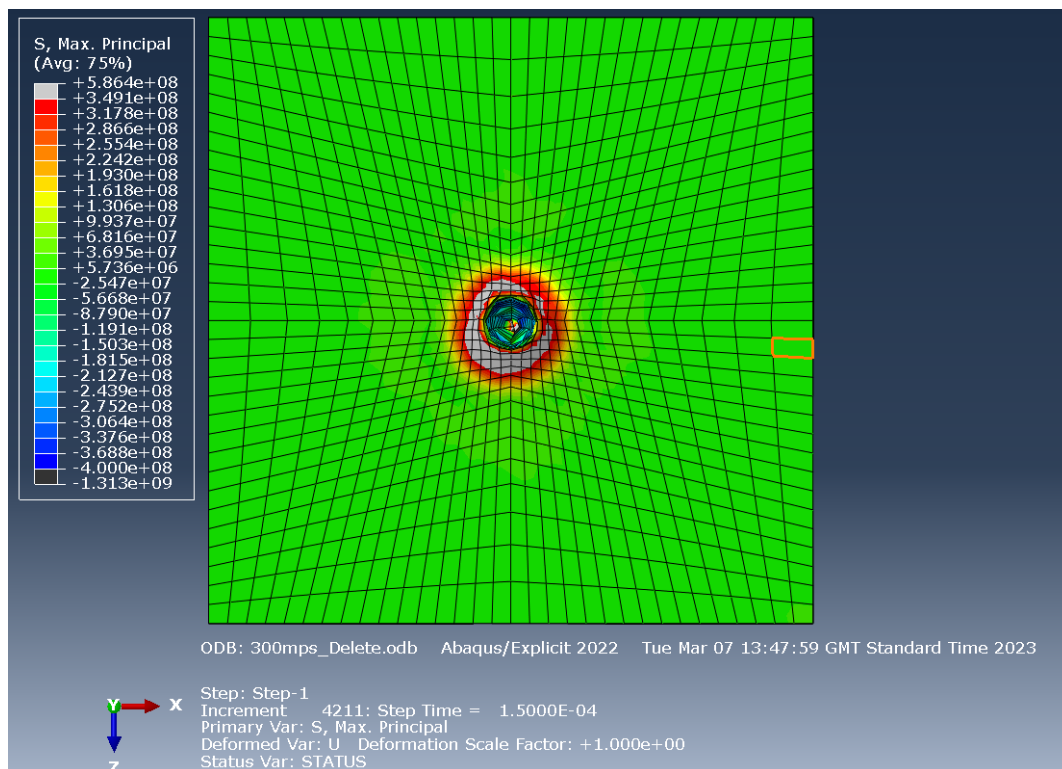


Figure 16– Model 2, 300mps, Step 2, Top

11.2. 400mps Delete

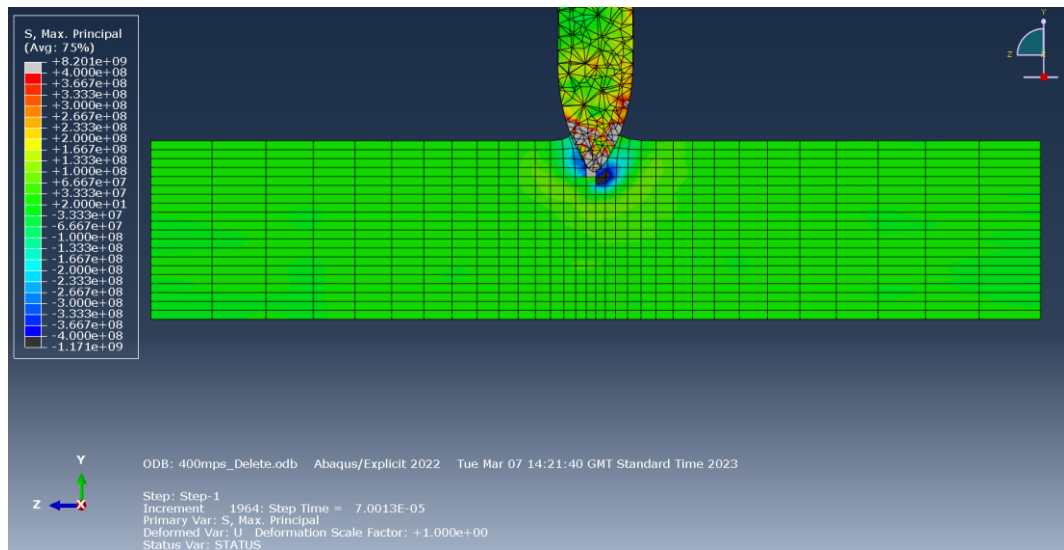


Figure 17 – Model 2, 400mps, Step 1

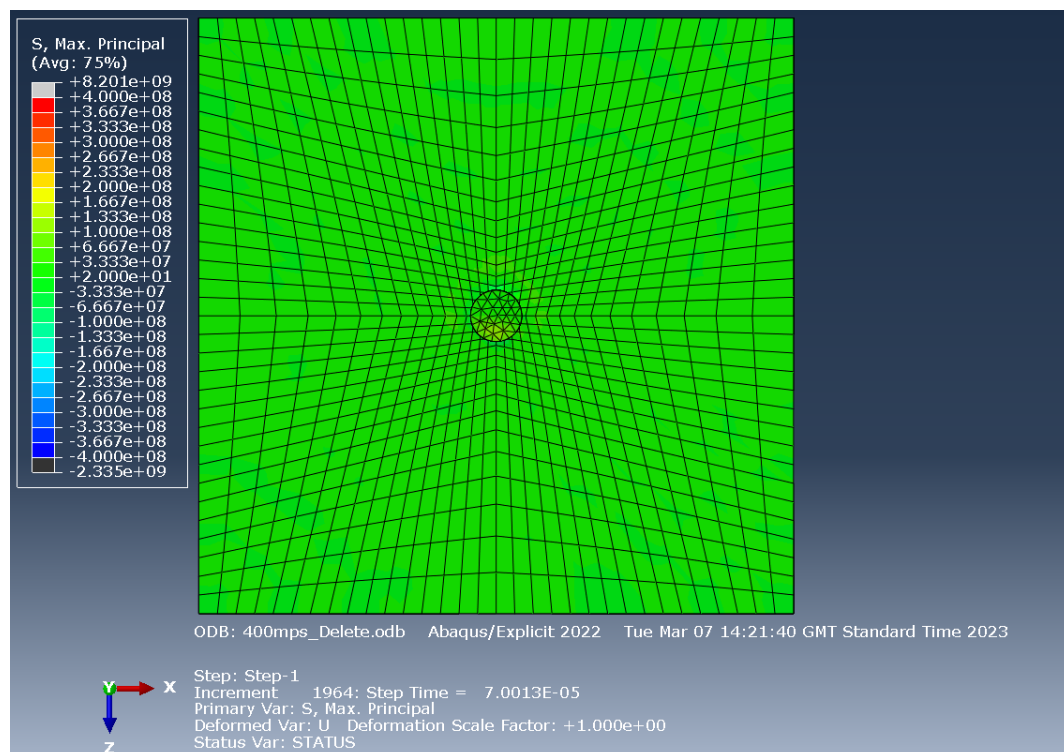


Figure 18 – Model 2, 400mps, Step1, Top

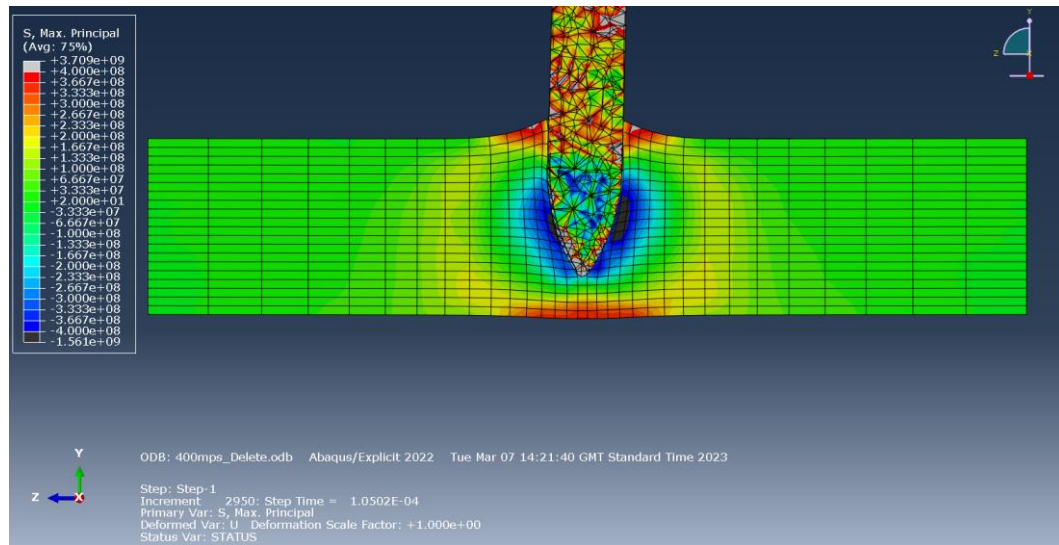


Figure 19 – Model 2, 400mps, Step 2

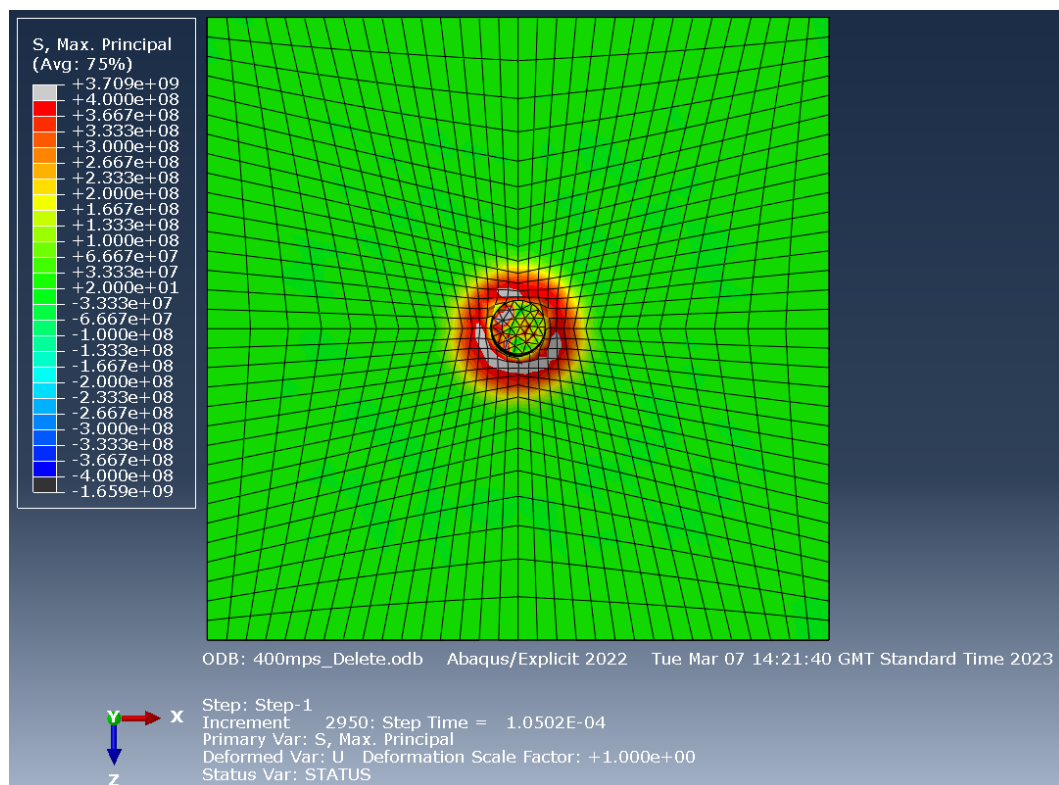


Figure 20 – Model 2, 400mps, Step 2, Top

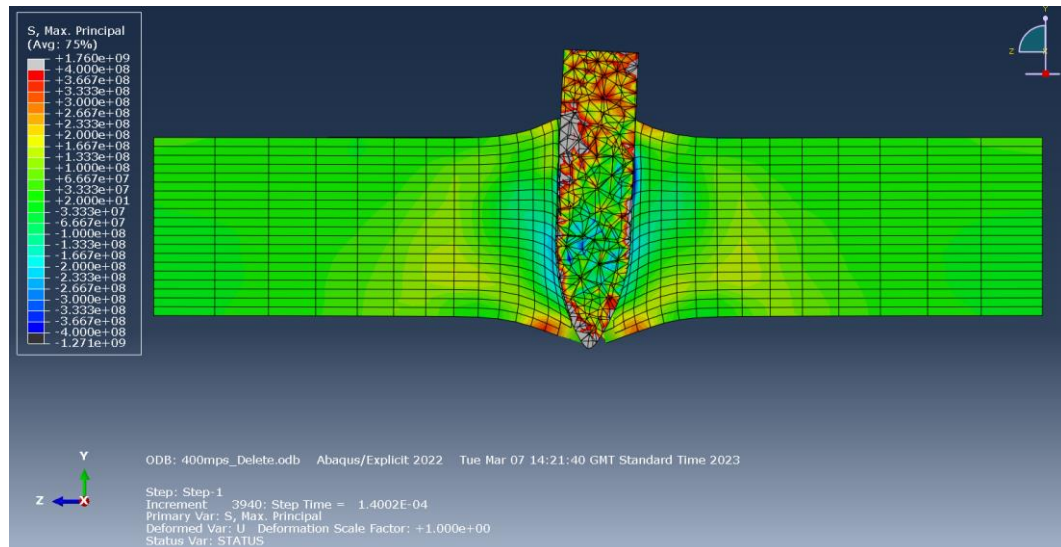


Figure 21 – Model 2, 400mps, Step 3

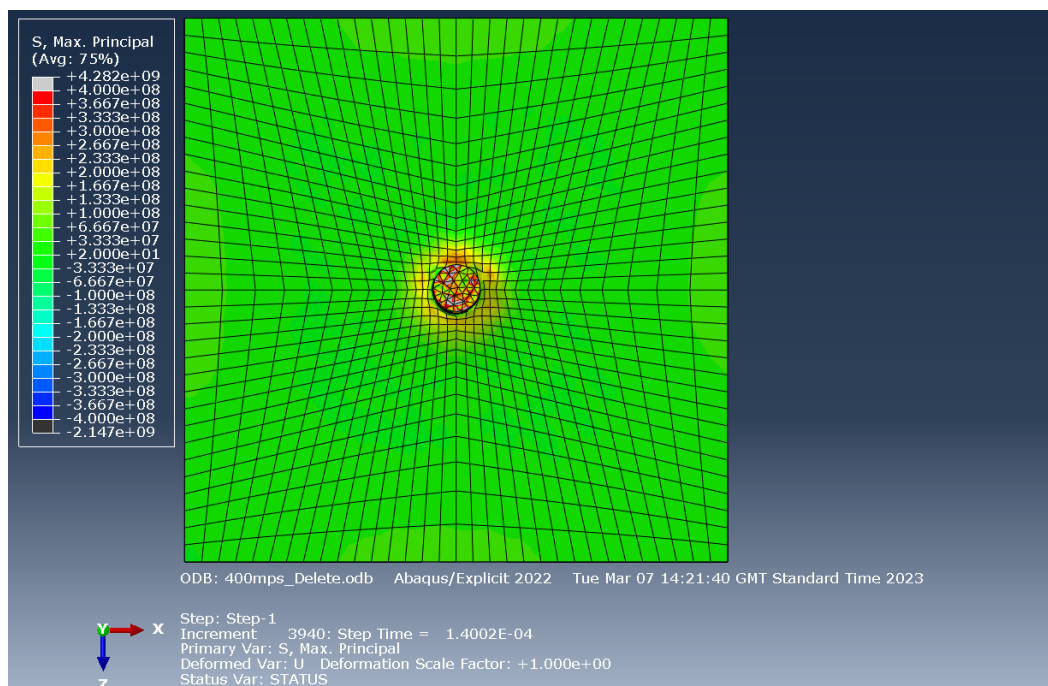


Figure 22 – Model 2, 400mps, Step 3, Top

11.3. 350mps at 45 delete

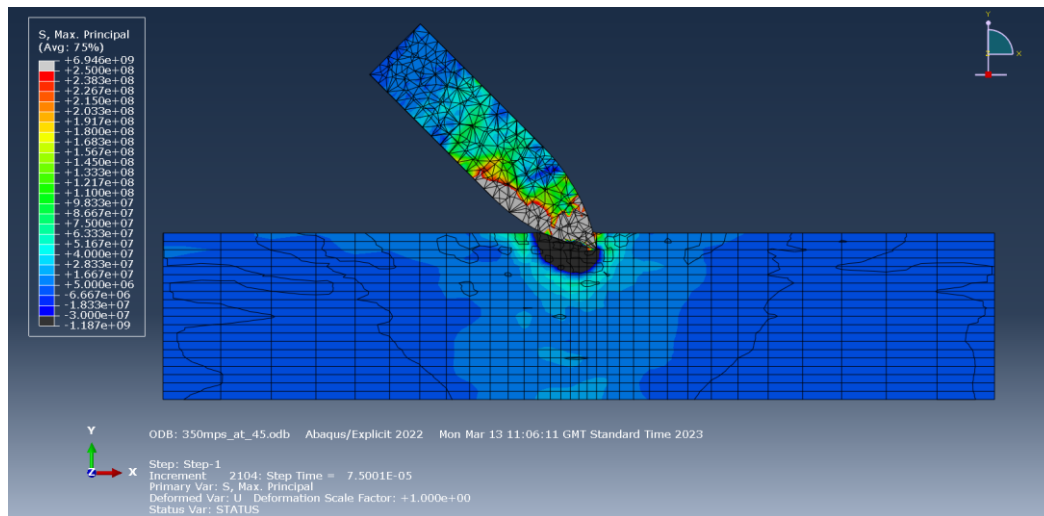


Figure 23 – Model 2, 350mps @ 45, Step 1

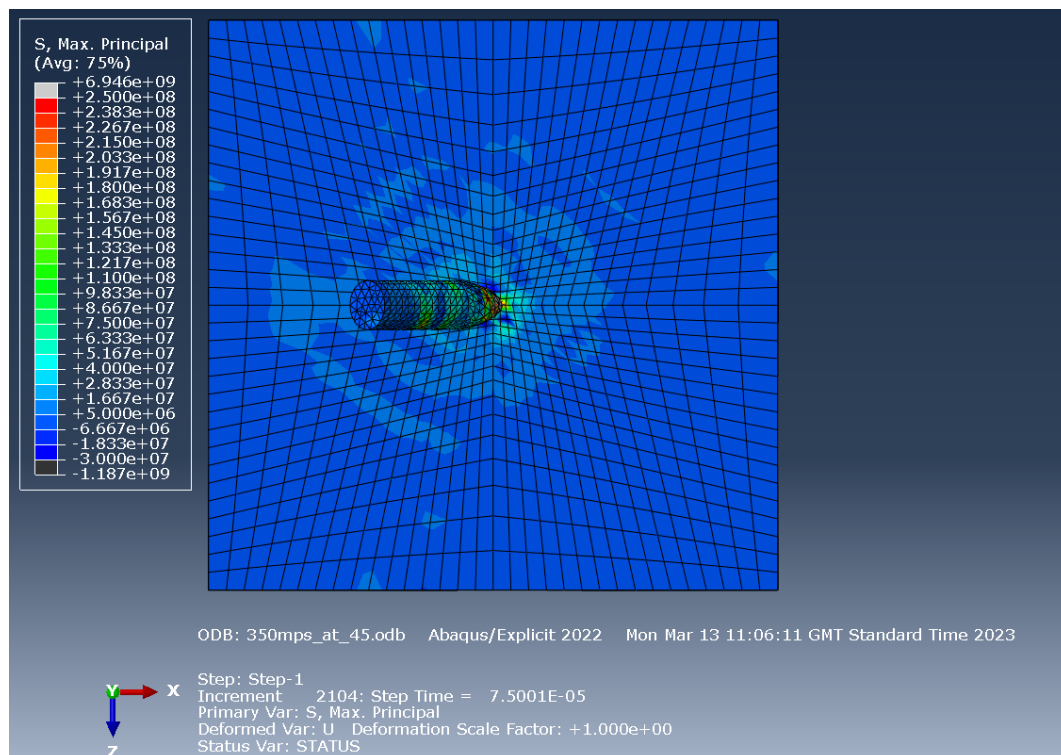


Figure 24 – Model 2, 350mps @ 45, Step 1, Top

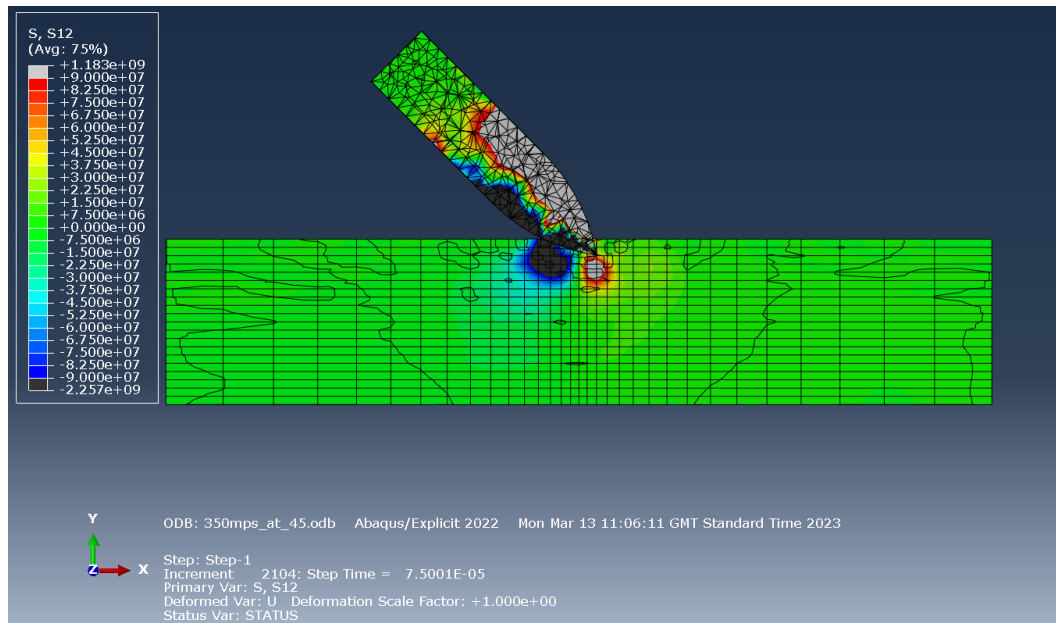


