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Design and Structural Analysis of Composite Prosthetic Running Blades for Athletes

A case of dynamic explicit analysis using Abaqus CAE

Yasser Alizadeh, Ph.D.

Abstract: This is a report on my mini project on designing composite prosthetic running blades for athletes. The focus is the implementation of explicit dynamics analysis within Abaqus CAE that simulates the extreme loading and impact conditions when such a prosthetic is used by an athlete. Material selection, static, impact, and explicit dynamic analyses as well as the results are explained and reported step by step.



Introduction to the problem and early initial assumptions

There are a few different designs of prosthetic running blades commercialized and used since the invention of the very first one by Van Phillips in 1989 (For US patent see[1]). He used “polymer impregnated and encapsulated laminates, including such laminates as carbon fibers and/or fiberglass or synthetic fibers such as Kevlar. [1]”

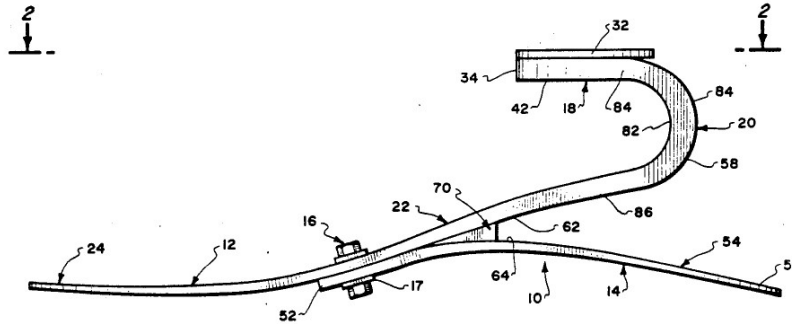


Figure 1- Van Phillips Running Blade [1]

One recent yet similar type of design to one of the Phillips is what is called C-shaped feet. These carbon-fiber based running blades such as the one shown in Figure 3 called Flex-Run by Ossur [2], are more commonly used for juggling pace and distance running[3] .

The other widely common design is called J-shaped feet such as the Cheetah Xtreme by Ossur Figure 2 and 1E90 Sprinter by Ottobock Figure 4 . They are designed for sprint and “quick return of energy” but not everybody might be able to use them effectively[3].



Figure 3- Flex-Run a C-Shaped foot by Ossur Inc



Figure 2- Cheetah Xtreme by Ossur



Figure 4- 1E90 Sprinter by Ottobock

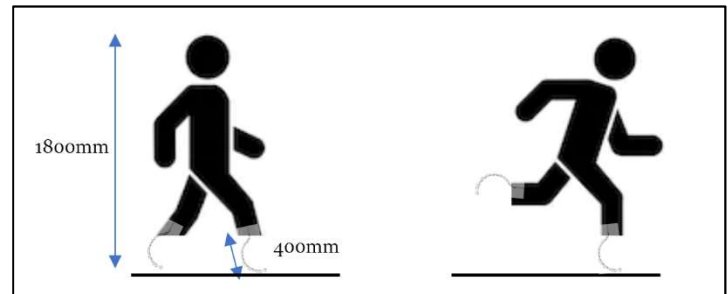
One study featured in Nature, has compared the impact of these three different designs type, their stiffness, and the height of blades and has concluded that J design has the most contribution to the runner velocity than stiffness or height [4]. Also, this type of the running blade has been identified as the interest of the problem, so design effort is focused on this type in this study.



Figure 5- J blade orientation relative to the sprint runner

To understand the extreme loading of the blade (worst-case scenario) as outlined by the problem, it seems safe to assume when runner is at the maximum speed and landing on one blade, the maximum impact occurs. Obviously, the weight of the runner is another important factor.

I will assume a **180 cm tall** runner which **weigh 700 N** or less with all his clothing gears (71.4 Kg). That means while the minimum requirement for the blade would be withstanding a 700 (in case of a slow walk) when shifting his weight completely from one blade to another as shown in Figure 6- left, in case of extreme impact runner is perhaps running around **6 to 10 m/s** (Figure 6-right), as explained in [4].



By assuming the velocity of **7 m/s** (7000 mm/s) the average contact time of each blade with the ground per [4] would be around **0.14 seconds** while the **step frequency** of the runner is assumed to be **0.4 Hz**.

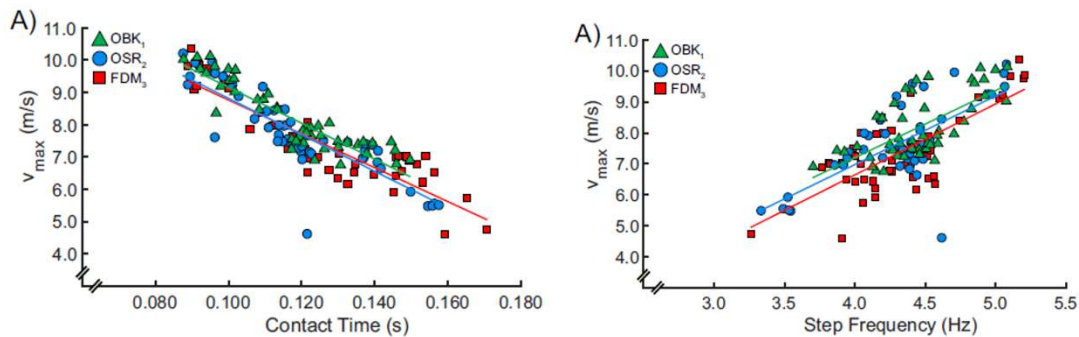


Figure 7- Average contact time and step frequency of 10 runners with 3 type of running blades including J-blade by Ossur (blue line) [4]

Height of the Cheetah (Xtend and Xtreme) models by Ossur is from 375mm to 530mm, they also have Nike spike pad to increase the traction and shock absorption. Although for the sake of simplicity, this rubber pad would not be included in the current study. They weigh around **1 Kg each**.

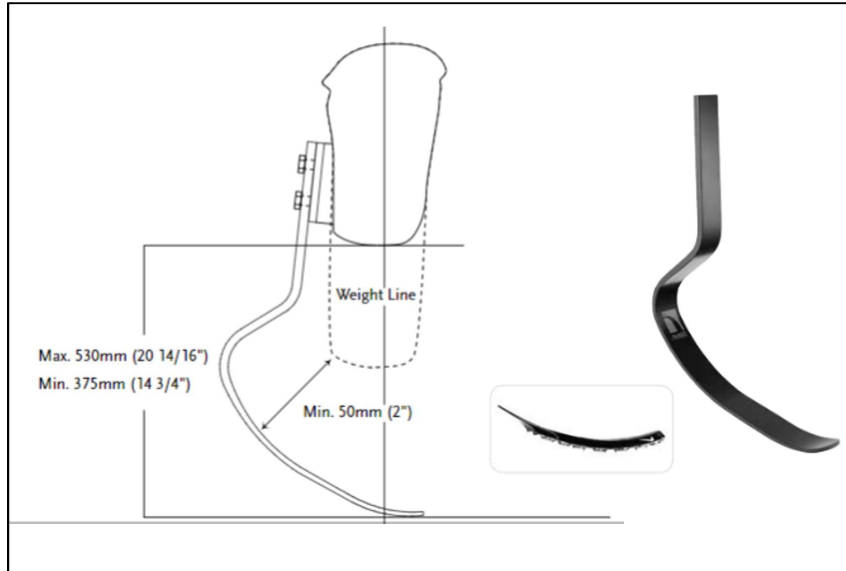


Figure 8- Dimensions of Flex-foot cheetah® xtreme (online Catalogue)

These running blade are also has pretty much constant width and thickness which justifies the use of shell element type for the case of simulation with Abaqus. I’m assuming around **100-140mm width** and **5-15 mm thickness** to be acceptable for my customized design. I’m also assuming mass of each blade could be up to 40% more than Ossur optimized fiber-carbon design, meaning up to **1.4 Kg**. This seems also appropriate when taking typical ski weights into considerations [5].

A preliminary general static analysis

I started the project with some simple explorative simulations of a simple C shaped blade (as shown in Figure 9) with Shell element type, to narrow down the design envelope size, proportionality of the blade relative to a typical runner (as shown in Figure 6) and test my loading, boundary conditions, symmetry, meshing and other simulation hypotheses in small scale before investing into the actual design of the J-blade. However, I’ll skip reporting those initial studies and will jump into design, modeling and simulation of the J-blade design.

