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**MODELING OF HUMAN SPINAL INJURY UNDER
CENTRIFUGE LOADING SCENARIOS**

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Penn State University

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1.0 STATIC SIMULATION DEVELOPMENT

1.1 Implicit Dynamic Simulation

The implicit dynamic simulation was the first spine simulation that was run. The implicit dynamic simulation served as a good starting point for Penn State to achieve the goal of long-term simulations. The simulation results that were obtained from LS-DYNA were input into the MATLAB damage model which produced element-wise damage results. The damage results and the spine model were exported to ParaView and element-wise damage was plotted on the spine model.

The implicit dynamic simulation was run using an acceleration rate of 6 Acceleration of Gravity, Per Second (G/s). The acceleration loading profile is shown below in figure 1. This simulation was run for a time period of 0.25 seconds and achieved a maximum acceleration of 1.5G (Gravitational Force). Test data from the USAF shows that pilots achieve a maximum acceleration of 9 G during centrifuge training. To achieve this large of an acceleration value in the simulation, the loading profile or simulation run time will need to be increased. The first implicit dynamic simulation that was run, was limited to a 48-hour runtime due to the available computational resources. Once the simulation's von Mises stress results were collected, they were input to the MATLAB damage model. The damage model was run assuming that pilots

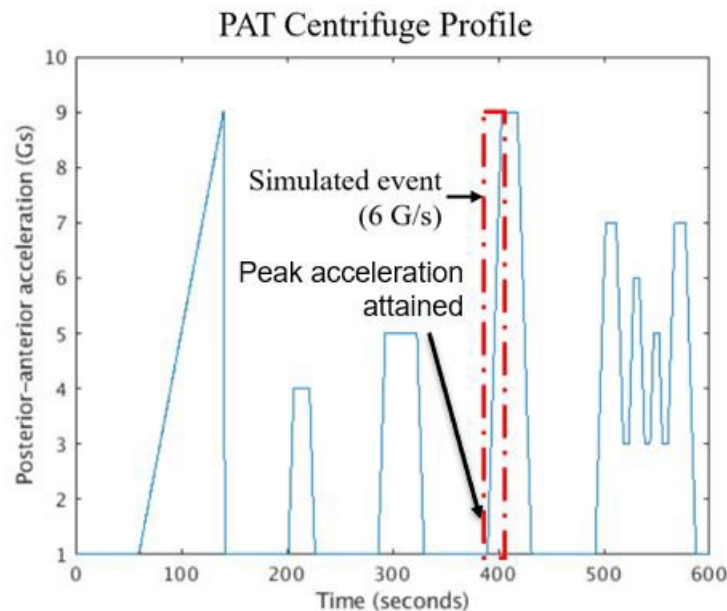


Figure 1. Acceleration loading profile used in implicit dynamic simulation

experience an acceleration load of 1.5G 600 times per day. The MATLAB damage plot for the C2-3 disc is shown in Figure 2. Each line on the damage plot represents the damage progression for a single element in the C2-3 disc.

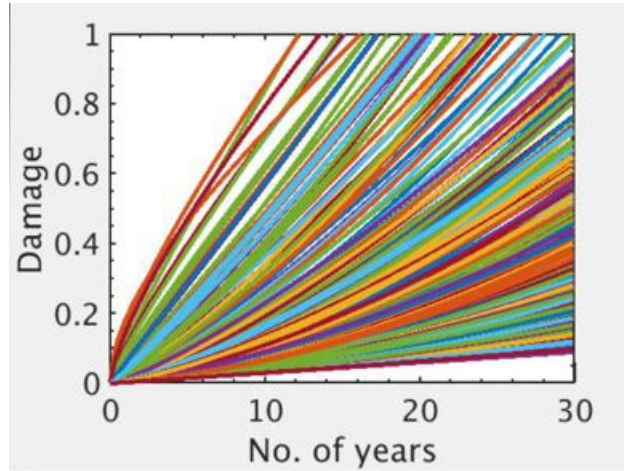


Figure 2. C2-3 Disc damage results

Once the MATLAB damage model ran for all five cervical discs, the damage data was manipulated so that it could be imported into ParaView. The ParaView damage plots are shown in Figure 3.