Figure 25 – Model 2, 350mps @ 45, Step 1, Shear

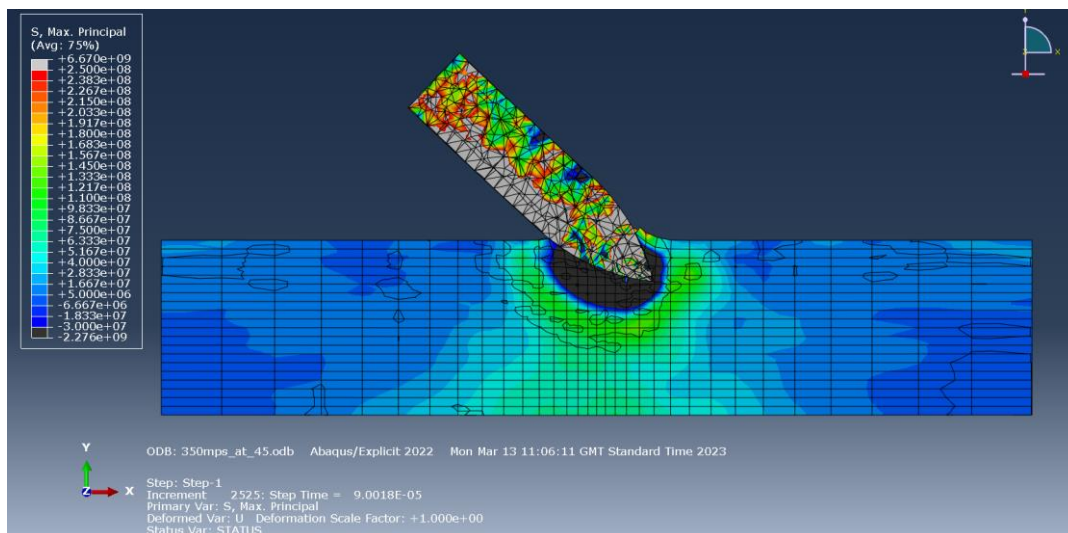


Figure 26 – Model 2, 350mps @ 45, Step 2

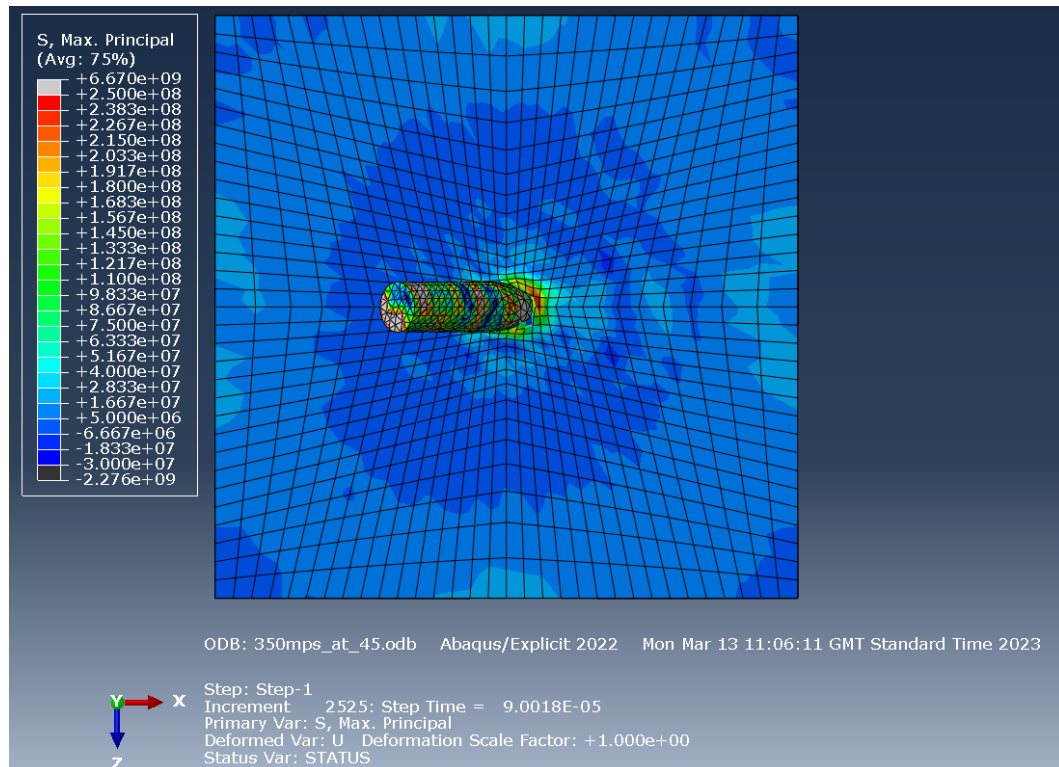


Figure 27 – Model 2, 350mps @ 45, Step 2, Top

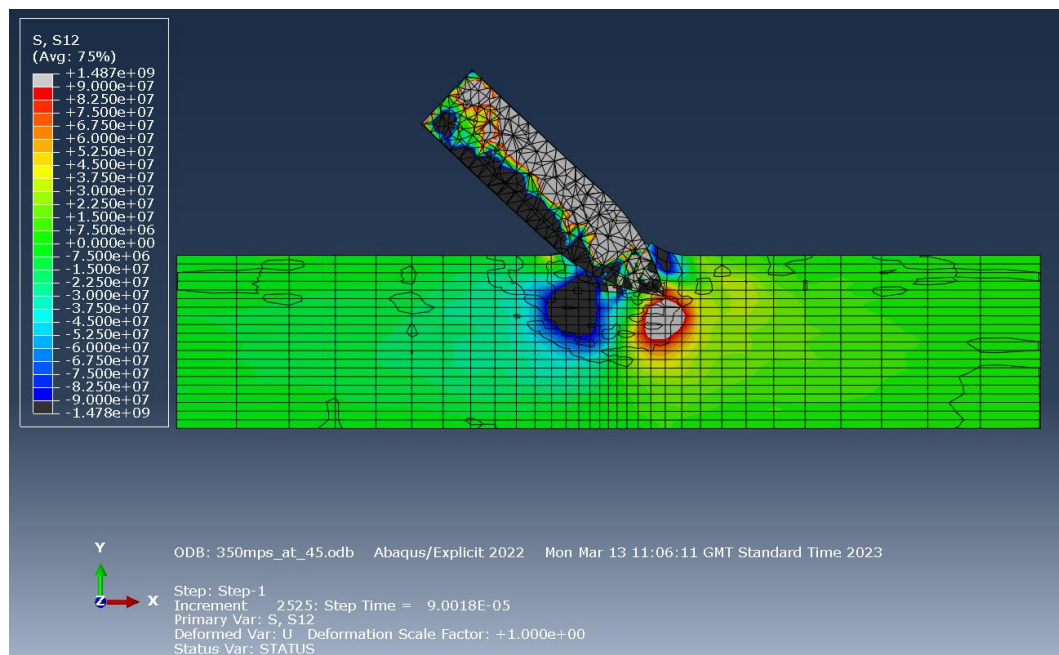


Figure 28 – Model 2, 350mps @ 45, Step 2, Shear

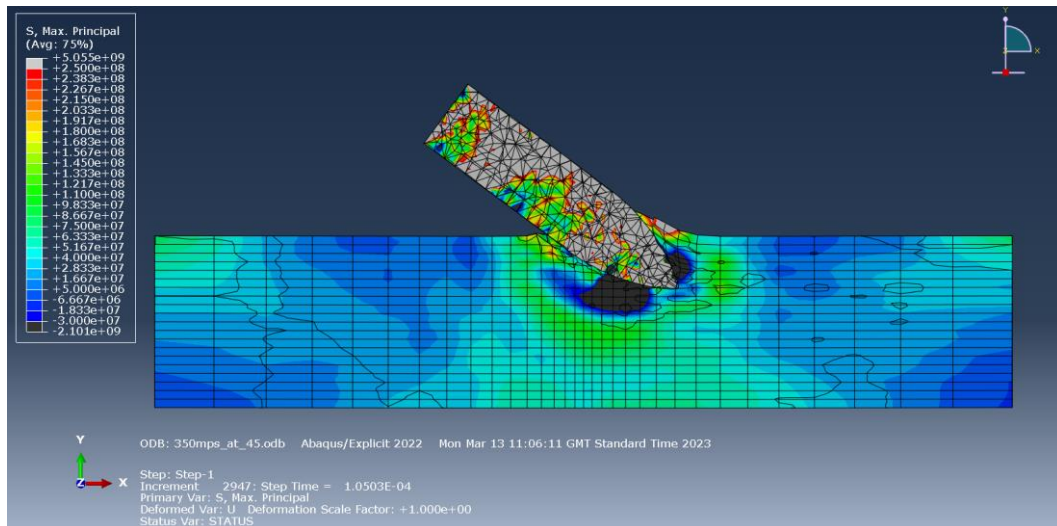


Figure 29 – Model 2, 350mps @ 45, Step 3

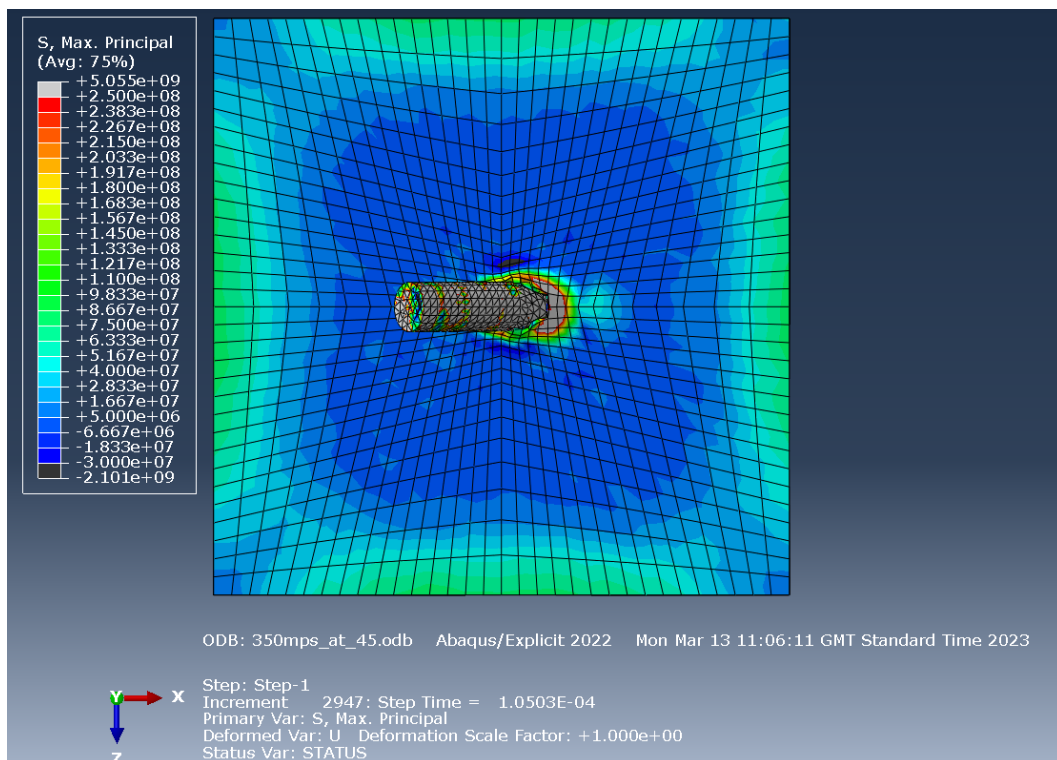


Figure 30 – Model 2, 350mps @ 45, Step 3, Top

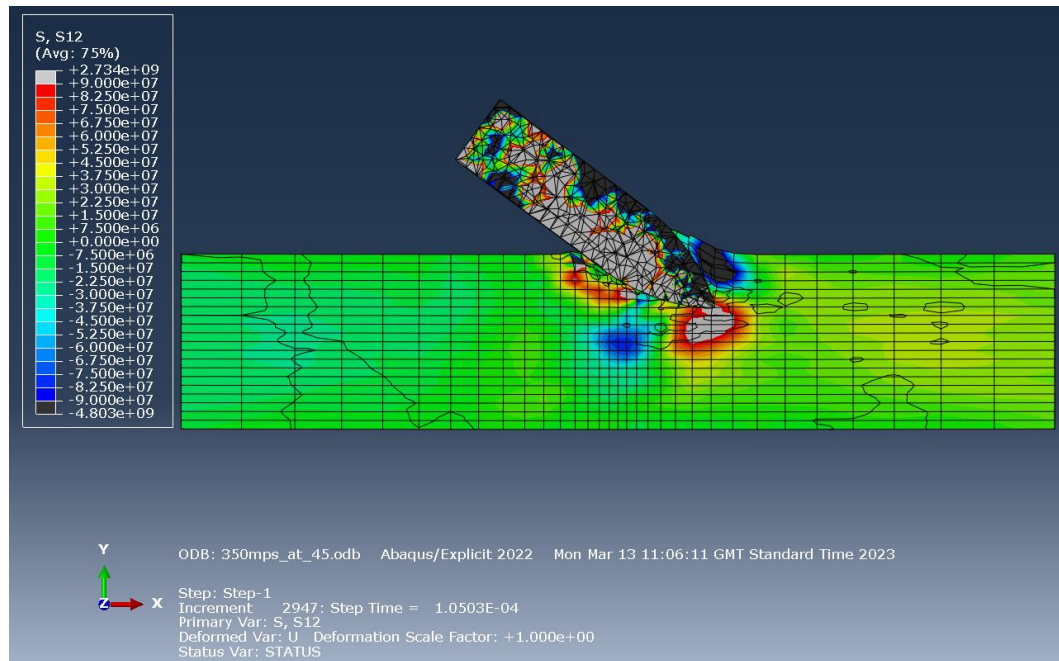


Figure 31 – Model 2, 350mps @ 45, Step 3, Shear

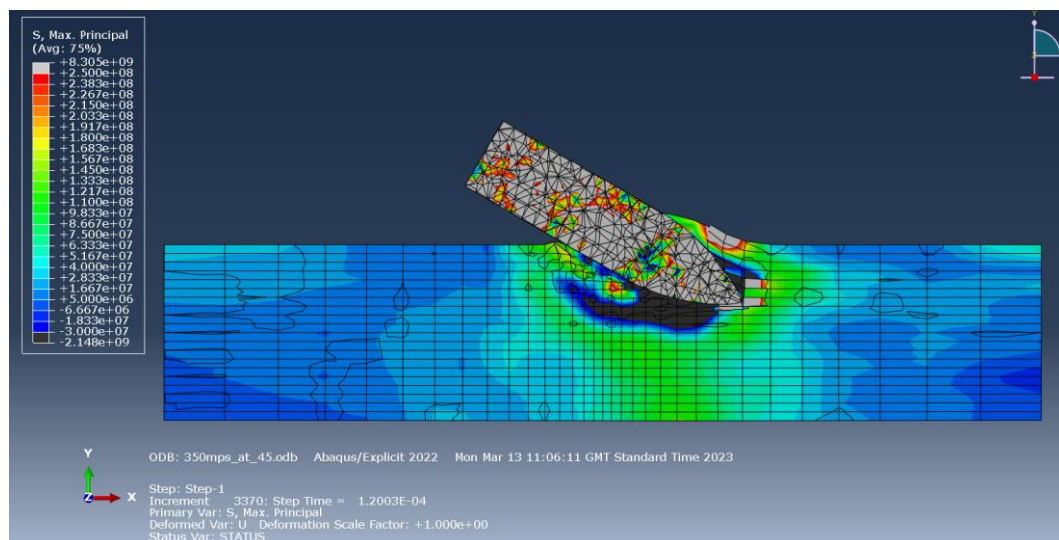


Figure 32 – Model 2, 350mps @ 45, Step 4

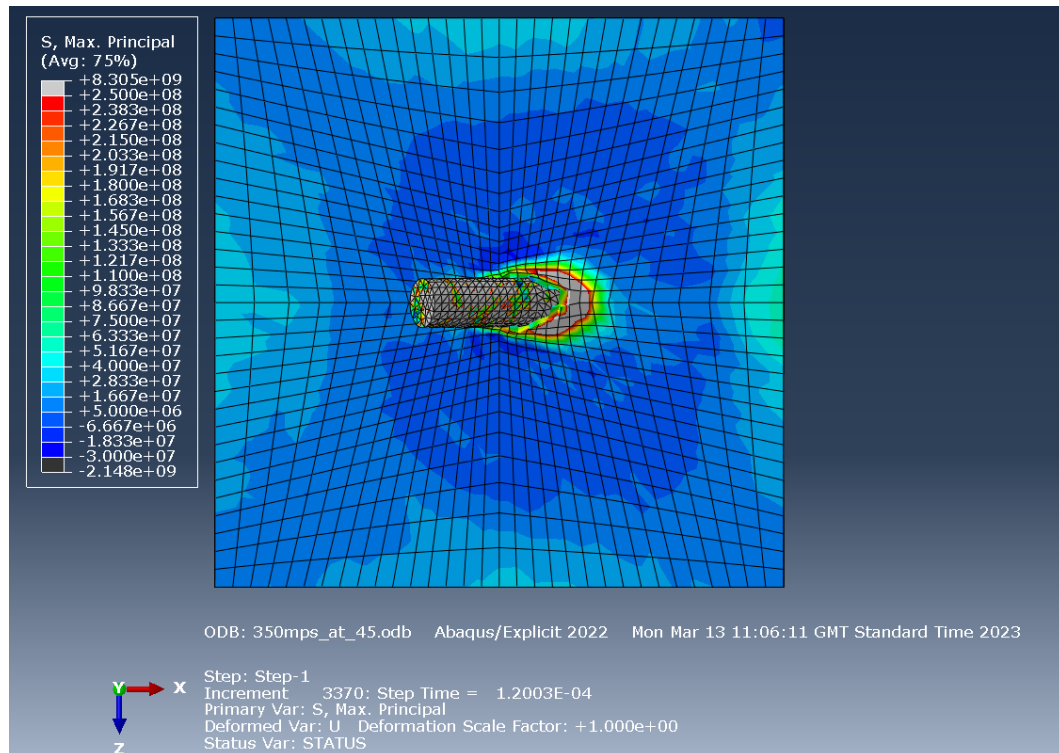


Figure 33 – Model 2, 350mps @ 45, Step 4, Top

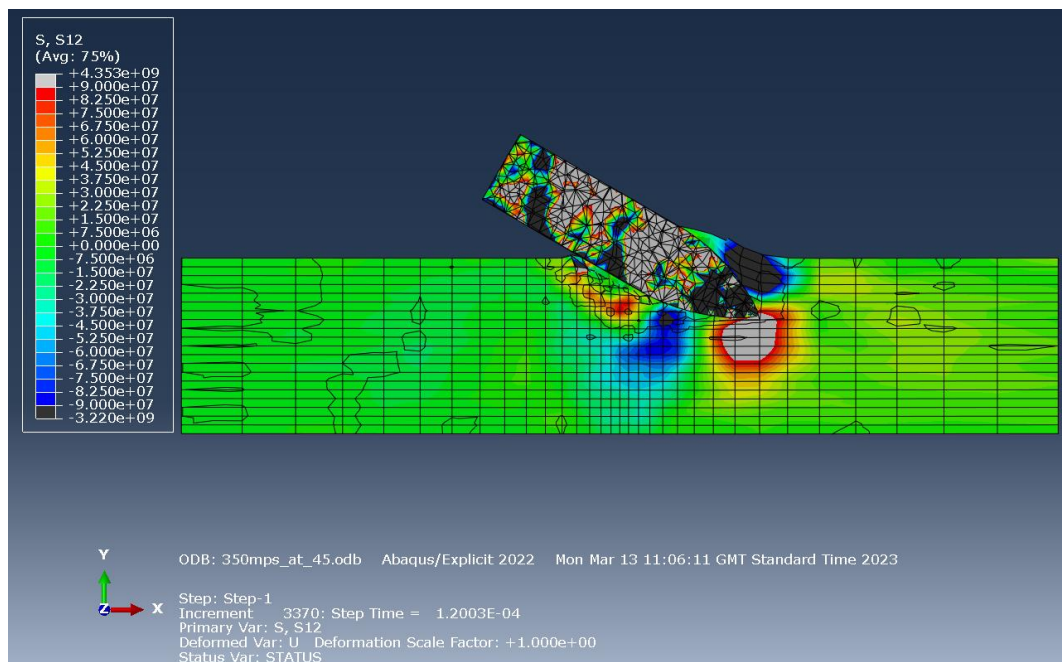