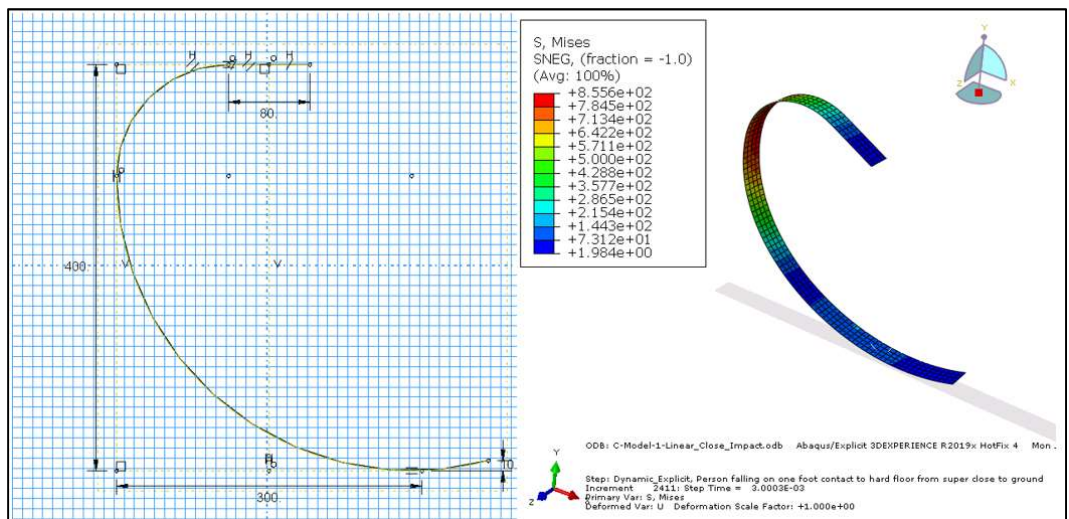


Figure 9-An initial set of modeling of a simple C-shaped blade

Explicit dynamic analysis

After the first rounds of simple static analysis, Figure 8 was used as a basis for designing the J-blade with the dimensions as shown in Figure 10 to simulate the impact of the blade into the ground. As mentioned, **shell type** element was used to model the part and sketch was extruded **100mm** to achieve the **width** of the blade. Also using datum planes, blade was split in half to use the symmetry later on if needed and partition the potential bottom surface of the blade that could hit the ground. An **analytically rigid floor** was modeled for two reasons. First, stress and deformation of the floor is out of interest of this study and including any stiff matrix adds to an unnecessary calculation time. Second, since I'm looking for the worst-case scenario for blade design, the more rigid the ground, the highest impact and stress on the blade. Blade was translated just above the ground (5mm clearance). The blade and hard floor assembly is shown in Figure 11.

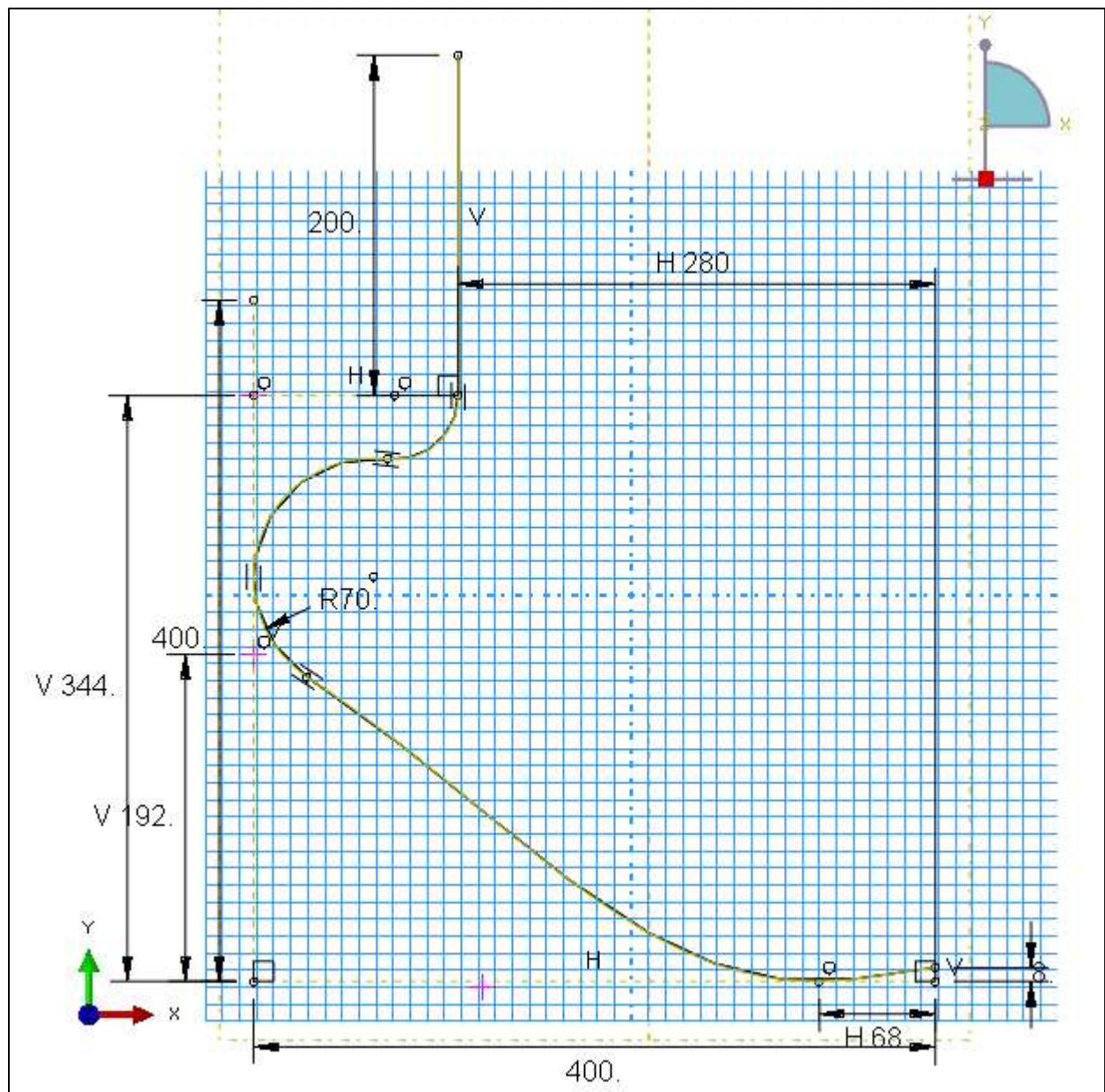


Figure 10- Design and dimensions of my J-blade, inspired by Cheetah Xtend model by Ossur

For the material, I started by exploring the possibility of using 7068 Aluminum alloy which is one of the strongest aluminum alloys commercially available (developed in mid 1990's). While density of this alloy is $2.85e3 \text{ kg/m}^3$ (**$2.85e-9 \text{ Ton/mm}^3$** for the entry in Abaqus) and its Young modulus of elasticity is **68000 MPa**, its yield strength and ultimate tensile strength in average are about 100 ksi (**689 MPa**) and 105 ksi (**724 MPa**) respectively per manufacturer [6], [7]. That has made this a new option for aerospace, automotive and even medical applications such as prosthetic limbs [8]. Figure 12 shows the material properties as entered into the simulation.

Although in the initial simulations round, symmetry was used to reduce the time and validating the model, by learning that even the full model could be simulated in around 2 minutes, I'm intentionally not going to use symmetry moving forward.

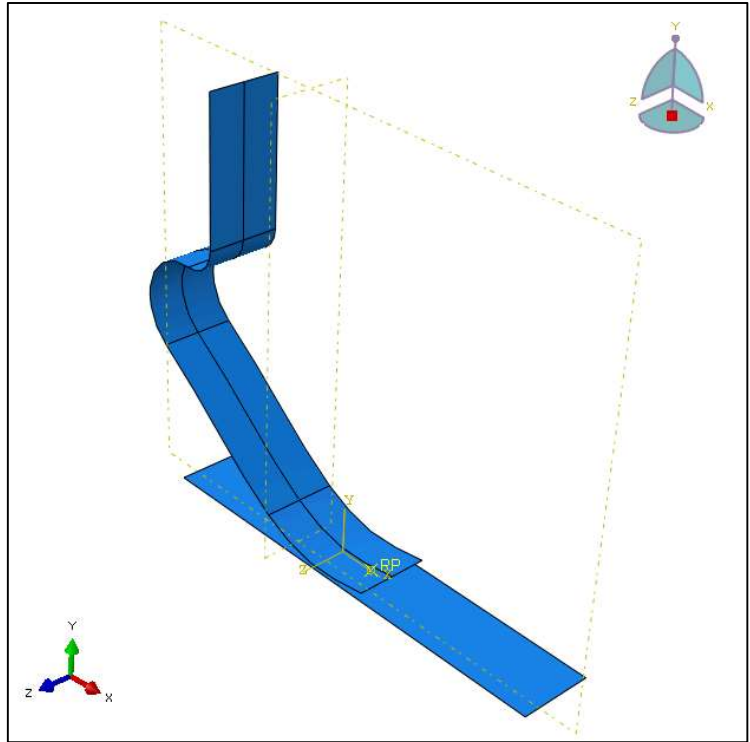


Figure 11- Blade and hard floor assembly

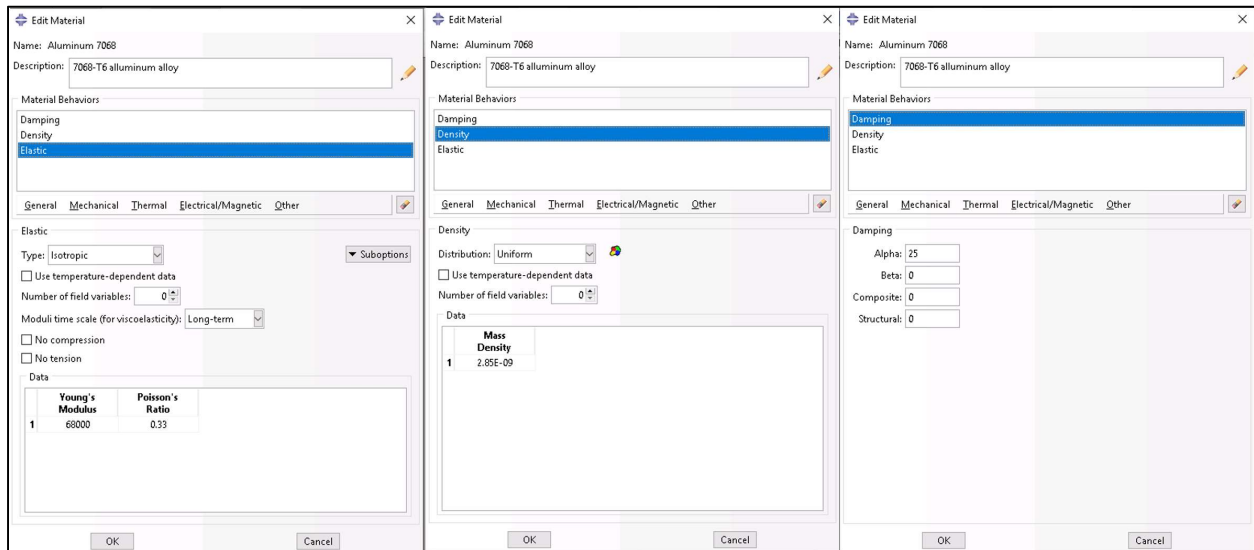


Figure 12- Data entry for the material properties of 7068-T6 Aluminum

For the section type, shell is selected and an initial **thickness** of **5mm** is assigned to the blade as shown in Figure 13. Figure 14 provides a visual check to ensure that thickness is added in the right orientation and there is no interference between the blade and the floor after adding the thickness.