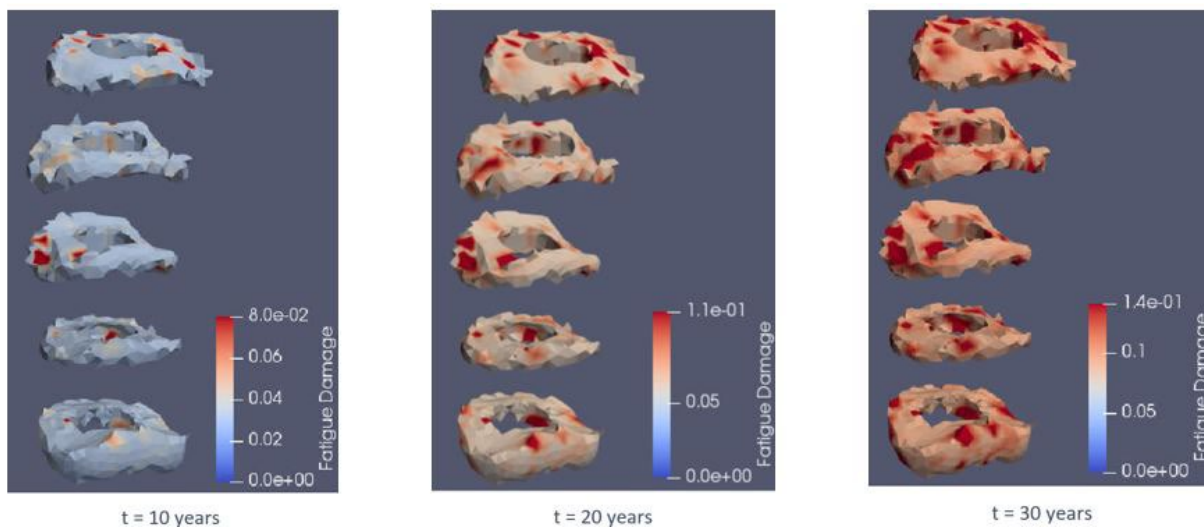


Figure 3. ParaView damage plots

The ParaView damage plots show that loading the spine at 1.5G daily for 600 cycles produces very little damage within the first 10 years; however, the damage steadily increases throughout the 30-year time period.

1.2 Initial Implicit Static Simulation

Due to the long run time and short simulation duration of the implicit dynamic study, the simulation was converted to an implicit static study. To make this conversion, Penn State modified the LS-DYNA keyword file by accessing the keyword manager within LS-PrePost. There are many simulation settings that affect

the simulation run time and duration.

The goal of the static simulation is to be able to achieve a longer simulation duration than the implicit dynamic study. The first three simulation settings that were examined are the maximum time-step, convergence tolerance, and the loading profile. With the current static simulation settings, the solver determines the time-step that it will use during each step of the simulation; however, the solver has a maximum time-step that it can use. The maximum time-step value is determined by the user. Increasing the time-step may slightly decrease the precision of the results, but increase the simulation duration. To help the solver reach equilibrium faster, the convergence tolerance may be increased, meaning a wider range of values would be accepted by the solver as equilibrium. Increasing the convergence tolerance will decrease simulation run time but may also decrease the accuracy of the results. Finally, the loading profile will greatly affect how the simulation runs. To achieve the desired high acceleration values, the load curve input into the model may be modified to be a constant acceleration or an acceleration curve that increases at a rate less than the 6 G/s that was previously used.

For the first static simulation, all of the variables of the static simulation remained at the default values. The initial static simulation used a maximum time-step of 0.01 seconds, a convergence tolerance of $1e-5$, and a loading rate of 6 G/s. The von Mises stress results from the base simulation are shown below in Figure 4. As displayed in Figure 4, the base static simulation only achieved a simulation time of 0.12 seconds. Although the simulation only achieved a simulation time of 0.12 seconds, it only ran for approximately 8 hours due to the solver failing to find equilibrium. For comparison, the implicit dynamic study ran for 48 hours and achieved a simulation time of 0.25 seconds.

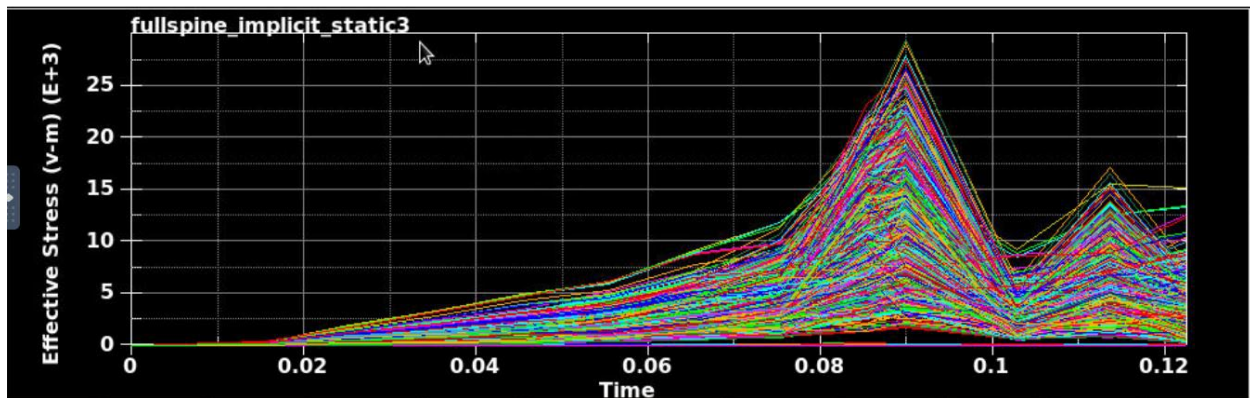


Figure 4. Baseline static simulation stress vs time results

The first variable that was changed was the maximum time-step that the solver was able to use. Since the solver was unable to find equilibrium during the baseline test, the maximum time-step was changed from 0.01 seconds, to 0.001 seconds. The results from this simulation are shown in Figure 5. This simulation achieved a simulation time of 0.25 seconds. Lowering the maximum time-step to 0.001 helped the simulation run smoothly but increased the run time. The simulation was ended when the 48-hour run time limit was reached.