Figure 34 – Model 2, 350mps @ 45, Step 4, Shear

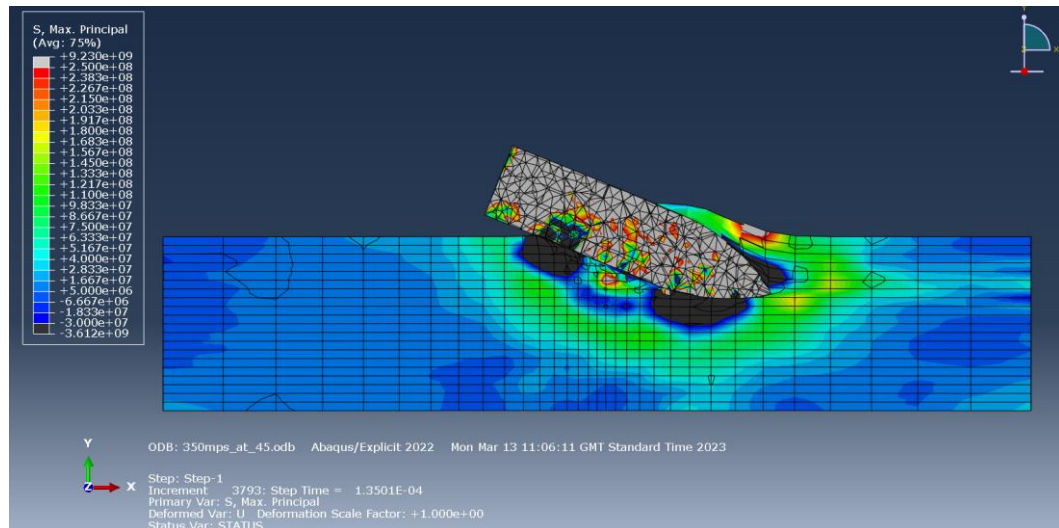


Figure 35 – Model 2, 350mps @ 45, Step 5

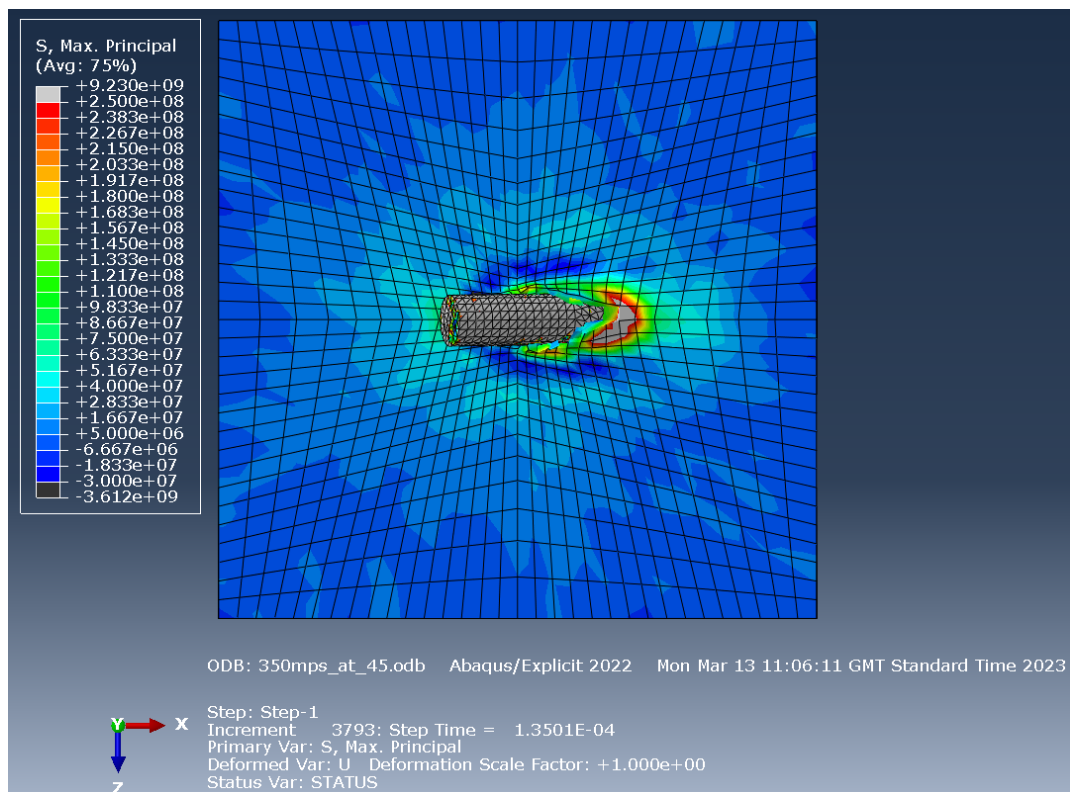


Figure 36 – Model 2, 350mps @ 45, Step 5, Top

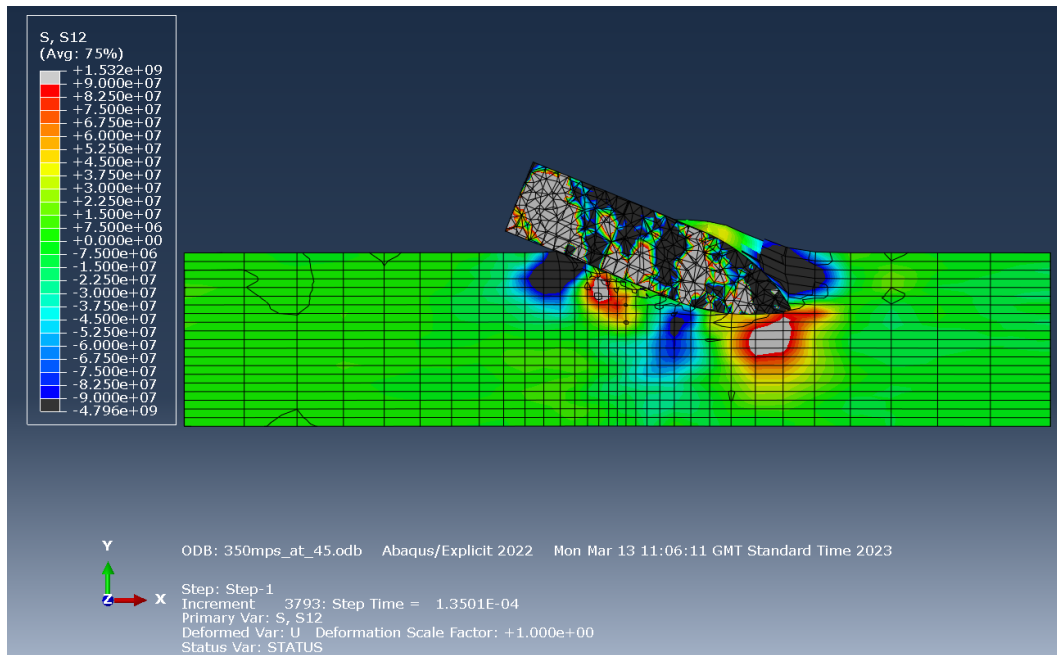


Figure 37 – Model 2, 350mps @ 45, Step 5, Shear

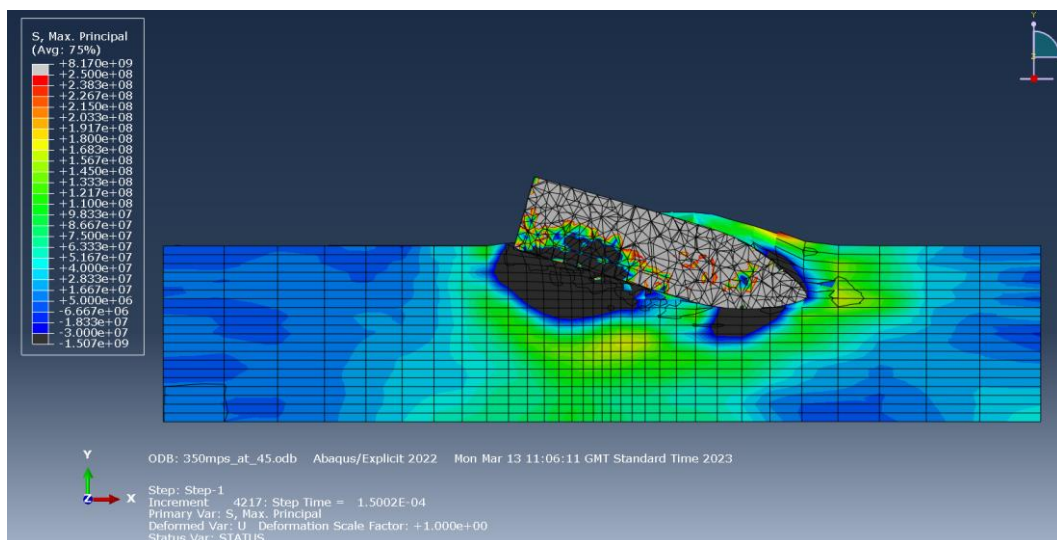


Figure 38 – Model 2, 350mps @ 45, Step 6

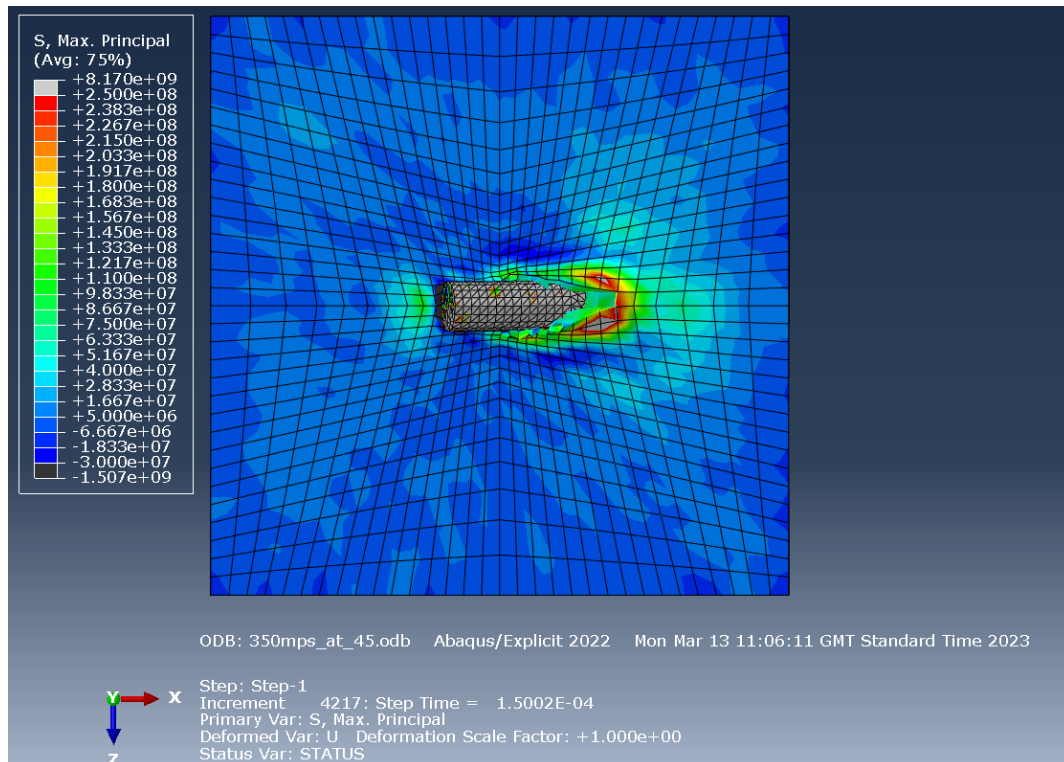


Figure 39 – Model 2, 350mps @ 45, Step 6, Top

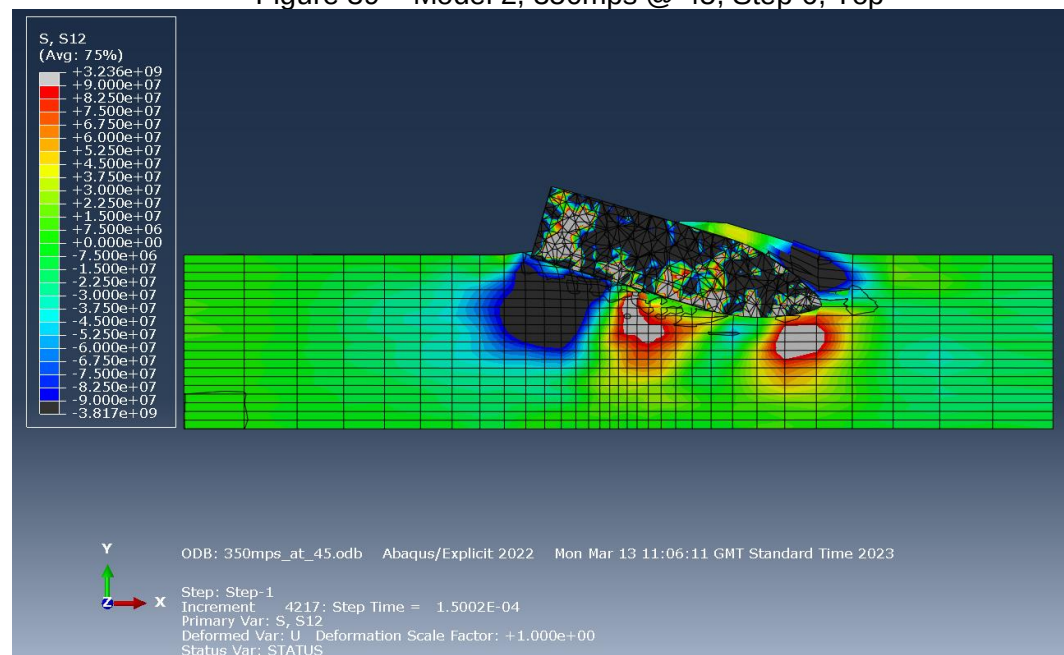


Figure 40 – Model 2, 350mps @ 45, Step 6, Shear

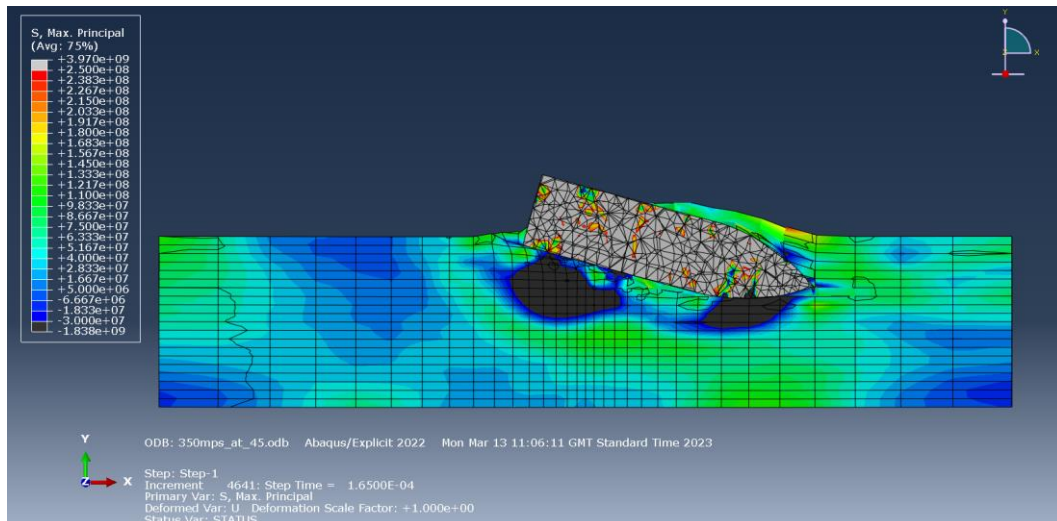


Figure 41 – Model 2, 350mps @ 45, Step 7

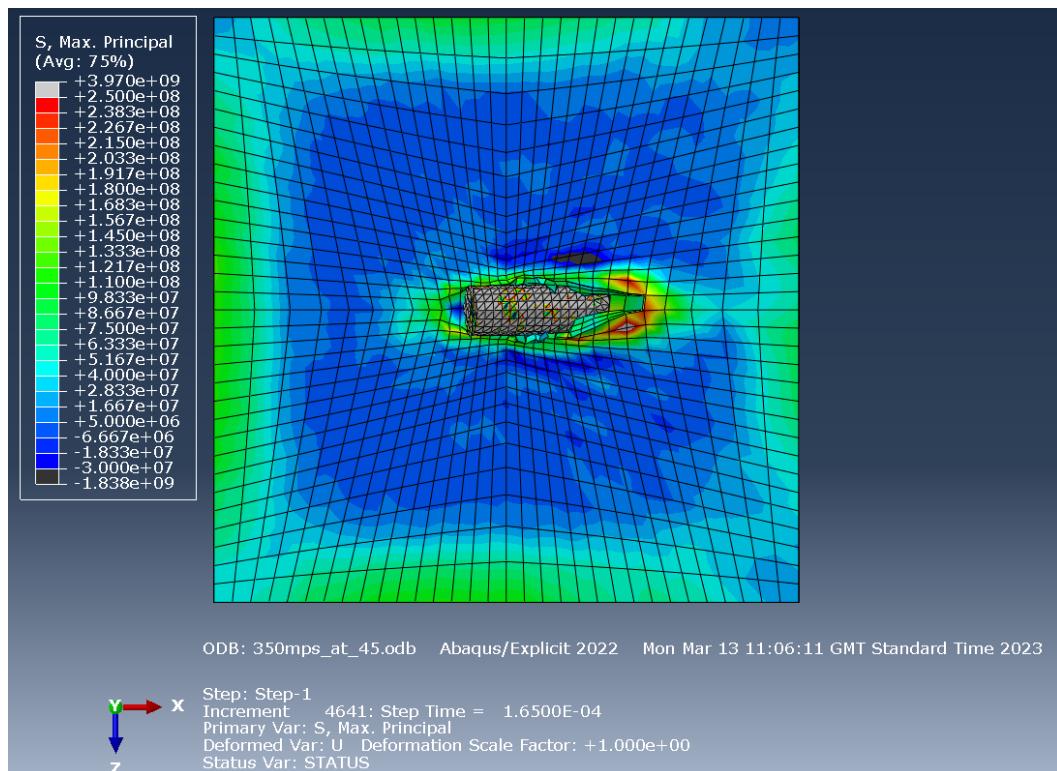


Figure 42 – Model 2, 350mps @ 45, Step 7, Top

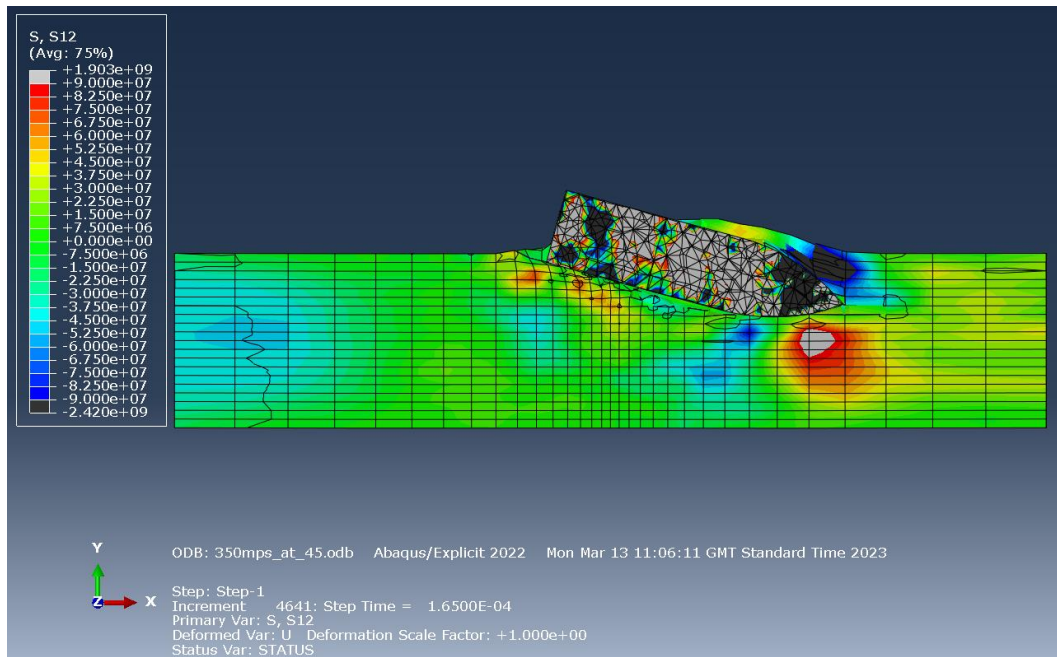