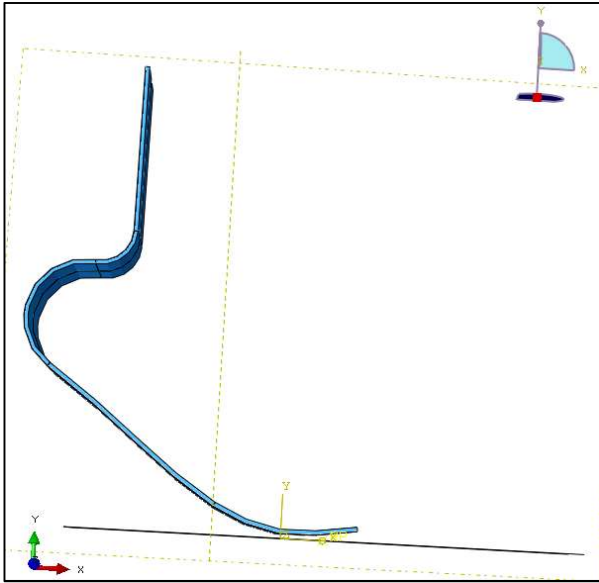


Figure 14- Verifying the blade thickness and clearance between blade and ground

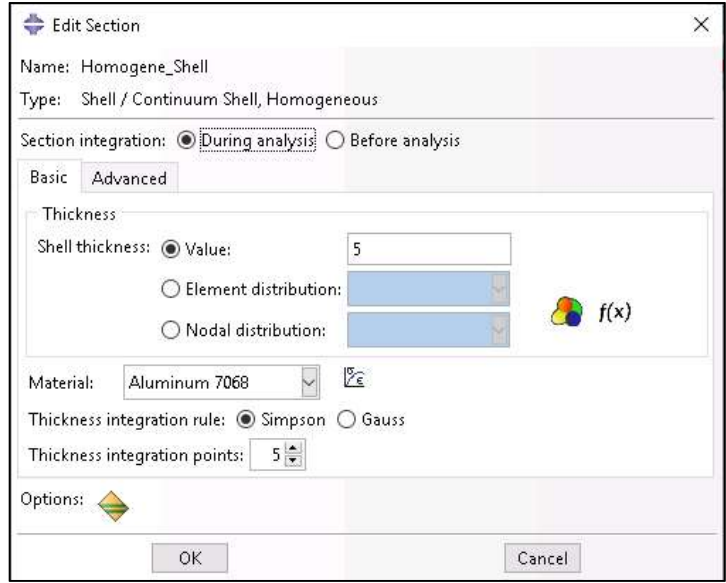


Figure 13-Section assignment

Boundary condition was then set for the ground. A reference point was defined on the analytically rigid ground and was constrained in all directions as shown in Figure 15.

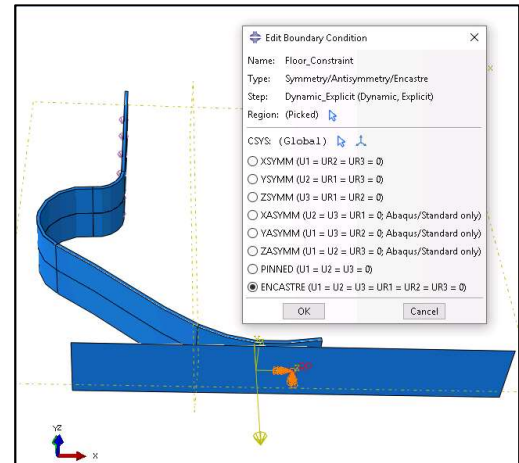


Figure 15-Boundary condition on the floor

For the load, first gravity was included in the simulation by adding the **gravitational acceleration of $9.81e3 \text{ mm/S}^2$** as shown in Figure 16.

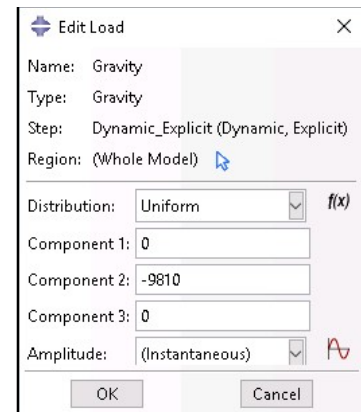


Figure 16-Applying gravitational force to the model

For the loading part, a **700N** runner falling slowing on one foot (blade) was considered for the first iteration. Also, the method of attaching the blade to the runner’s socket cap was considered a simple all surface bonding. Therefor the magnitude of the **load** on the selected surface was calculated as **0.035 MPa** ($700\text{N}/(200 \times 100) \text{ mm}^2$) and entered into the simulation as shown in Figure 17.

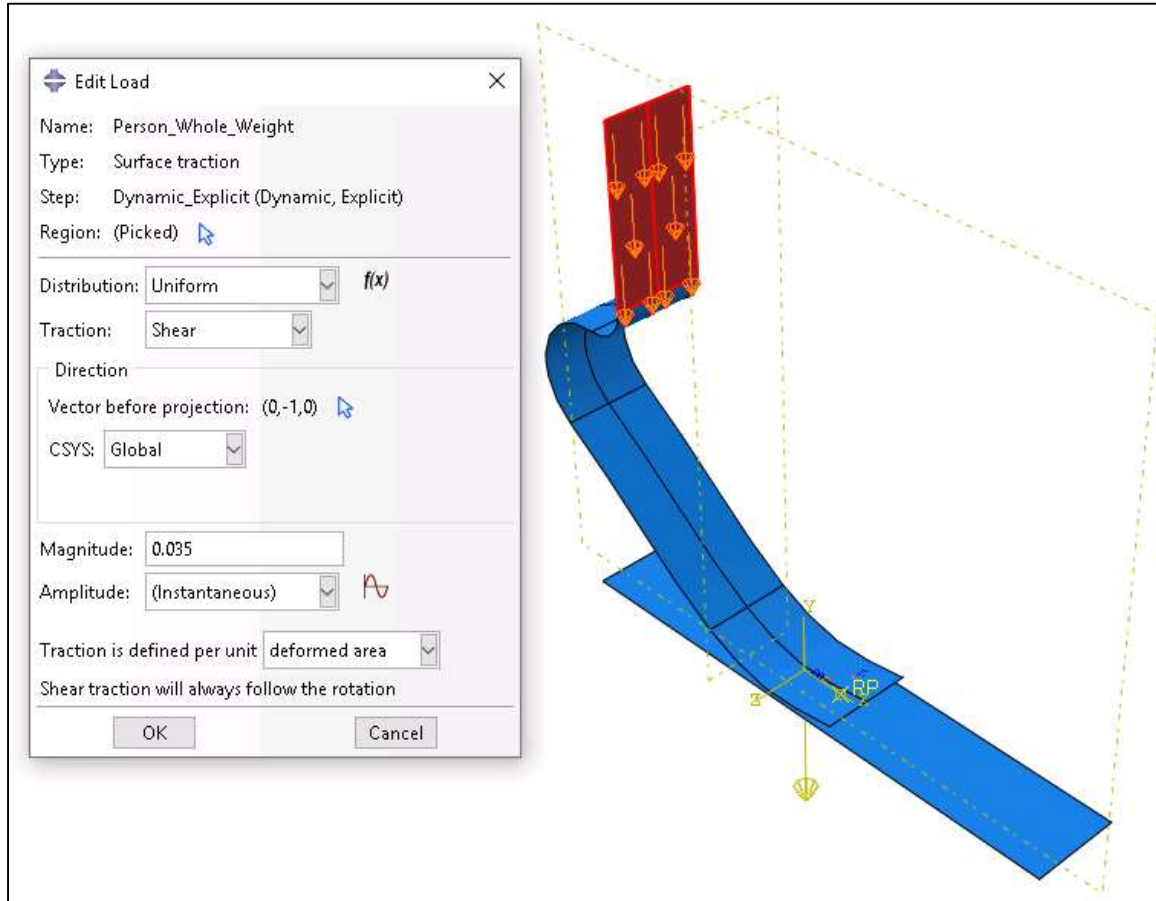


Figure 17- Implementing runner’s weight and blade weight

Finally, a small **initial vertical velocity** of **-100mm/s** was added to simulate runner’s slowly stepping on one blade (with whole body weight). This is the first iteration and later on maximum velocity (horizontal, vertical and angular) would be added Figure 18.