Figure 43 – Model 2, 350mps @ 45, Step 7, Shear

11.4. 350mps at 45 Non Delete

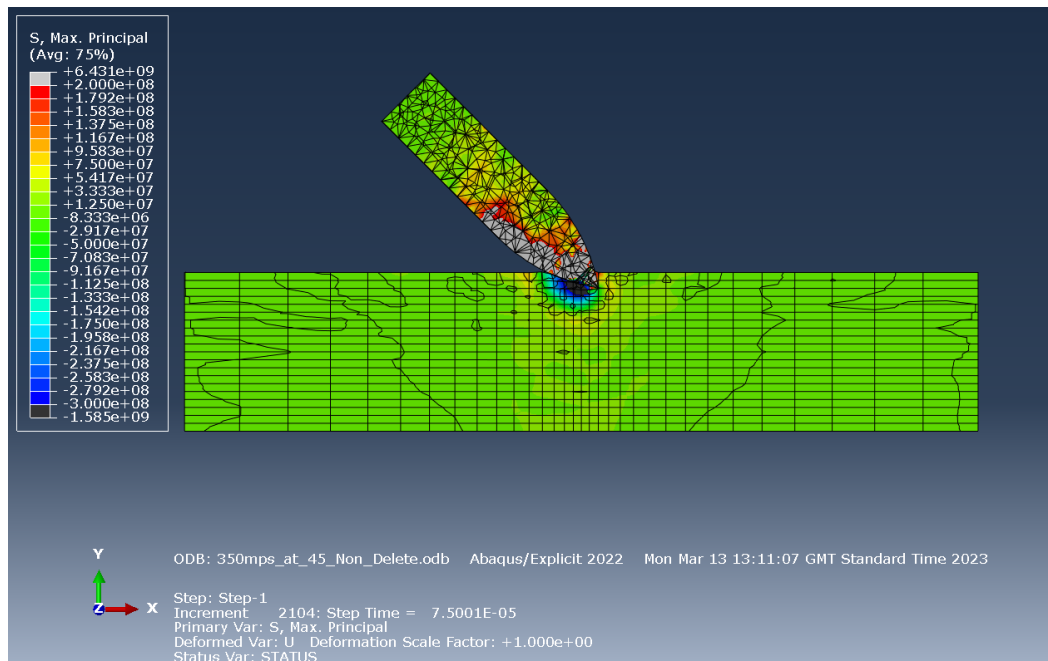


Figure 44 – Model 2, 350mps @ 45 Non Delete, Step 1

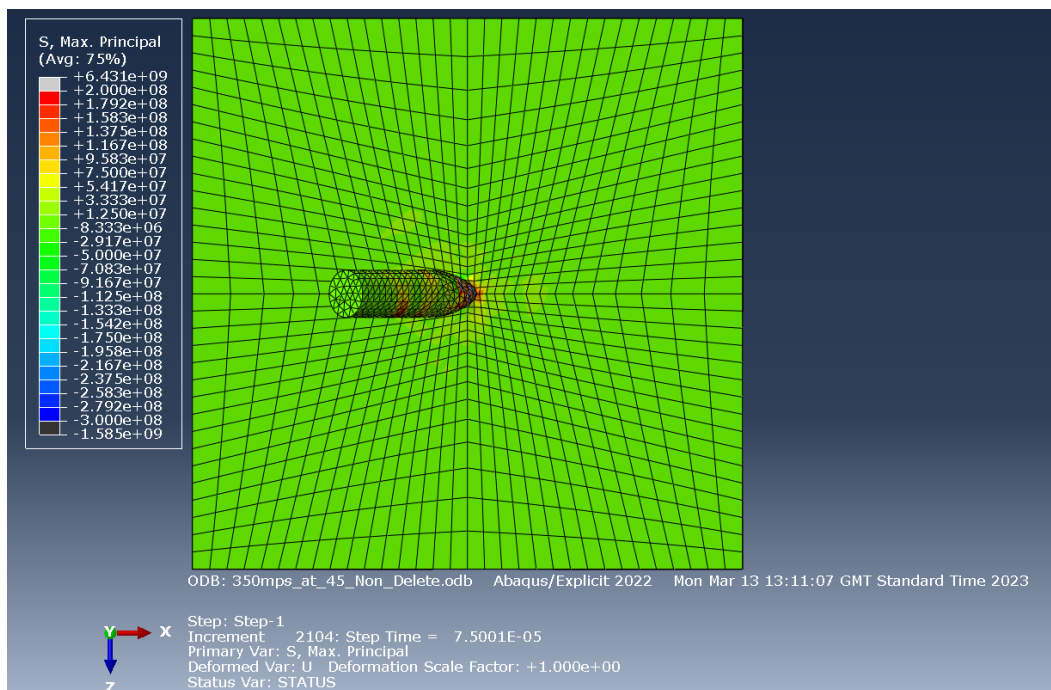


Figure 45 – Model 2, 350mps @ 45 Non Delete, Step 1, Top

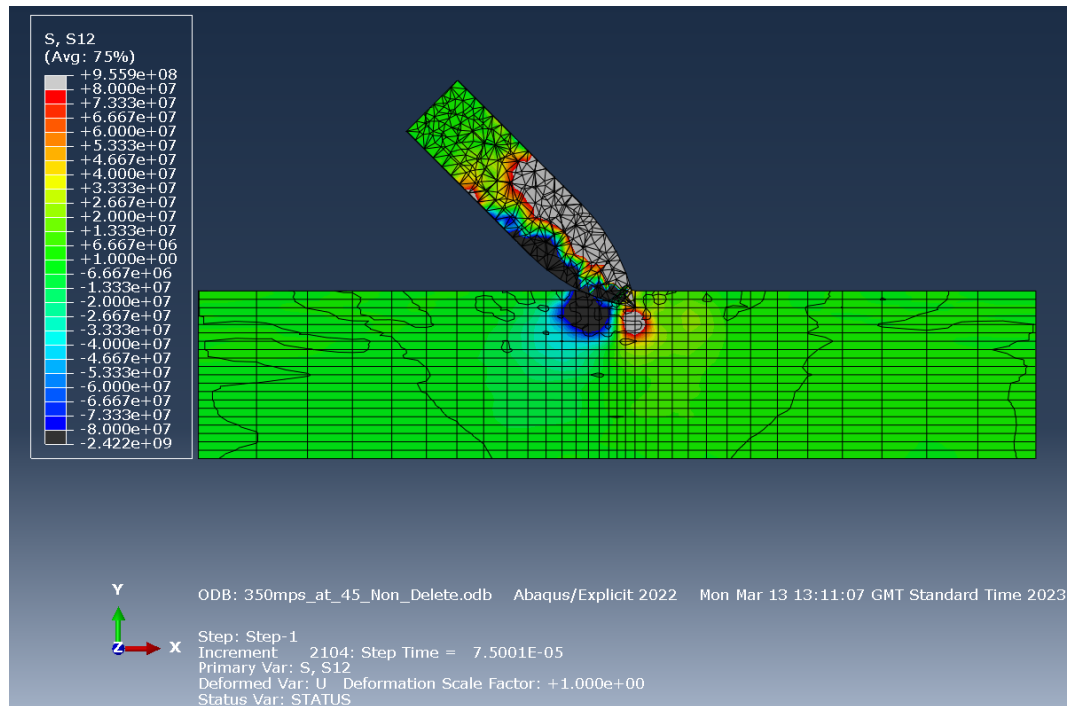


Figure 46 – Model 2, 350mps @ 45 Non Delete, Step 1, Shear

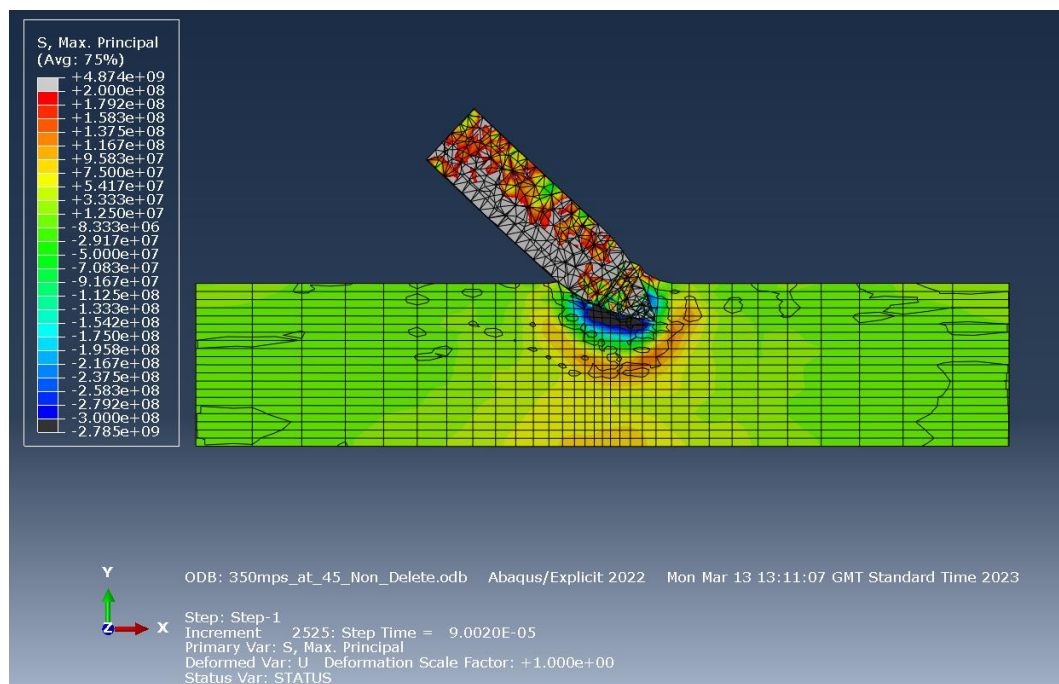


Figure 47 – Model 2, 350mps @ 45 Non Delete, Step 2

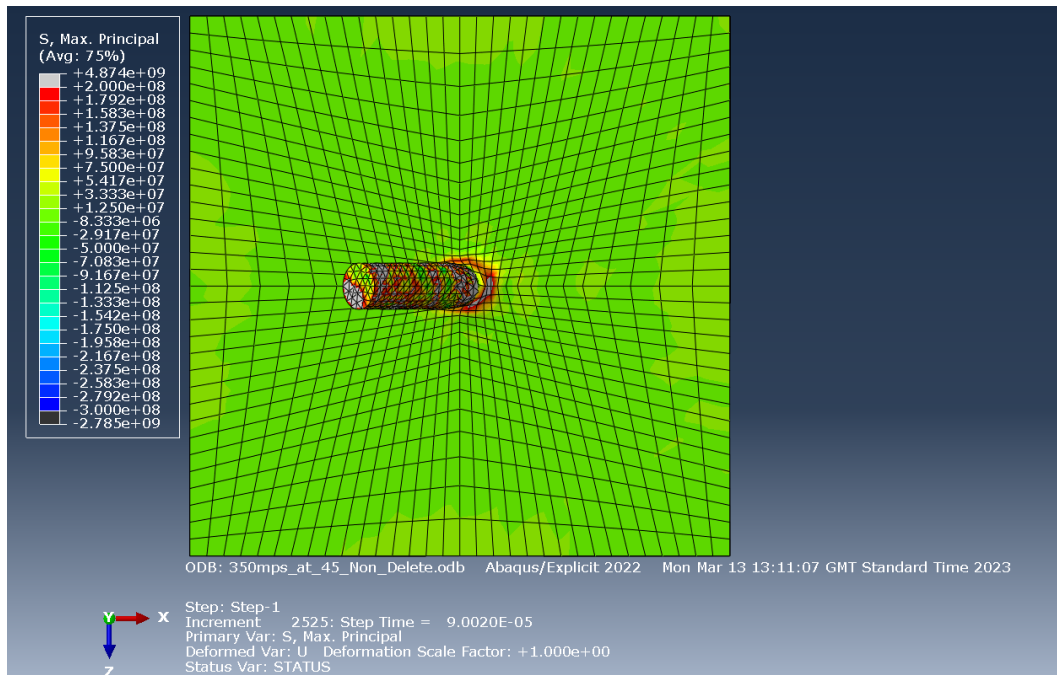


Figure 48 – Model 2, 350mps @ 45 Non Delete, Step 2, Top

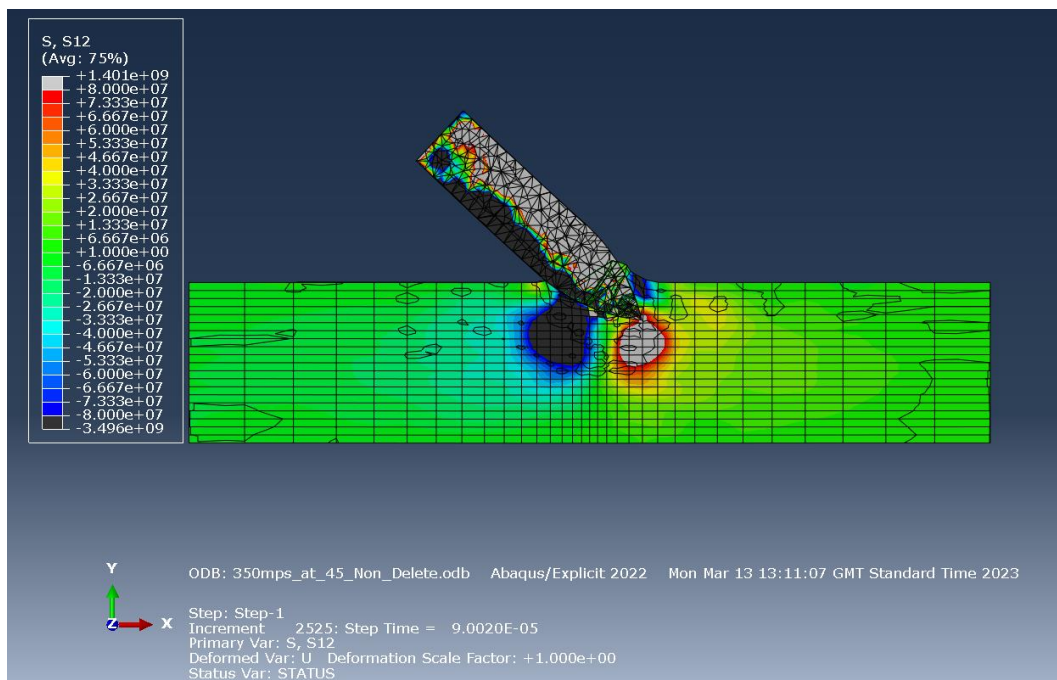


Figure 49 – Model 2, 350mps @ 45 Non Delete, Step 2, Shear

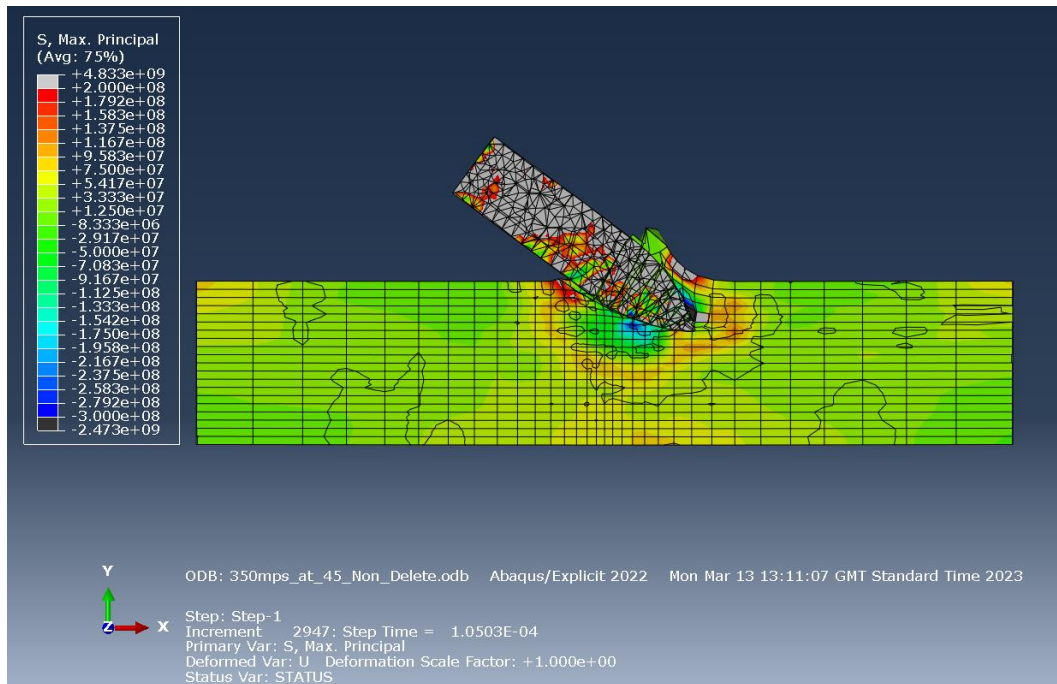


Figure 50 – Model 2, 350mps @ 45 Non Delete, Step 3

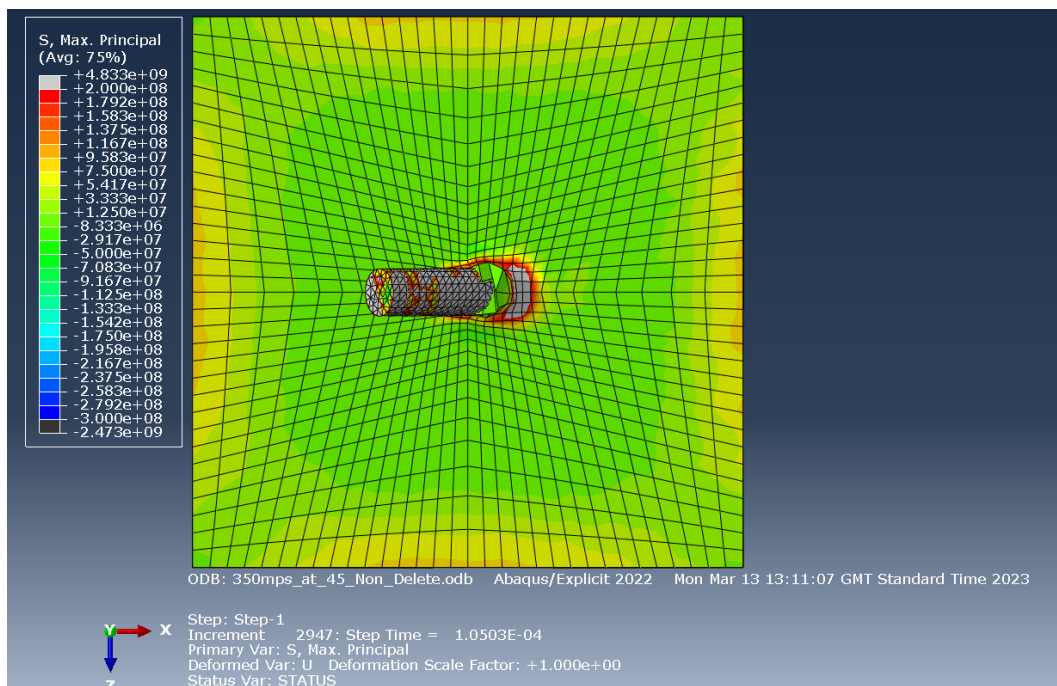