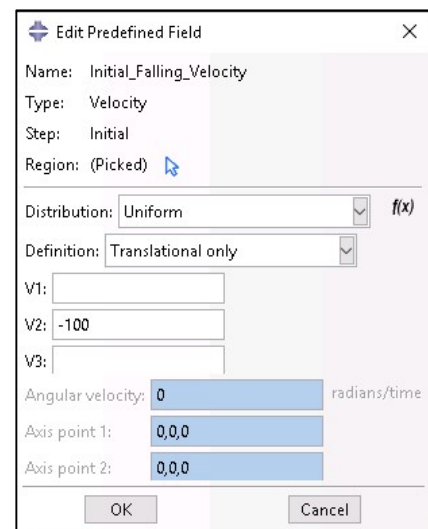


Figure 18-Initial Velocity of a slow pace

For the contact definition of blade and the hard floor a **coefficient of friction** of **0.25** was chosen as initial value based on my prior experiences (0.1 to 0.25 coefficient of friction is seen for glass and silicon wafers on 0.05mm surface finish aluminum surface). In reality this number would be likely higher for most applications including track, turf, or concrete floor. The normal interaction was set as hard contact Figure 19.

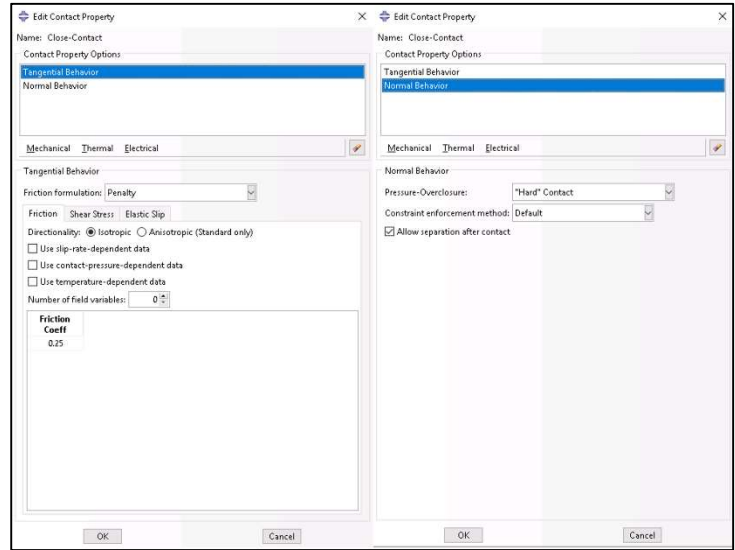


Figure 19- Contact properties definition

Meshing was done on the blade only by choosing an **S4 element type** (4 node doubly curved general purpose shell, finite membrane strain) in explicit mode and full integration as shown in Figure 20.

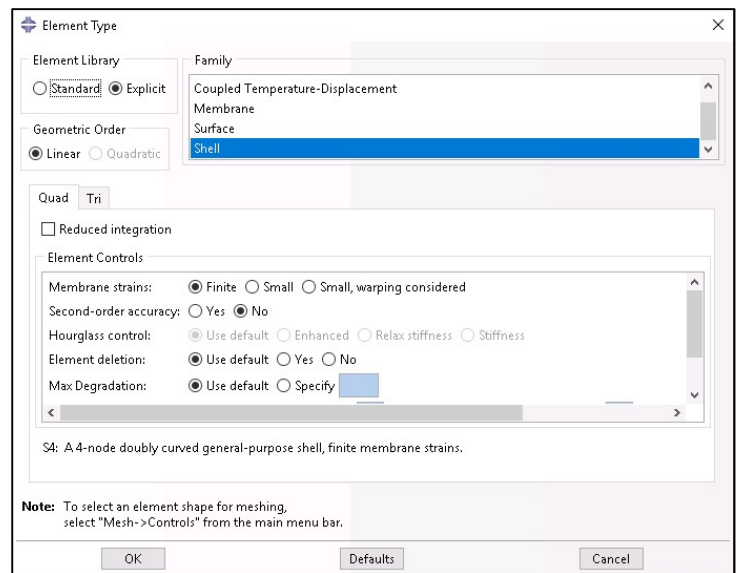


Figure 20-Element type

Only quadrilateral mesh built in **structured** way was used to generate the mesh as shown in Figure 21. That led to a an ideal shape (all non-distorted squares) meshing with 1308 elements and 1430 nodes as shown in Figure 22.

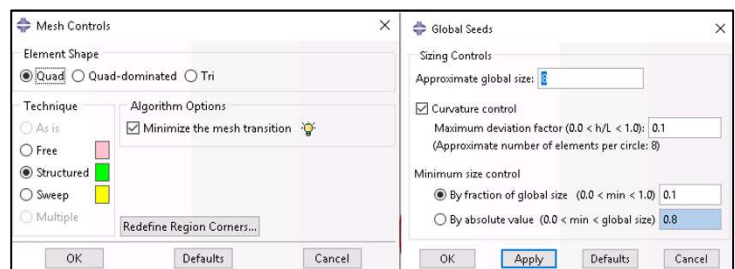


Figure 21-Mesh control and size control of the mesh

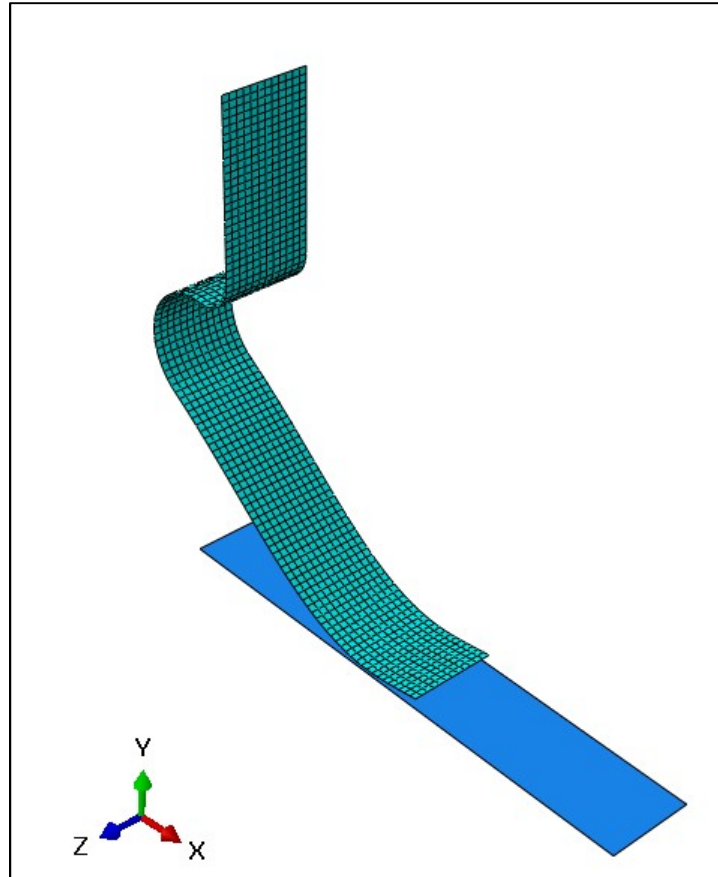


Figure 22-Meshed blade

Simulation results:

A dynamic explicit simulation for the time period of 0.05, was good enough to simulate the impact of the athlete switching weight on one blade from 5mm above vertically to the ground.

Figure 24 shows the von-mises stress changes in the blade in a few different time intervals.

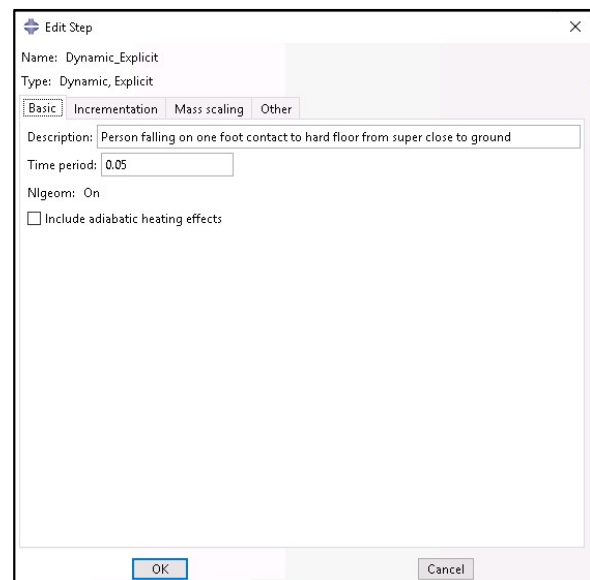


Figure 23

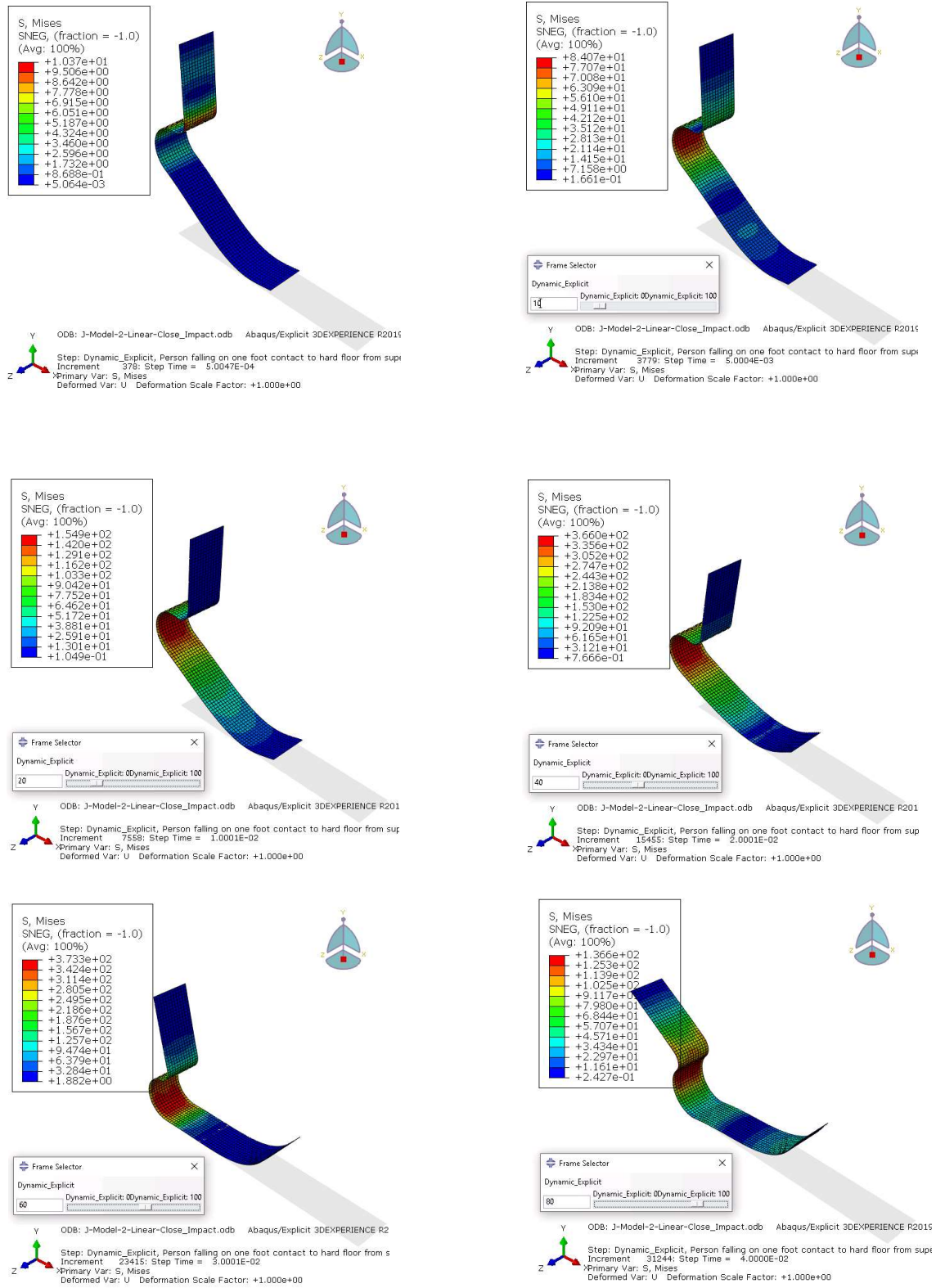


Figure 24- Von Mises stress on the blade in different time intervals

At no point the max Von-misses gets even close to the yield strength of the Aluminum 7068 which 689MPa, which means blades at this scenario stay in elastic region (no plastic deformation).

About the deformation aspect, displacement of the top surface on the Y axis is of interest. As Figure 25 shows the maximum elastic deformation on Y axis gets to around 165mm before blade start sliding on the ground horizontally (due to my surface traction loading setting).

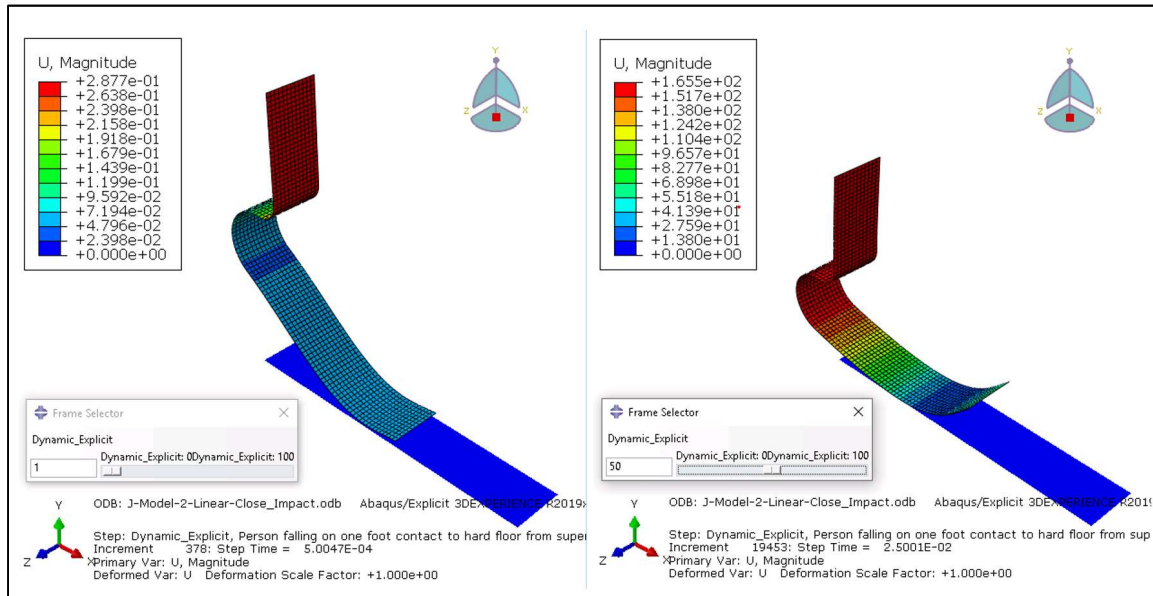


Figure 25- U2 at step 1 and 50

But before changing the loading setting to test for the real worst-case scenario (like jumping down from a height vertically) or adding 6-7 m/s velocity on X direction. I checked for two things; first weight of the blade, and second ratio of artificial strain energy to total internal energy.

Weight is important as part of the design goals. Getting a query on mass properties reveal the mass of the blade is 1.24e-3 ton or 1.24Kg. This falls within our initial acceptable design goal and is only 24% above the top of the line commercially available Ossur Extend blade with around 1Kg weight.

Ratio of artificial strain energy to the whole model kinetic energy, is an important indicator of proper meshing and minimum hourglass phenomenon in explicit dynamic analysis. While the maximum artificial strain energy reads as 8.219joule the maximum value of the whole model kinetic energy is calculated as 55150 joule, leading to a ratio of 0.00014, which is much less than 2% as the rule of thumb for the acceptable limit.

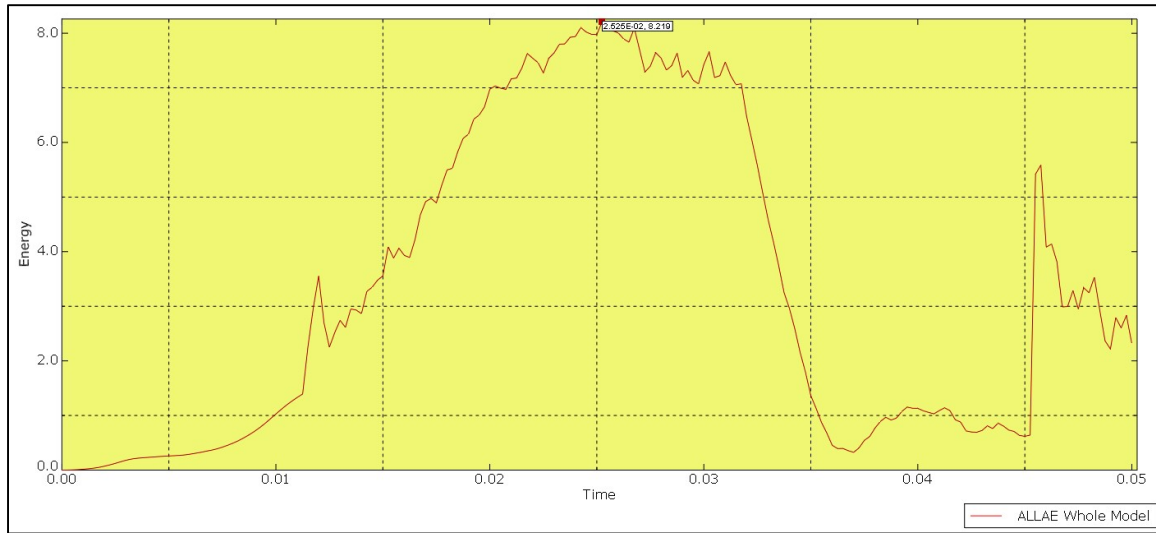


Figure 26- Maximum artificial strain energy of the whole model is calculated as 8.21 joule