Figure 51 – Model 2, 350mps @ 45 Non Delete, Step 3, Top

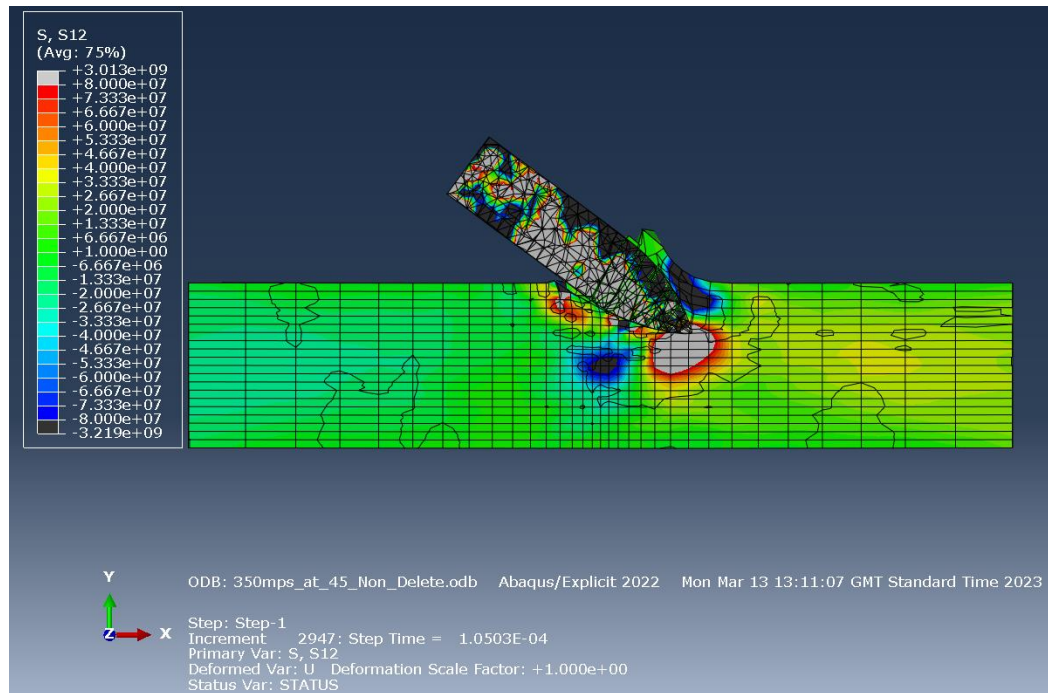


Figure 52 – Model 2, 350mps @ 45 Non Delete, Step 3, Shear

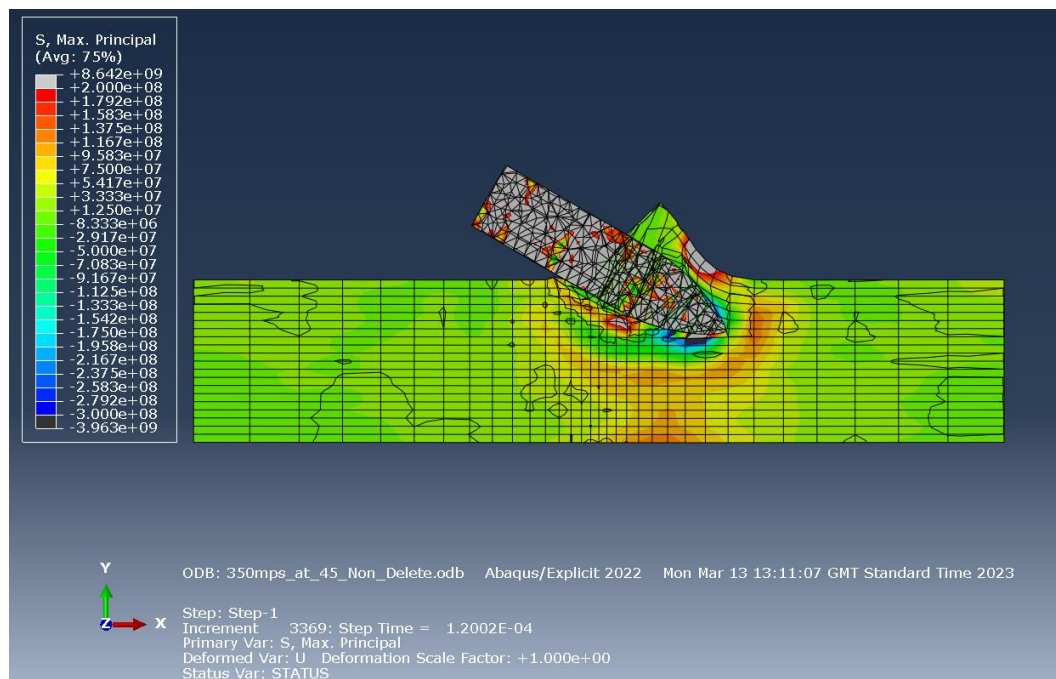


Figure 53 – Model 2, 350mps @ 45 Non Delete, Step 4

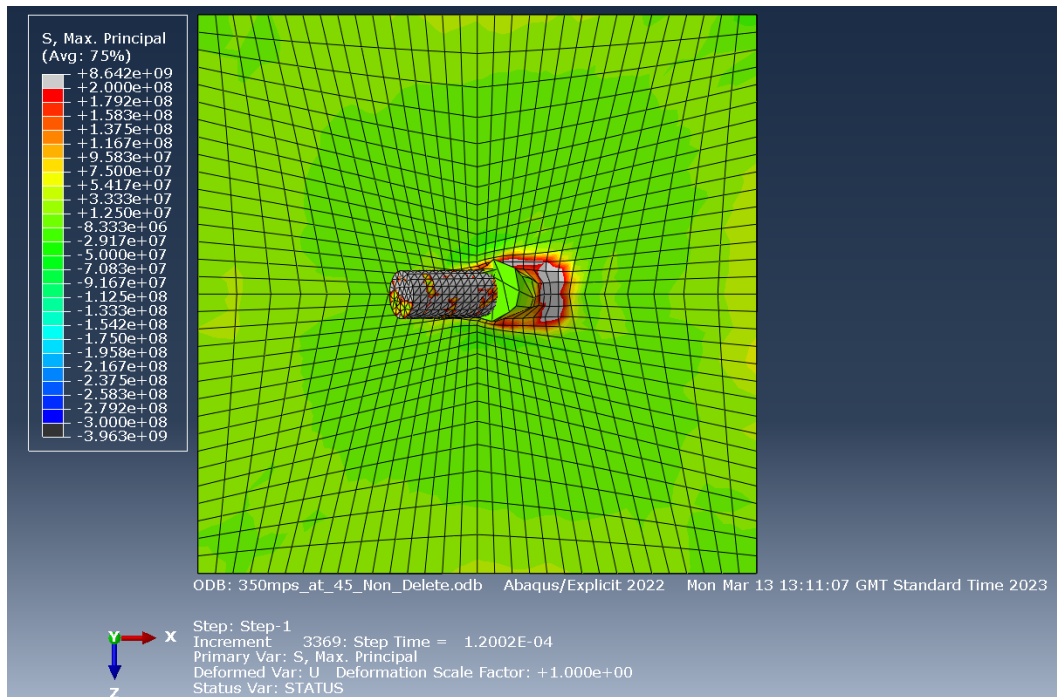


Figure 54 – Model 2, 350mps @ 45 Non Delete, Step 4, Top

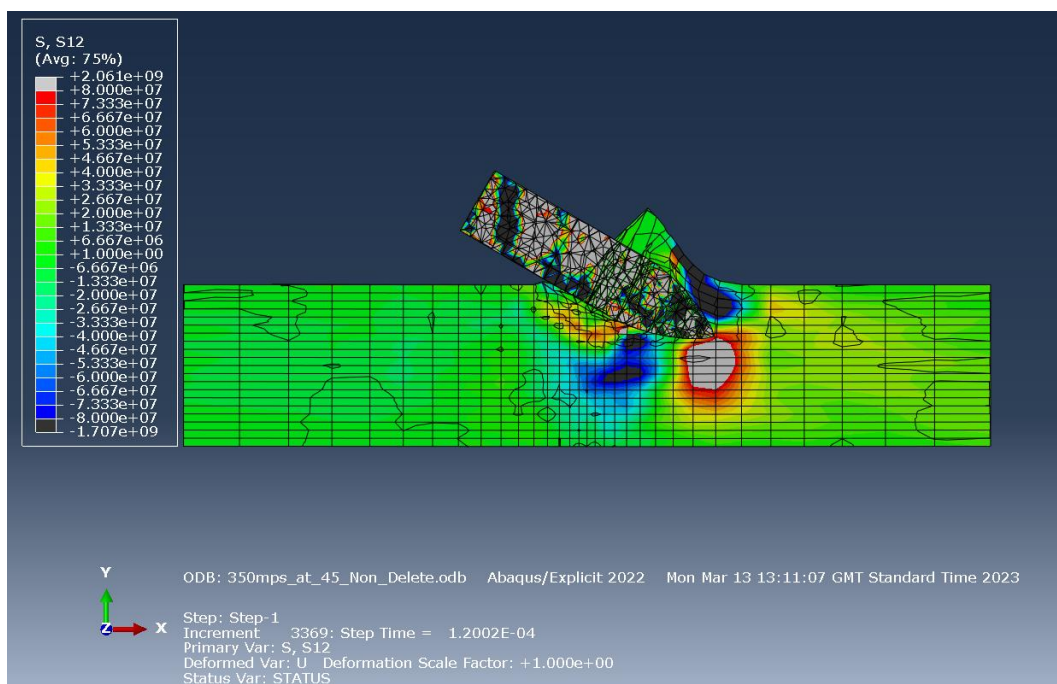


Figure 55 – Model 2, 350mps @ 45 Non Delete, Step 4, Shear

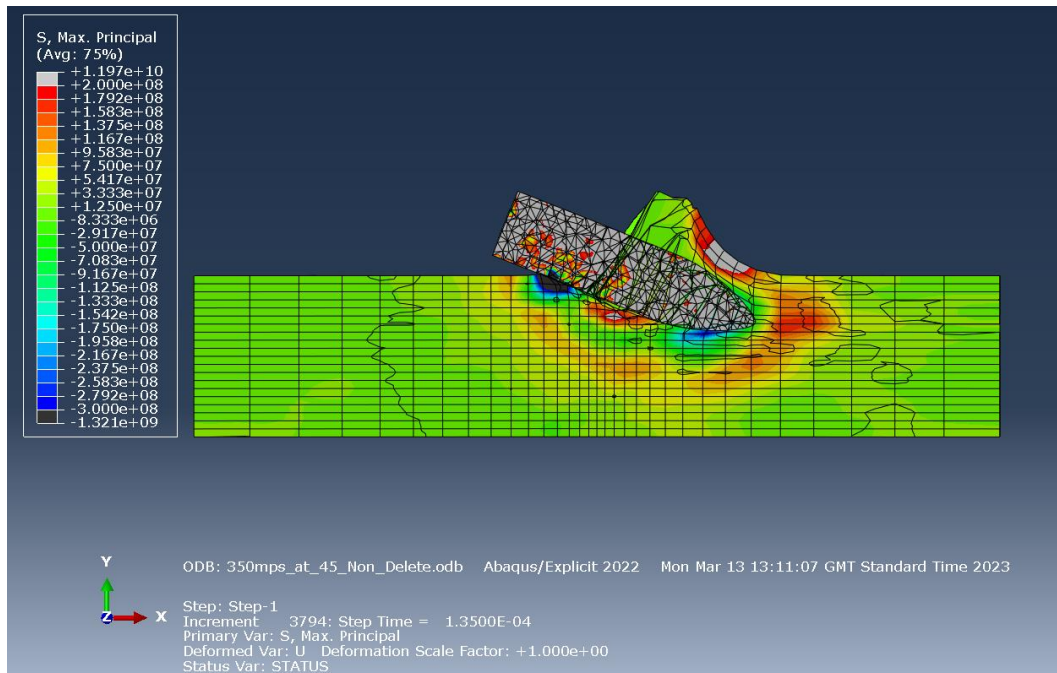


Figure 56 – Model 2, 350mps @ 45 Non Delete, Step 5

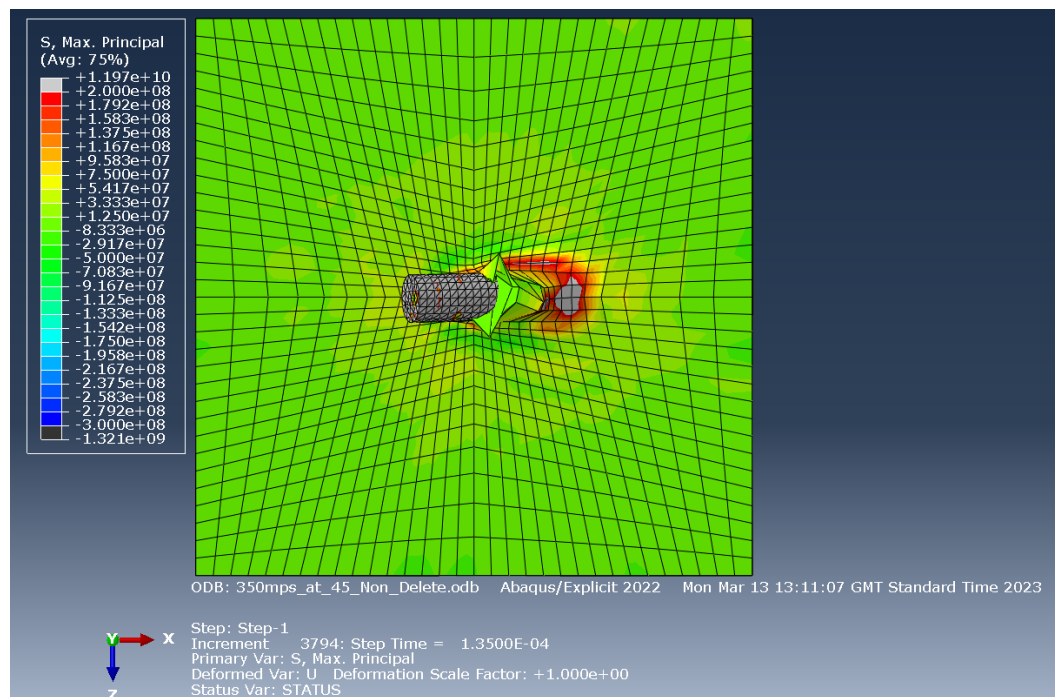


Figure 57 – Model 2, 350mps @ 45 Non Delete, Step 5, Top

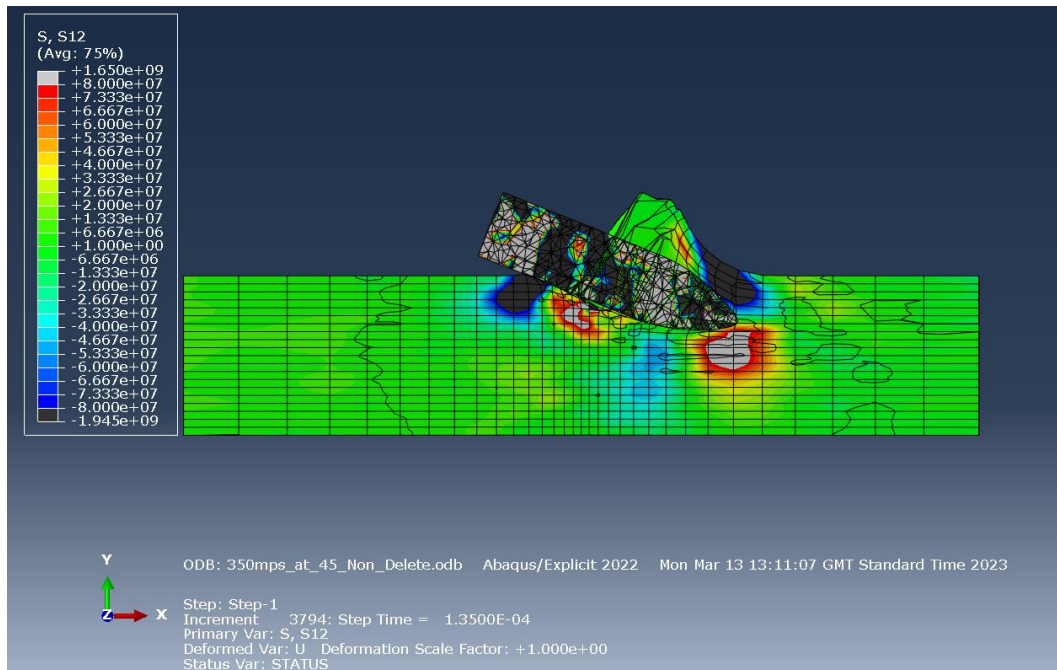


Figure 58 – Model 2, 350mps @ 45 Non Delete, Step 5, Shear

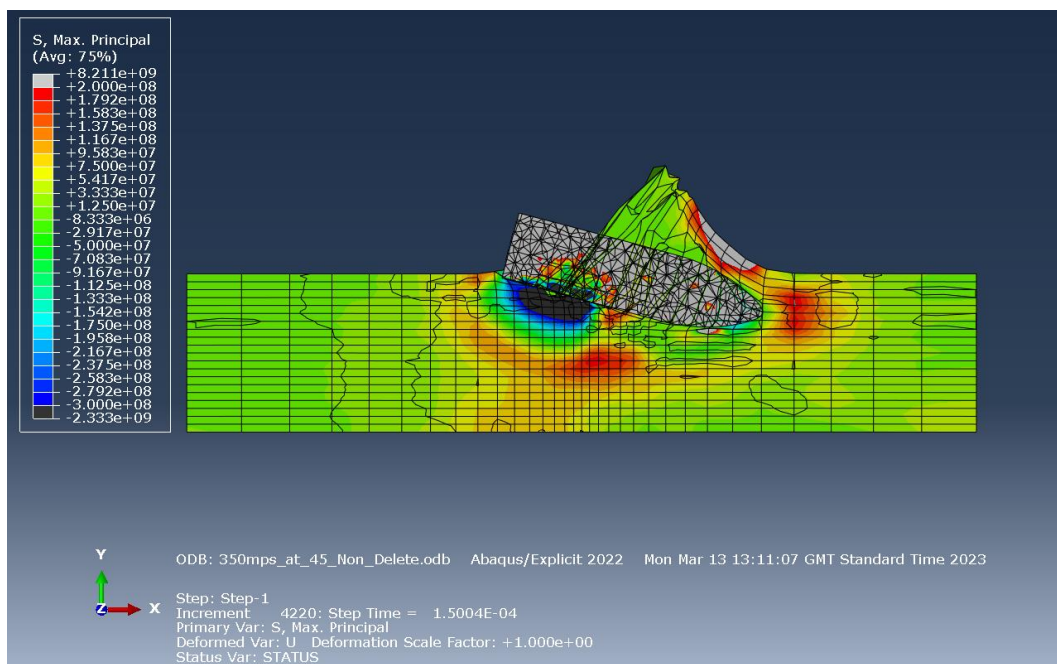


Figure 59 – Model 2, 350mps @ 45 Non Delete, Step 6