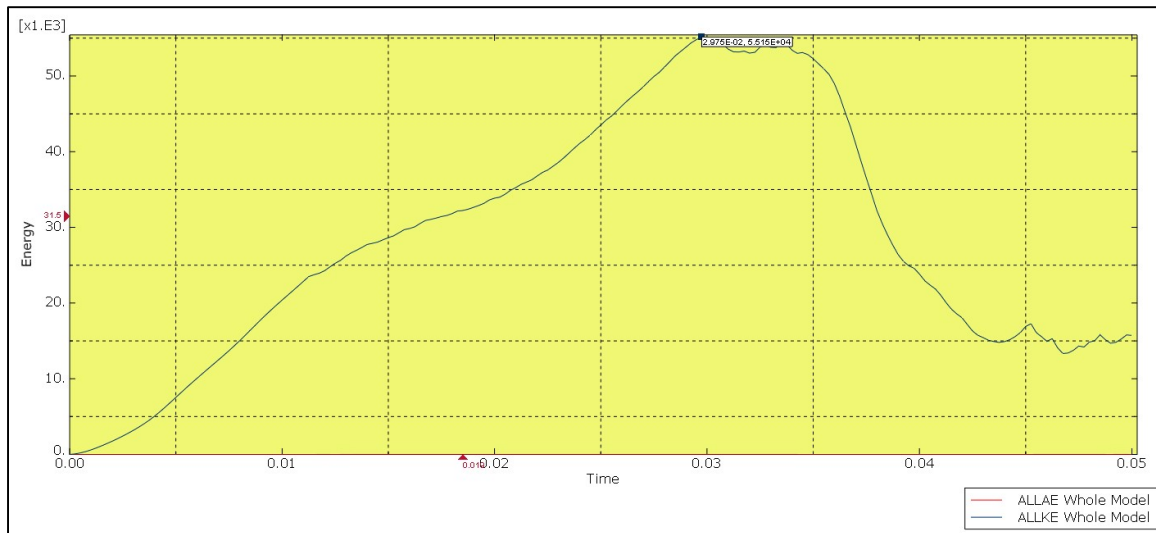


Figure 27- Maximum kinetic energy of the whole model is calculated as 55150 joule

In the next round of simulation, I add an initial velocity of 7 m/s on X direction and increase the initial Y velocity to simulate a condition of falling 1 m while running (a situation like hurdling). Also, to further reduce the weight of the blades, material is changed to composite as explain below. That also helps with the extreme loading situation since most likely the max Von-mises would exceed the yield strength of 7068 alloy too.

Explicit dynamic modeling of composite blade in hurdling situation

Although it's impossible to imagine the “worst-case scenario” for this open-ended problem, a reasonable extreme loading could be imagined for when the runner is participating in a hurdling event. Hurdles are 3 foot and 6 inches tall (1.06m) in an Olympic event. So, a vertical fall of 1000 mm is added to the simulation. That translates to **4420 mm/s** as the **vertical velocity** just before hitting the ground ($v = \sqrt{u^2 + 2gdu}$ where $u = 0, g = 9810 \frac{mm}{s^2}$, and $du = 1000mm$). Horizontal velocity of the runner perhaps has little effect overall on the extreme loading situation, yet we will consider an initial velocity of 7000 on the horizontal axis as well.

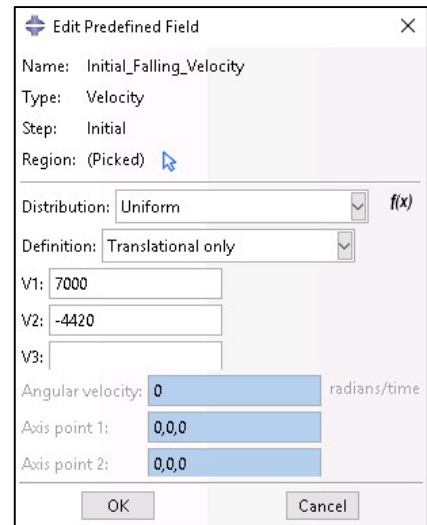


Figure 28- Modified initial velocity for the extreme loading scenario

Also as mentioned earlier, the typical contact time of each blade on the ground is **0.14s** [4]. This is added as the **amplitude** for the unloading as below.

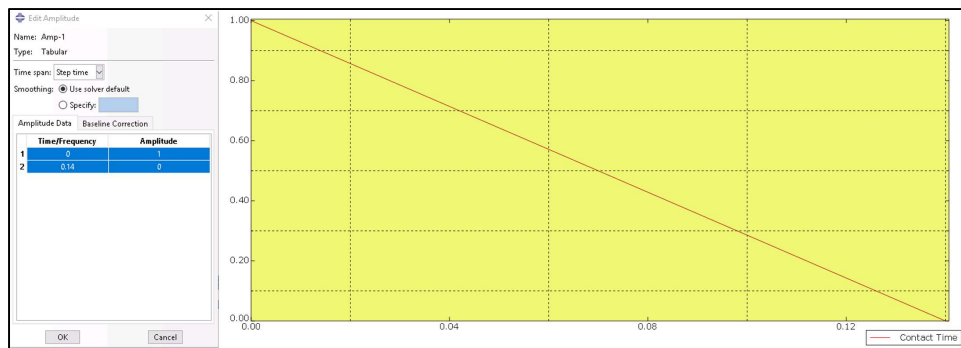


Figure 29- With a 7m/s the average contact time of runner's each blade is 0.14 [4]. With the blade being modeled in close distance of the ground, it's reasonable to model this as unloading amplitude from time zero to 0.14s

To add the composite, the section assignmet was deleted and a composite layup was built using conventional shell as shown in Figure 30.

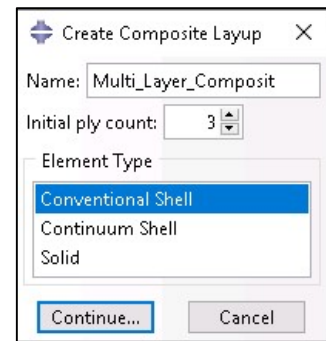


Figure 30-Creating Conventional Shell Composite Layup

For the **tensile** and **shear modulus** of composites available online sources were used and **HM Carbon Fiber UD** and two layers of **Kevlar** were picked for composite layup [9]. To maintain the overall thickness of 5mm two kevlar layers of **1.5mm thickness** were used around a **2mm** core Carbon Fiber UD. Ultimate tensile strength of the carbon fiber and Kevlar fabrics are outlined as 1000 MPa and 1300 MPa longitudinally (for reference the ultimate tensile strength of 416 stainless steel alloy is 741 MPa) and 40MPa and 30MPa respectively at 90 degree. Density of these materials are even less than previous case of aluminum at **1600 Kg/m³** and **1400 Kg/m³** respectively (entered in Abaqus as ton/mm³).

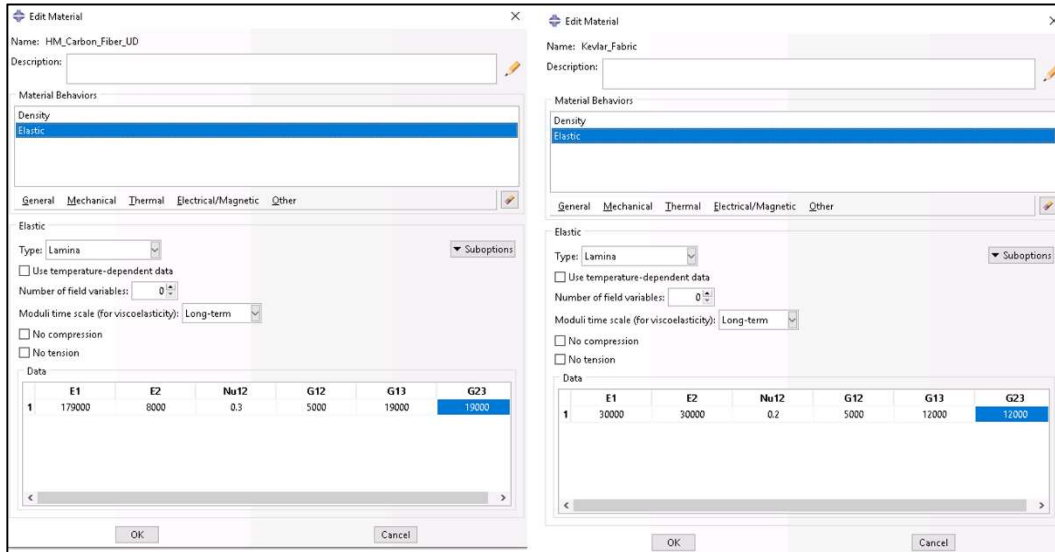


Figure 31-Properties of two carbon fiber UD and Kevlar fabric used in the composite layup

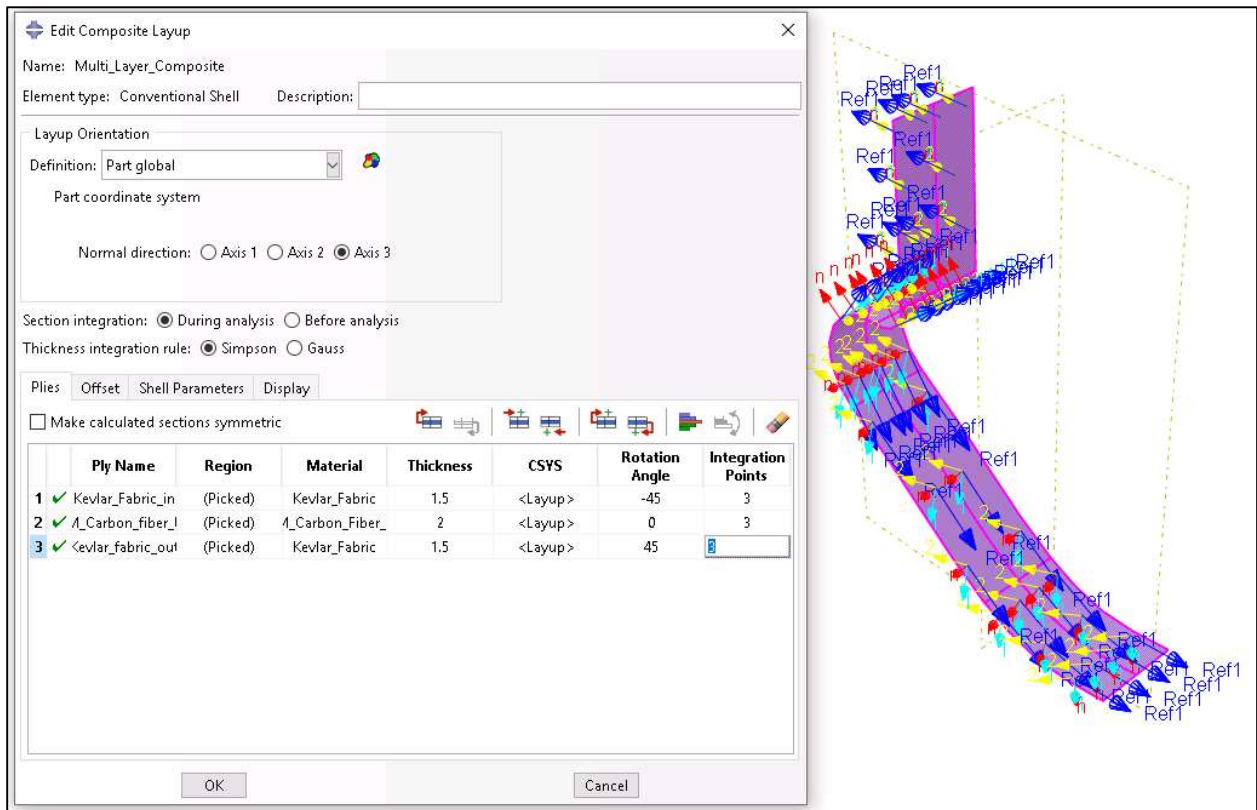


Figure 32- Composite layup of the blade

A query on the ply stack plot confirms the right orientation of the composites on the blade sections.

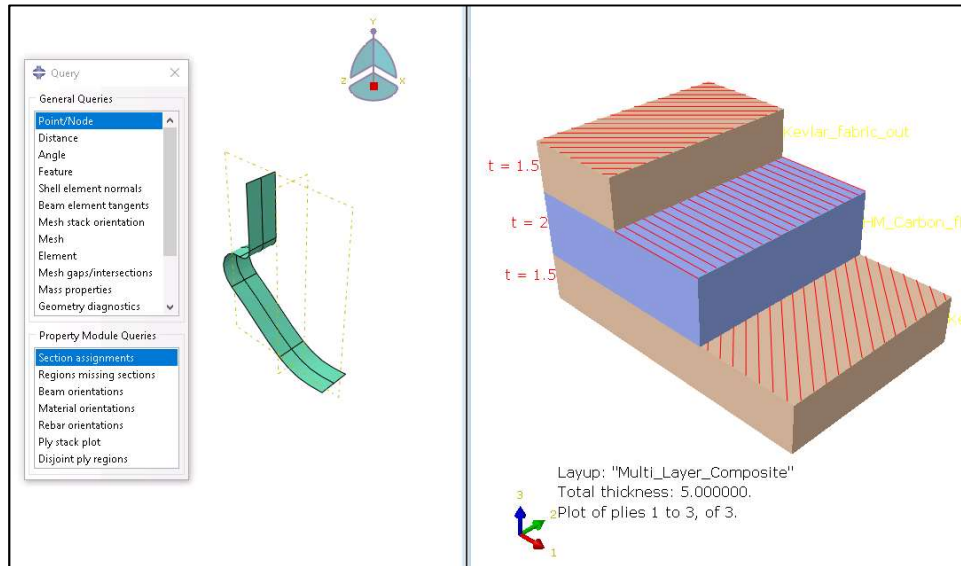


Figure 33- Ply stack up query to confirm the lamina orientation

One more time the artificial strain energy relative to whole kinetic energy of the model is calculated well below 2% acceptance limit (~0.07%).

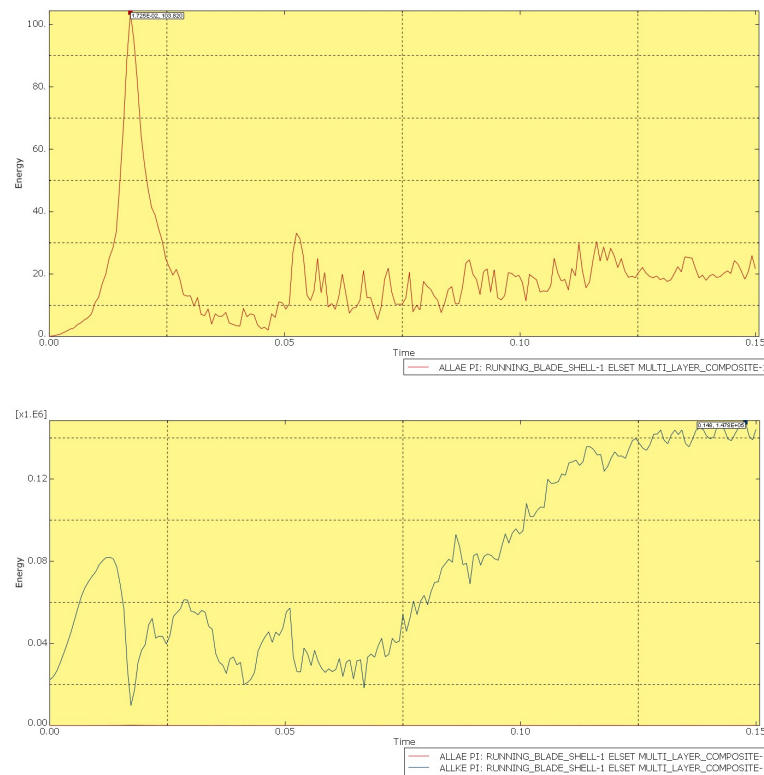


Figure 34- Artificial strain energy (top) vs Kinetic Energy and artificial strain energy (bottom)

Also max von-mises stress stays below ultimate tensile strength of the materials as shown below.

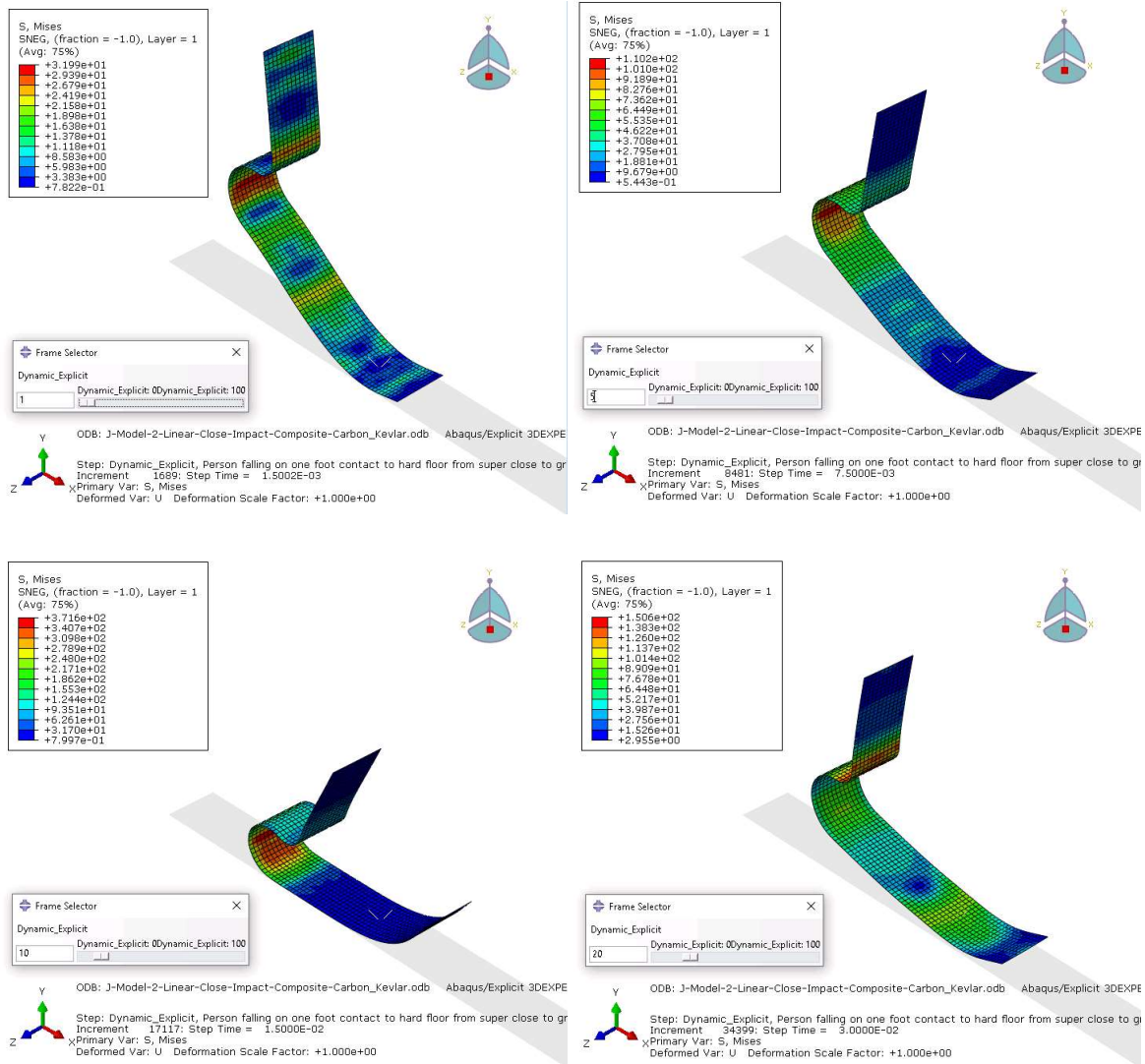


Figure 35- Von-Mises stress in 0.0015 second, 0.0075 second, 0.015 second, and 0.03 second after contact

Max von-mises happens at time (0.018 seconds) for a region shown in in Figure 36.