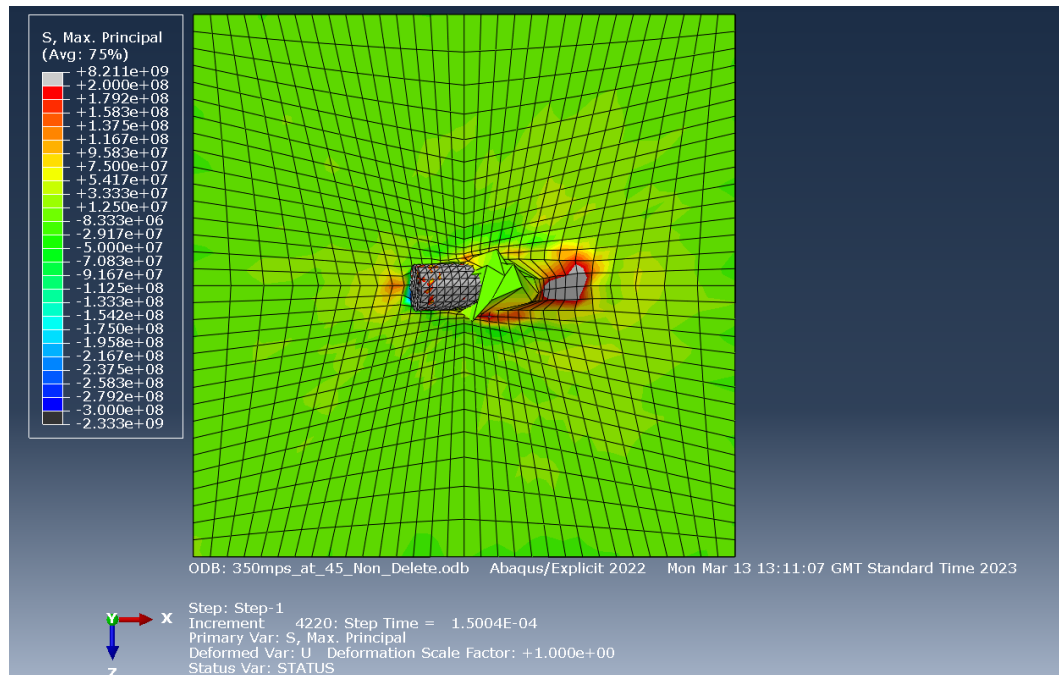


Figure 60 – Model 2, 350mps @ 45 Non Delete, Step 6, Top

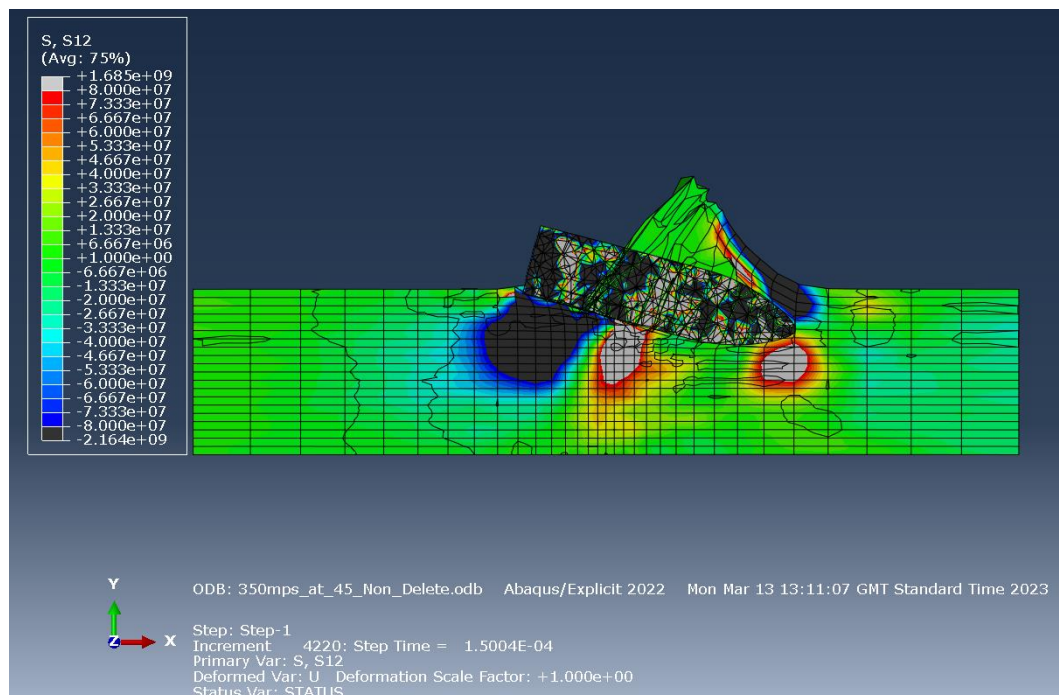


Figure 61 – Model 2, 350mps @ 45 Non Delete, Step 6, Shear

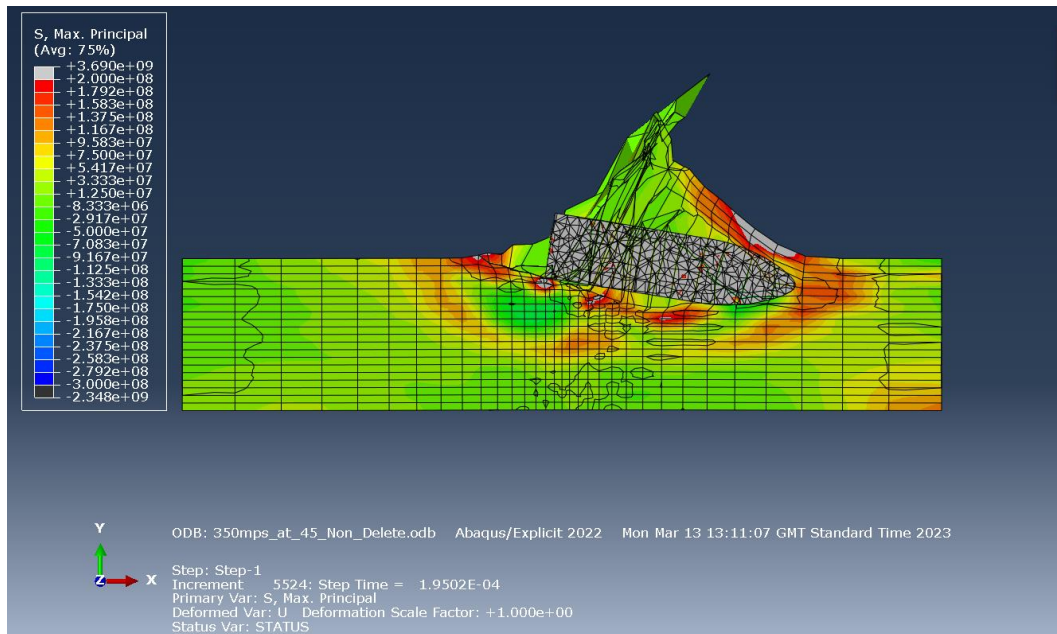


Figure 62 – Model 2, 350mps @ 45 Non Delete, Step 7

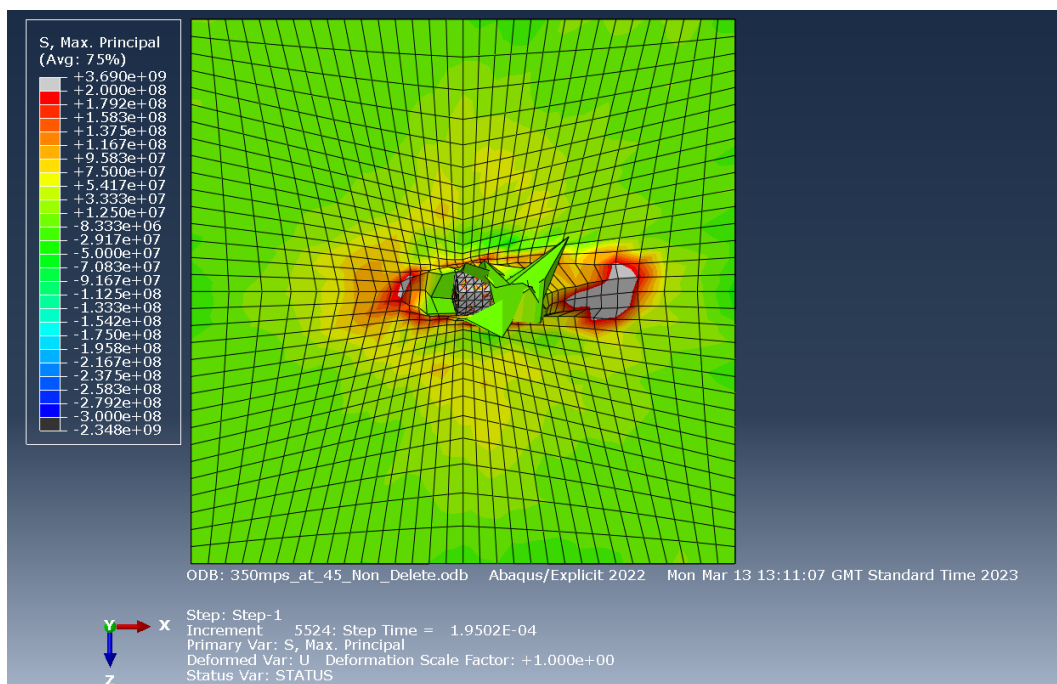


Figure 63 – Model 2, 350mps @ 45 Non Delete, Step 7, Top

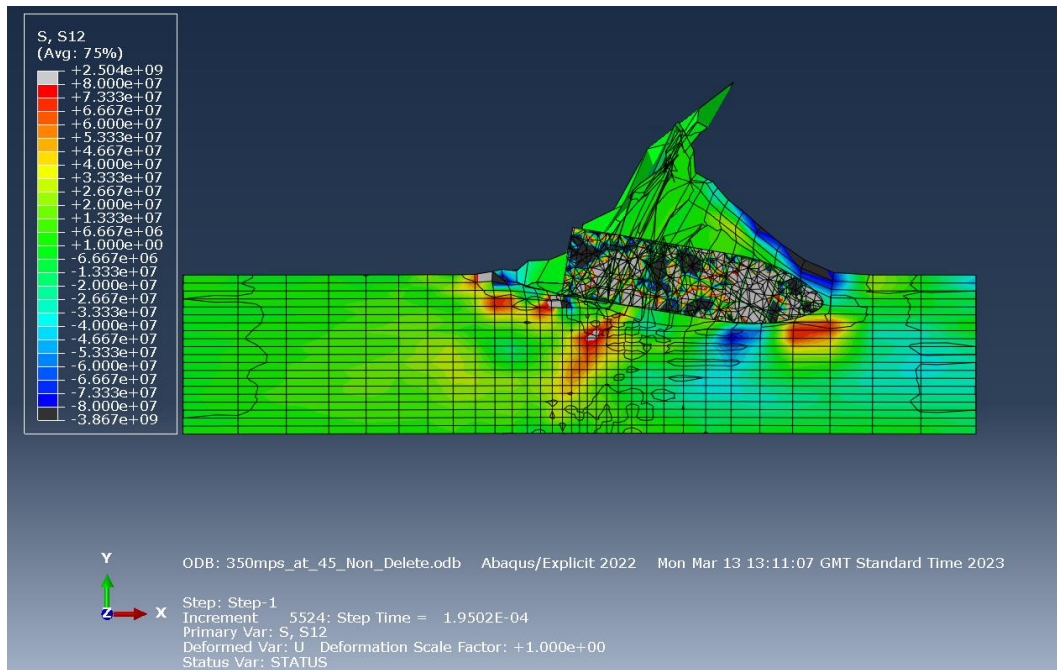


Figure 64 – Model 2, 350mps @ 45 Non Delete, Step 7, Shear

12. Annex C: Model 3

12.1. Model 3: Geometry

Projectile: To allow for a more complex geometry and the possibility of a bi material projectile Solidworks was used to create a more accurate depiction of the 7.62mm x 39mm NATO standard round [2]. The models created in Solidworks can be found below in Figure 65.

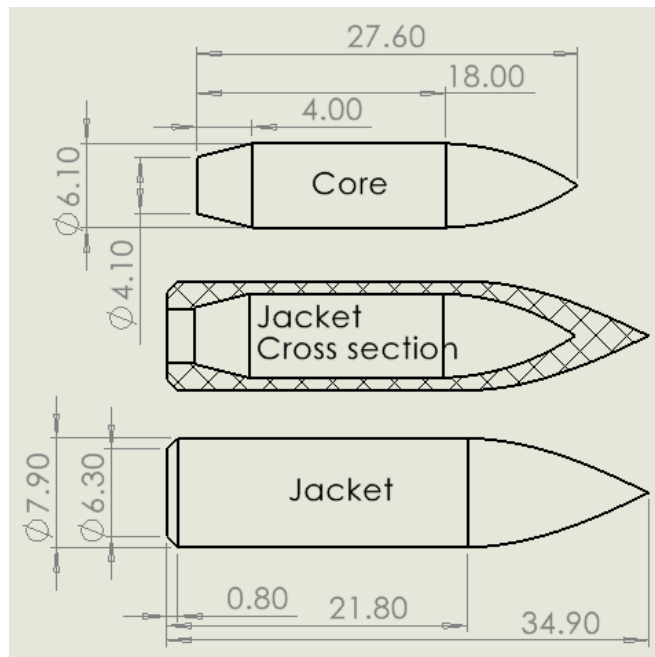


Figure 65 – 7.62 mm x 39mm Bullet Geometry

Target Plate: As with model 2 the dimensions of the target plate were kept the same as they were as an appropriate size for the projectile. The target plate in this model is 0.1m x 0.1m x 0.02m which is subdivided into quarters to allow biased meshing.

12.2. Model 3: Mesh

Projectile: For this model attempts were made to have a separate jacket and core with differing materials but due to time constraints a merged projectile was deemed suitable. In Abacus the two parts of the model were merged keeping the shared nodes intact. This allowed for meshing of both the core and jacket with shared nodes so that they could interact with the target more accurately.

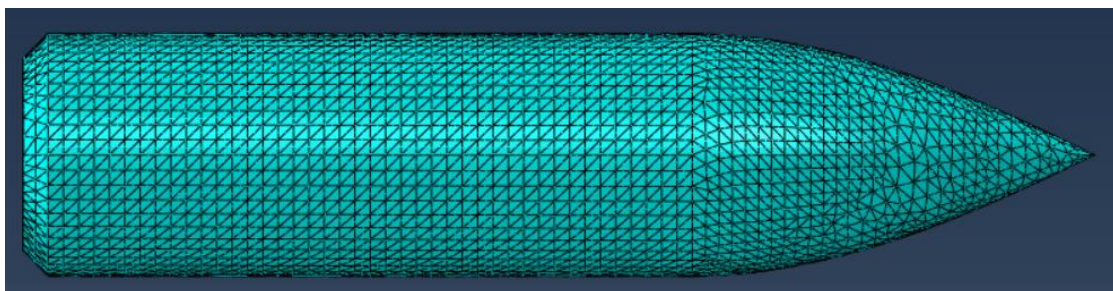


Figure 66 - Model 3 Merged Projectile Mesh

Target Plate: Using the partitions created in the target plate model a Biased seed was created that graduate towards the centre on both the top and bottom surfaces. This seed was biased from 0.003 on the edge to 0.001 in the centre. The vertical edges including the centre were finer graduated to 0.005 The remain edges where globally seeded to 0.01. The resultant is the mesh below in Figure 67.

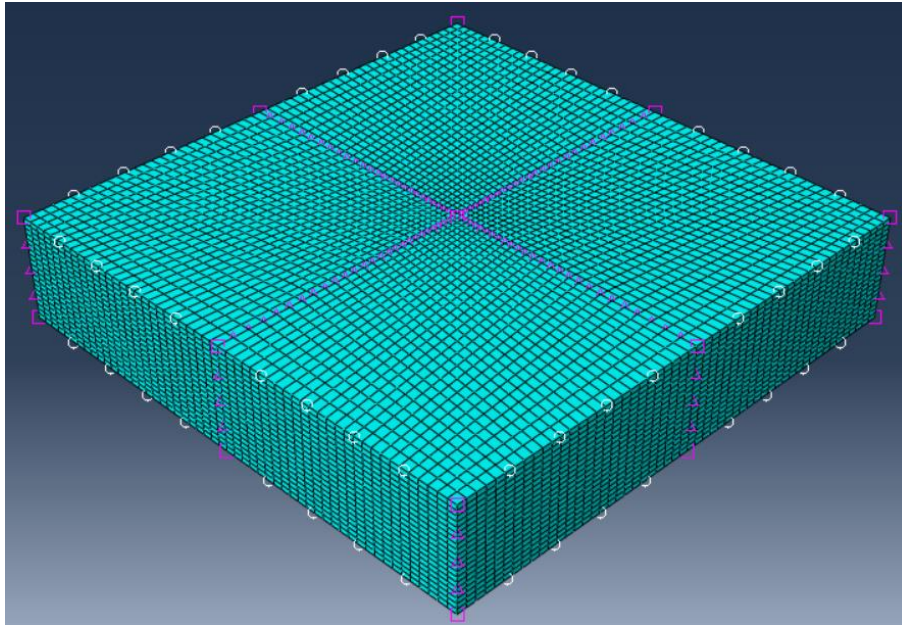


Figure 67 - Model 3 Target Plate Mesh

12.3. Model 3: Results

Developing on model 2, Solidworks was used to develop a more accurate geometric model that reflects the internal aspects of the round itself. This allowed for a merged part to be created and a mesh that better defines the internal structure. In addition to this it would eventually allow for different material allocation inside the projectile which is accurate to reality. The figures below show how as the projectile impacts corresponding compression and tension waves are formed and a shear stress along the axis of penetration is developed. As the projectile penetrates further the stress concentration demonstrates how in theory the external shell of the bullet would be ablated away leaving the steel core to 'punch' through. Lastly it shows how the UTS of the material is reached on the back side of the plate with the shearing of the surface as the projectile passes through the material. The projectile fully penetrated the material indicating that at this velocity the impact of a 7.62mm x 39mm round is likely to penetrate the shell of a cruise missile.