Figure 36 shows the Von-Mises stress for a node at this region that experiences the highest stress throughout the simulation as **465 MPa**.

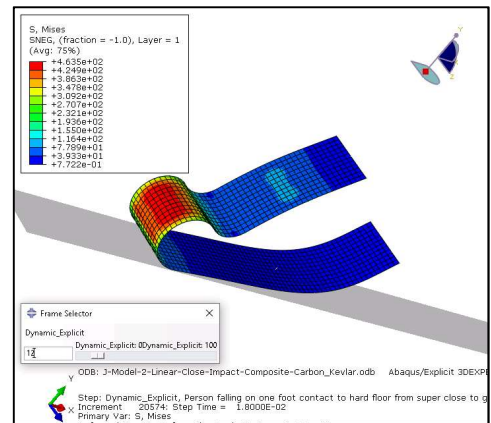


Figure 36- Region that experiences the max Von-mises

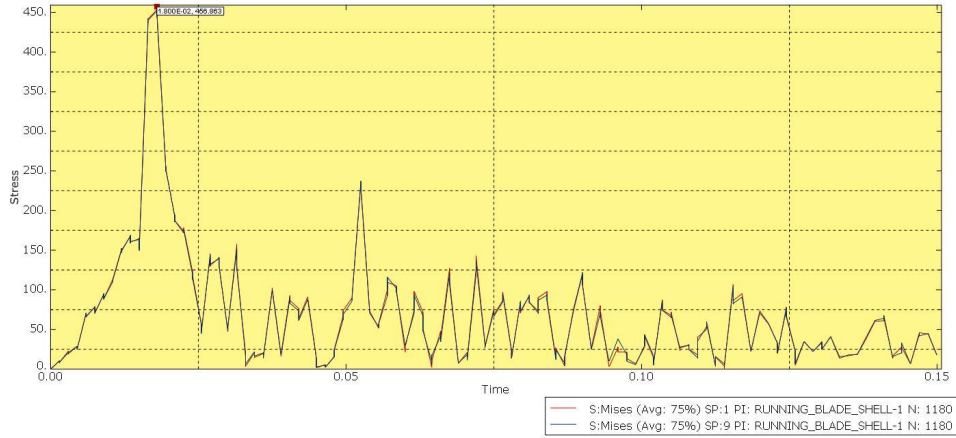


Figure 37- Von-Mises stress at Node 1180 through simulation

Figure 38 in the other hand shows the amount of displacement on Y direction in the same time intervals.

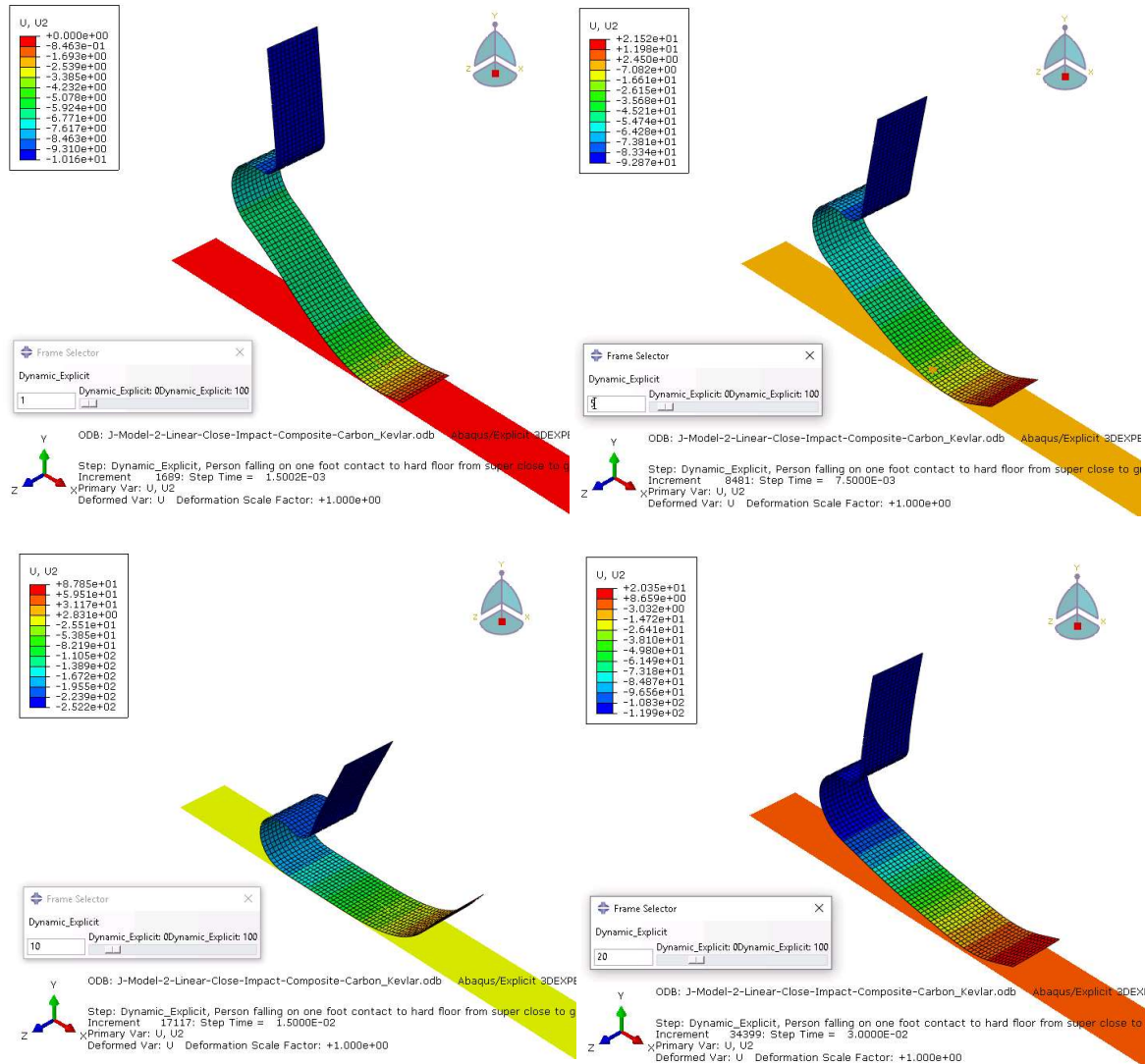
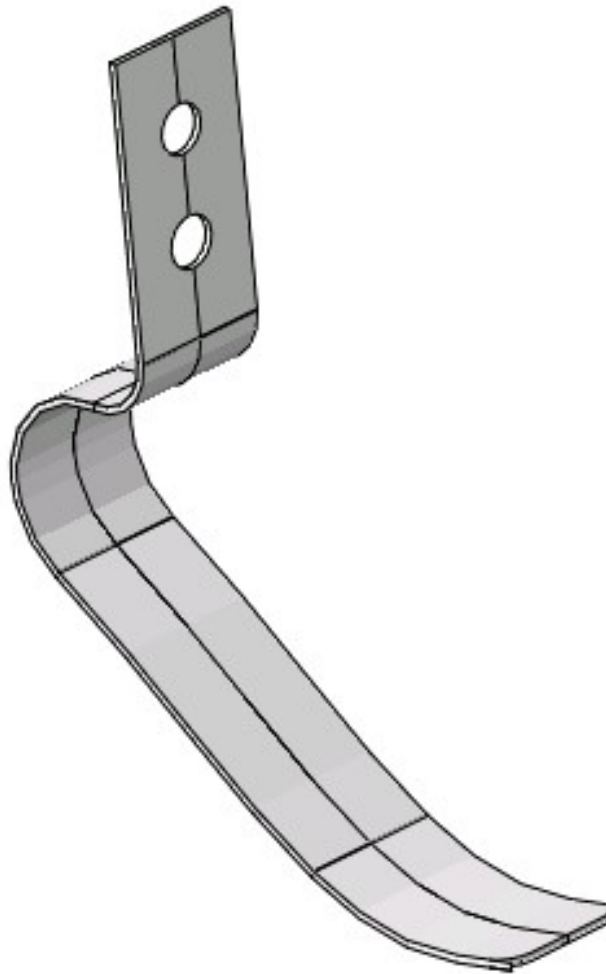


Figure 38- Displacement on Y direction at 0.0015 second, 0.0075 second, 0.015 second, and 0.03 second after contact

Conclusion

This design, with all the assumption mentioned earlier meet the design goals. First the maximum Von-mises in the blade is always less than 465MPa for the composite design that is at 30% of the ultimate tensile strength of the composite materials. So, assuming the feasibility of making a three layer composite as mentioned earlier and overlooking the properties of the bonding, material should withstand the extreme loading situation and even high cycles of loading.

Also moving from Aluminum 7068 to this composite material while maintaining the same thickness, weight of blade was reduced to 0.647 Kg which even considering the extra weight of the socket cap, bolts and shock absorber elastomer add-ons, the total weight should stay below 1Kg, which is the ideal goal.



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