12.4. 450mps Non Delete

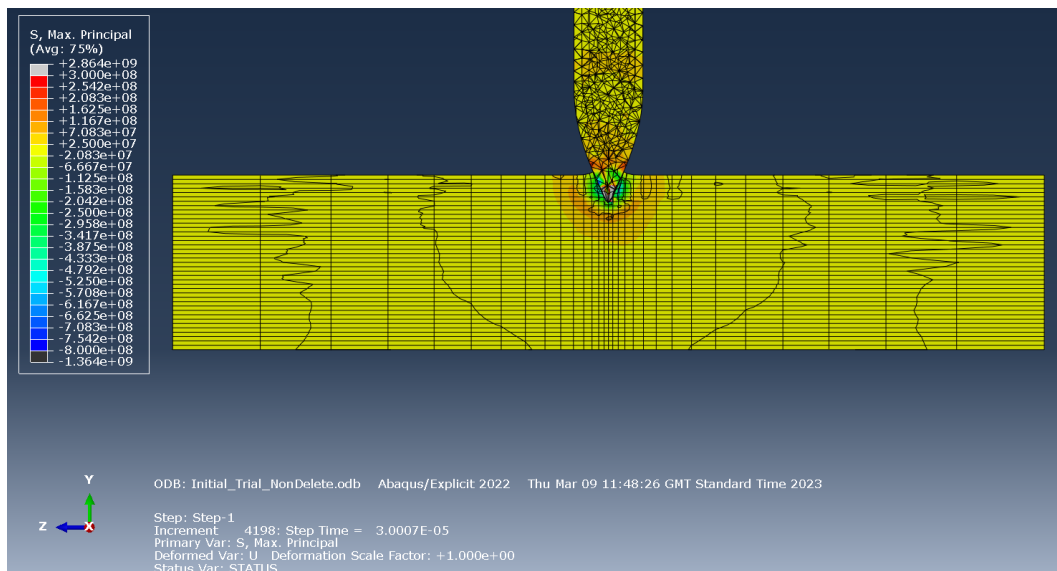


Figure 68 – Model 3, 450mps Delete, Step 1

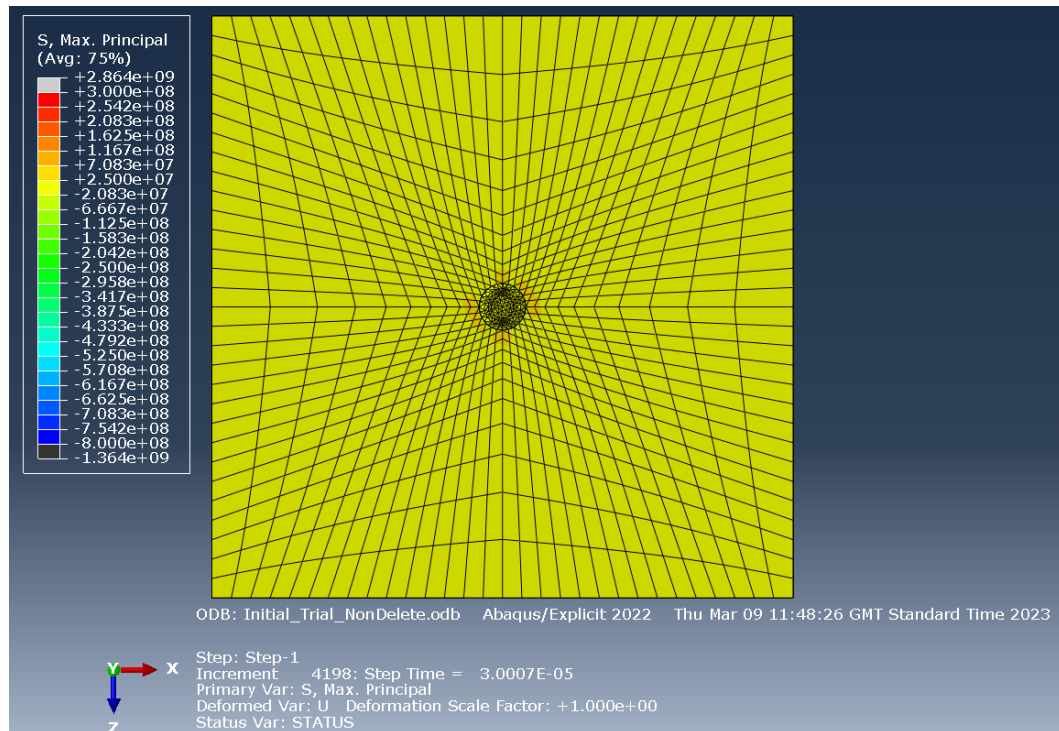


Figure 69 – Model 3, 450mps Delete, Step 1, Top

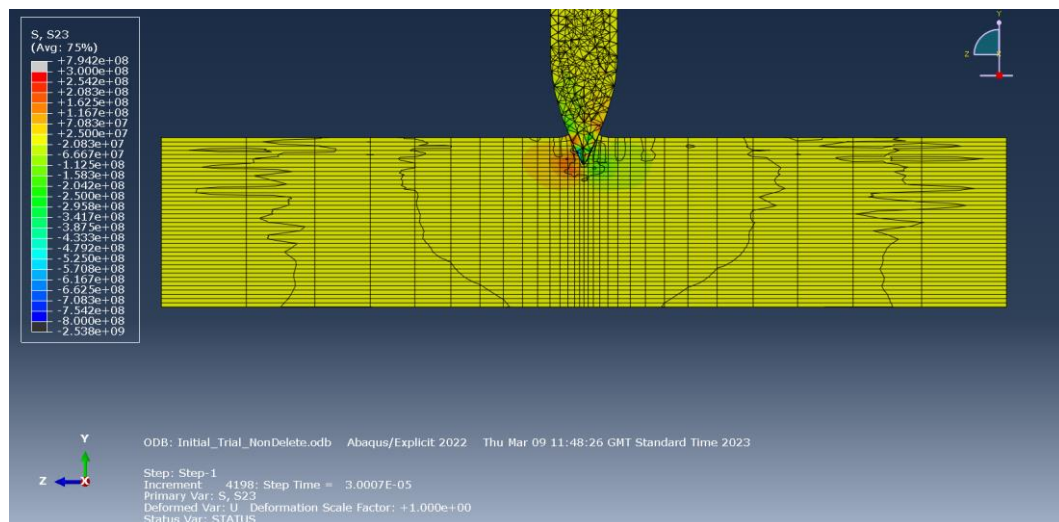


Figure 70 – Model 3, 450mps Delete, Step 1, Shear

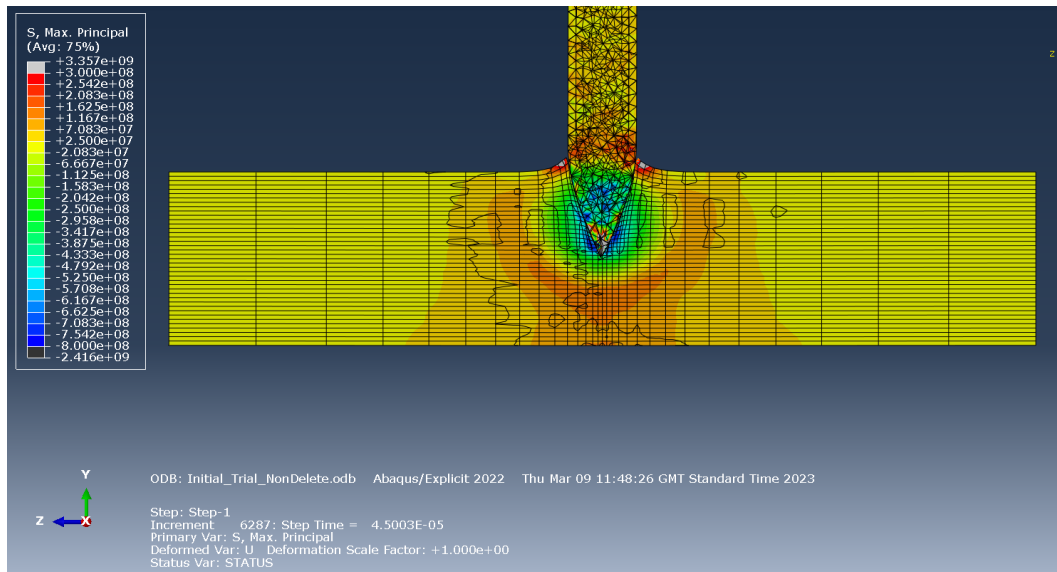


Figure 71 – Model 3, 450mps Delete, Step 2

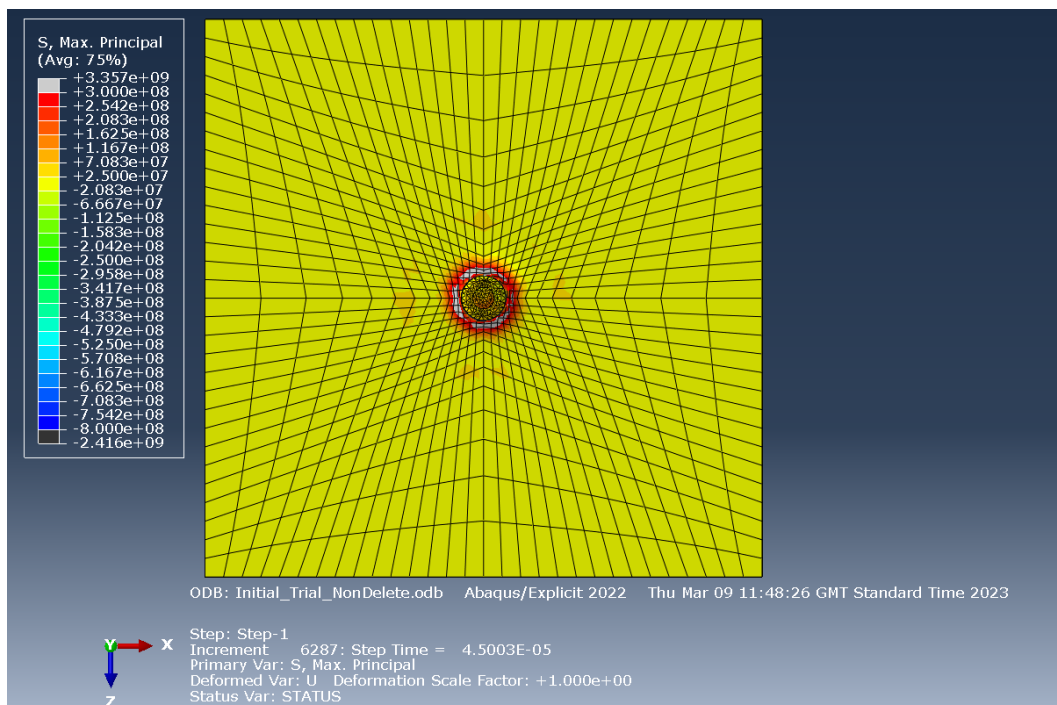


Figure 72 – Model 3, 450mps Delete, Step 2, Top

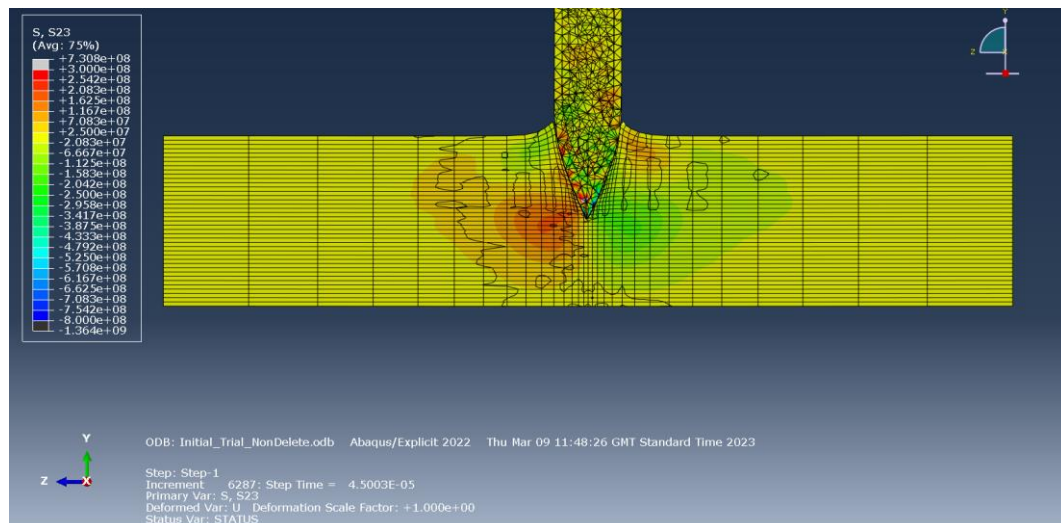


Figure 73 – Model 3, 450mps Delete, Step 2, Shear

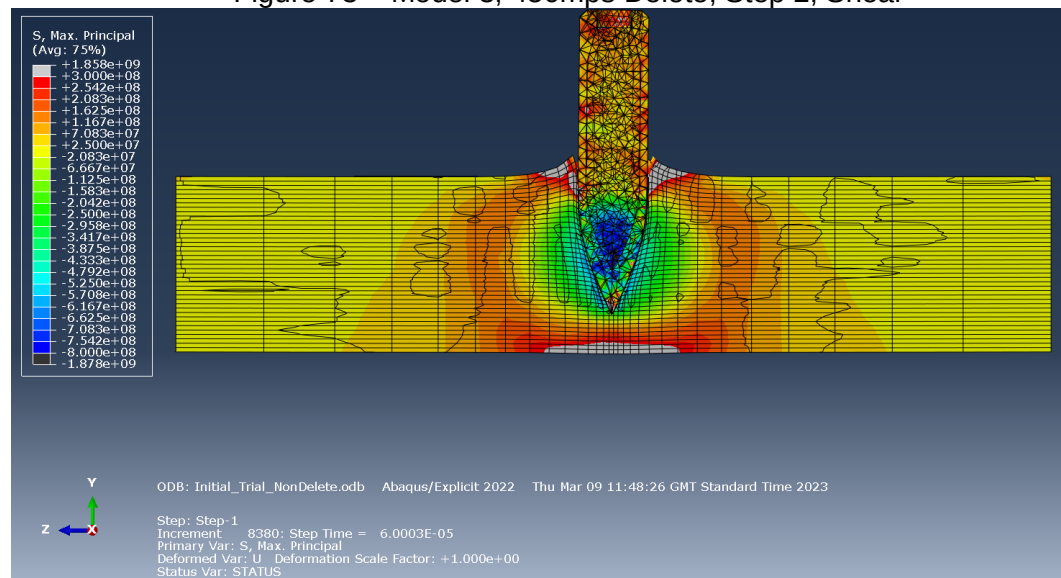


Figure 74 – Model 3, 450mps Delete, Step 3

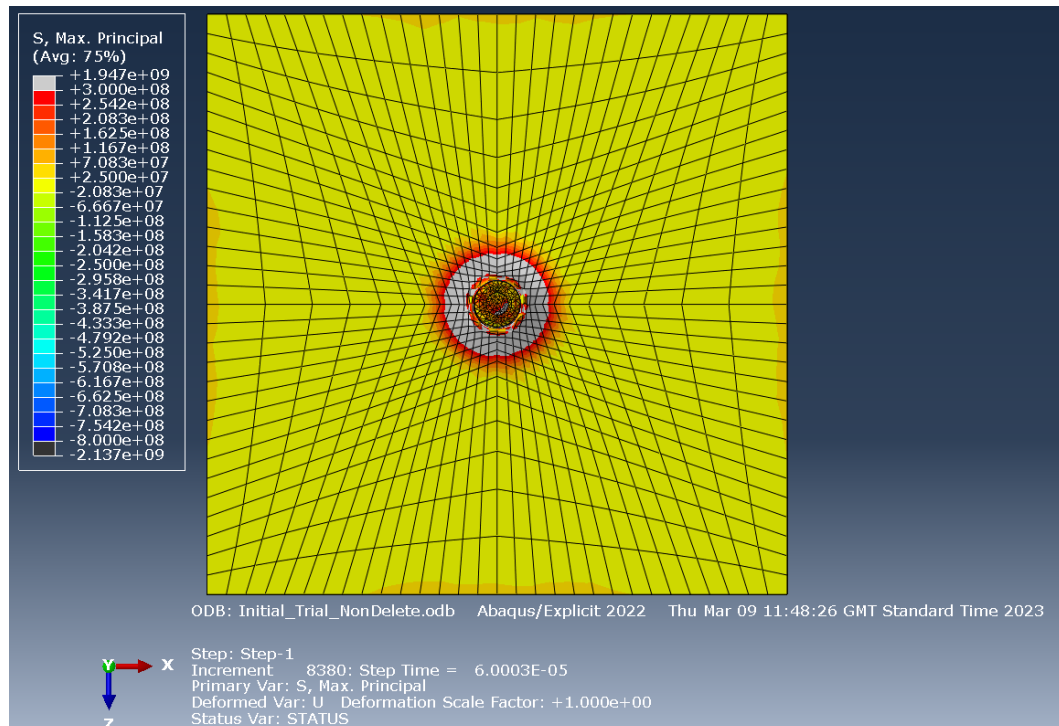


Figure 75 – Model 3, 450mps Delete, Step 3, Top

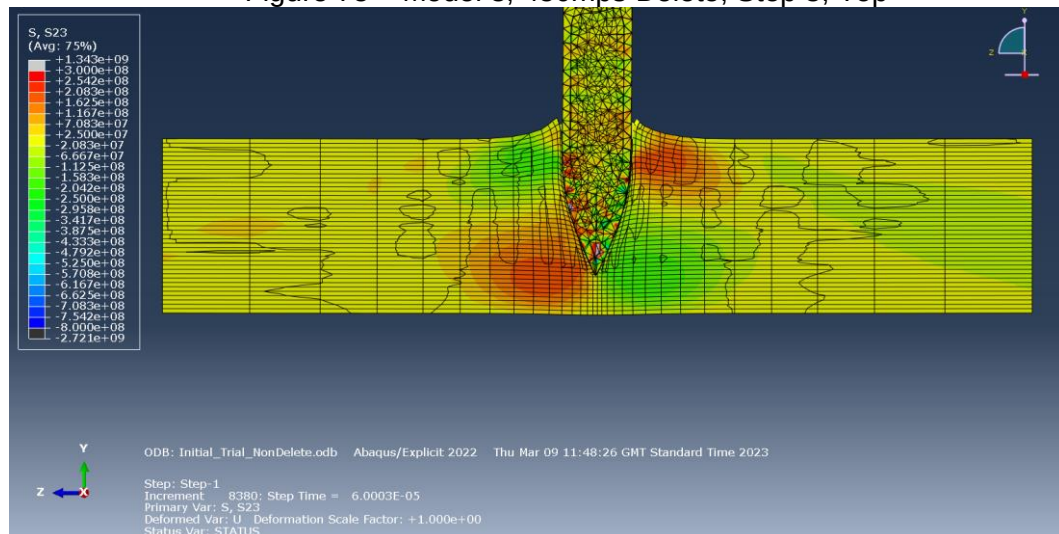


Figure 76 – Model 3, 450mps Delete, Step 3, Shear

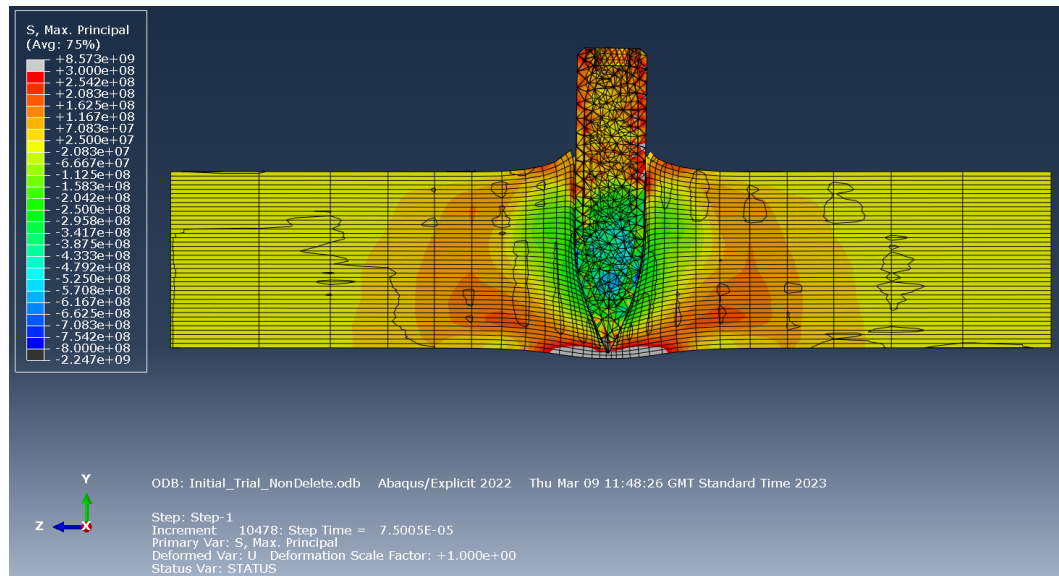


Figure 77 – Model 3, 450mps Delete, Step 4

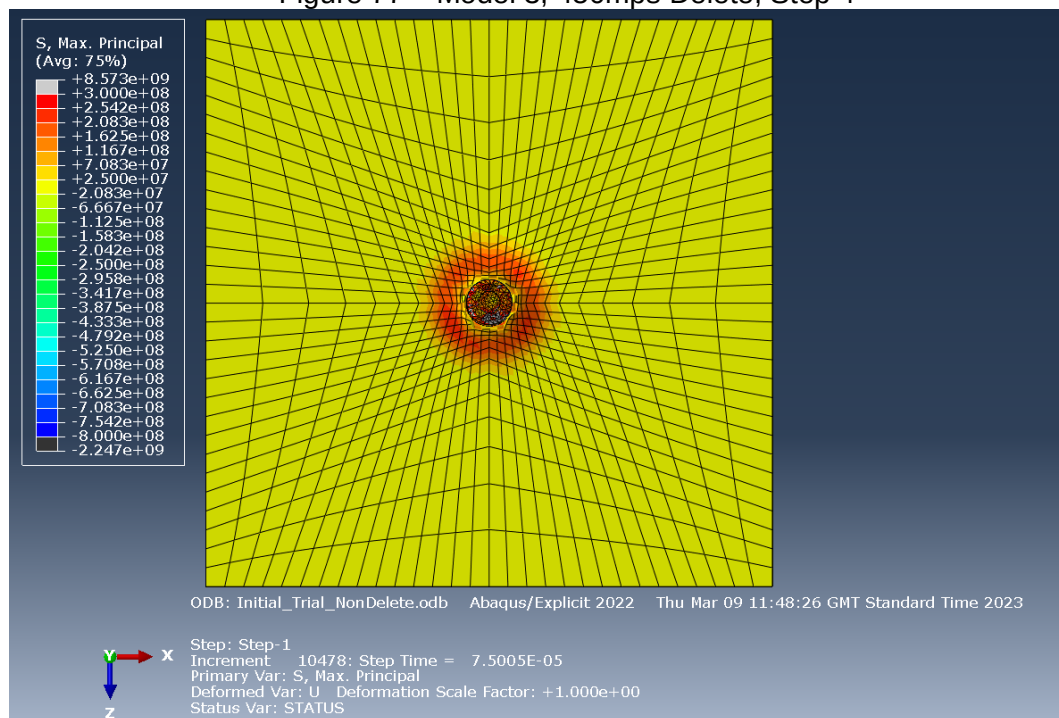


Figure 78 – Model 3, 450mps Delete, Step 4, Top

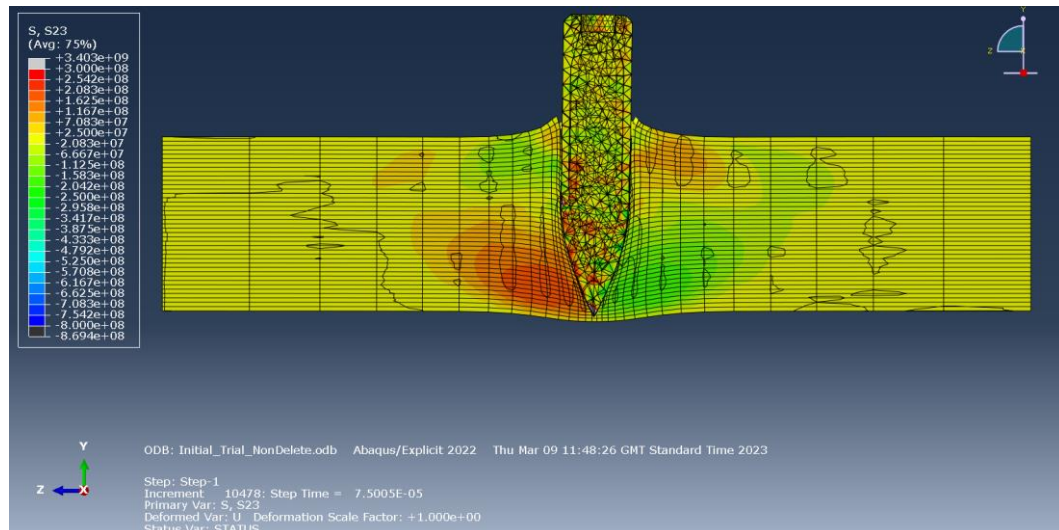


Figure 79 – Model 3, 450mps Delete, Step 4, Shear

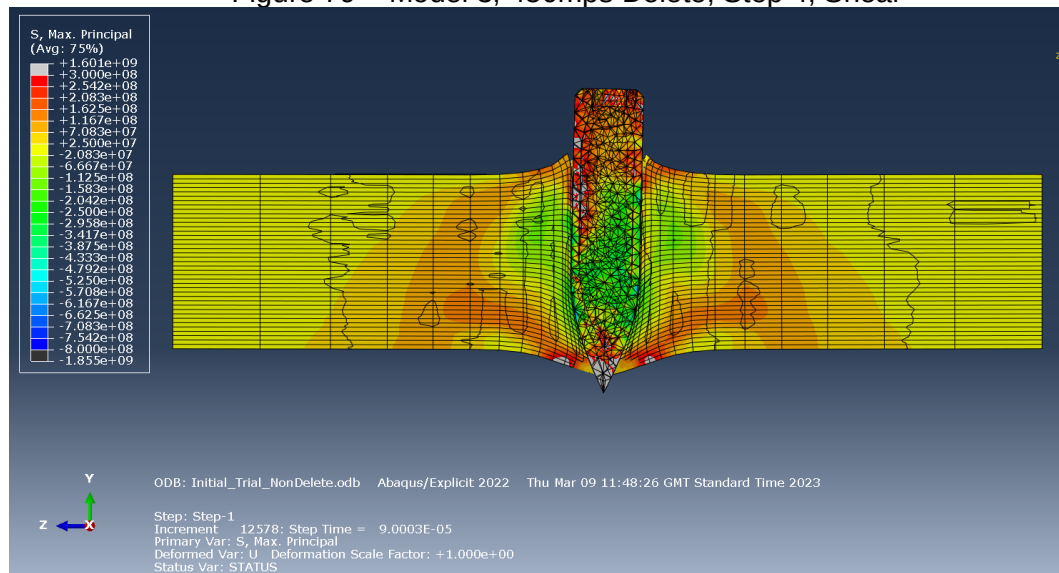


Figure 80 – Model 3, 450mps Delete, Step 5

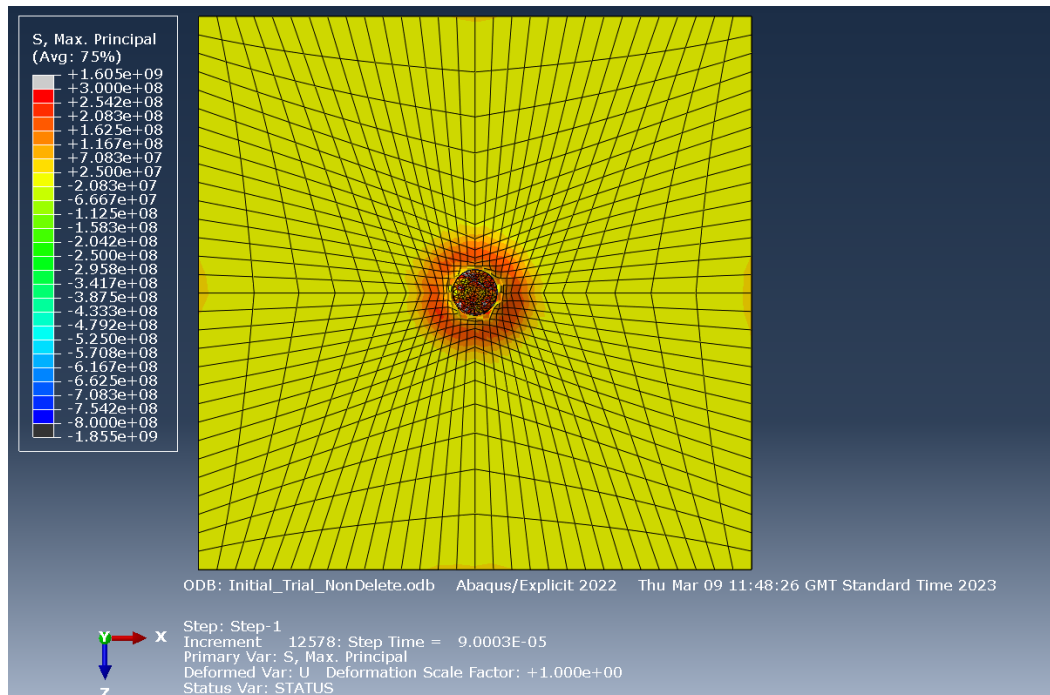


Figure 81 – Model 3, 450mps Delete, Step 5, Top

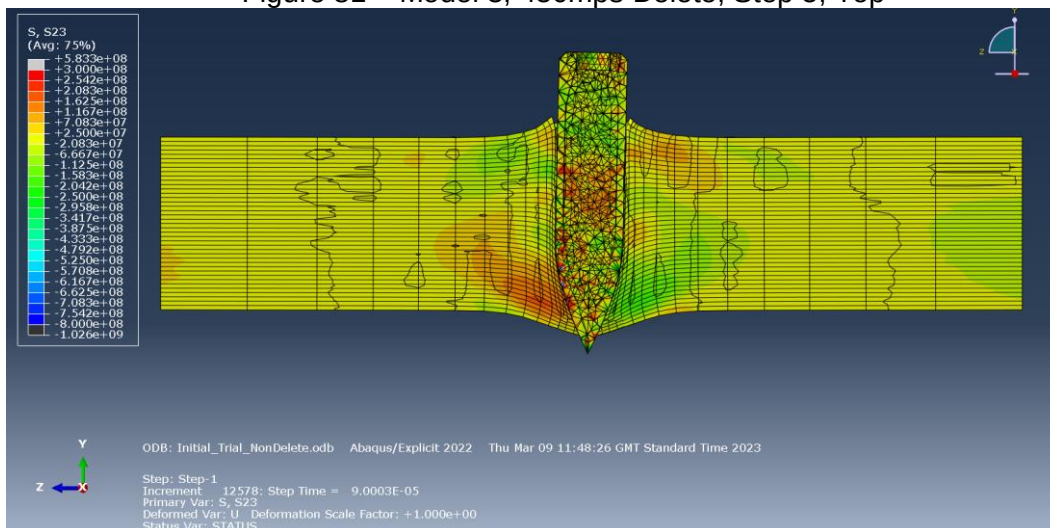


Figure 82 – Model 3, 450mps Delete, Step 5, Shear