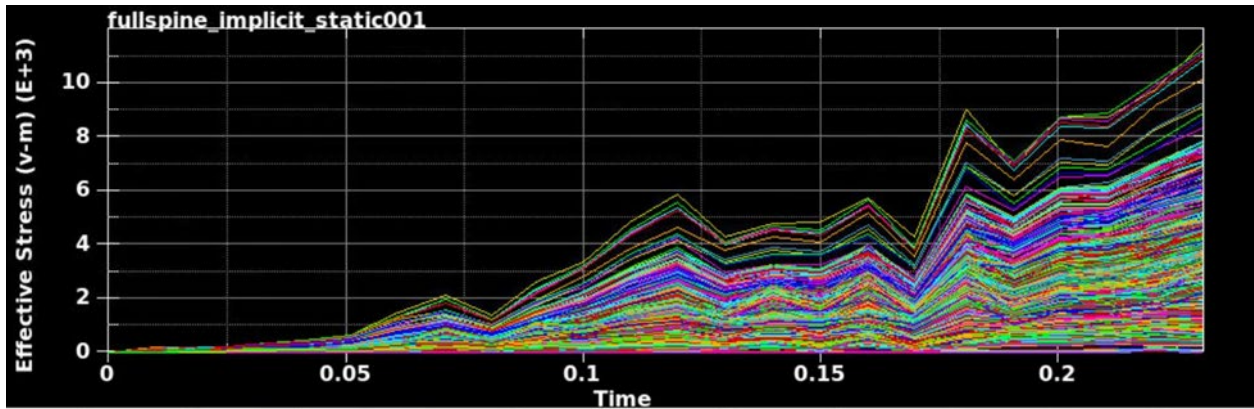


Figure 5. Static simulation with 0.001 time-step stress vs. time results

For the next simulation, the max time-step was reset to 0.01 seconds and the convergence tolerance was changed from $1e-5$ to $1e-3$. The increase in convergence tolerance increased the simulation time from 0.12 seconds to 0.2 seconds. The stress results from this simulation are seen in Figure 6. Based on the results, increasing the convergence tolerance also caused an increase in the von Mises stress within the C2-3 disc; however, the stress appeared to fluctuate.

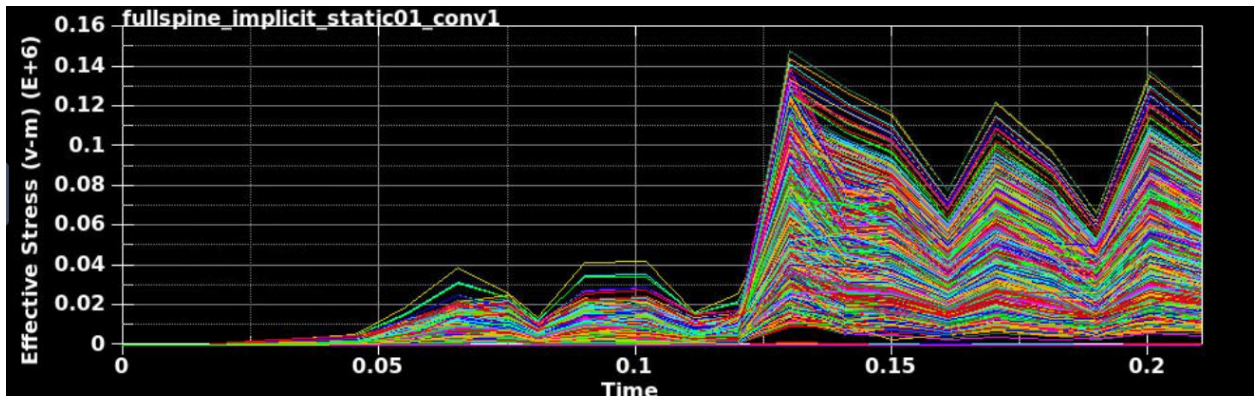


Figure 6. Static simulation with $1e-3$ convergence tolerance stress vs. time results

The final simulation that was run used the same convergence tolerance and maximum time-step as the base simulation; however, the loading condition on the spine was changed. In the previous simulations, acceleration increased at a rate of 6 G/s. The load that was placed on the spine was changed to a constant acceleration of 3G. The simulation duration was only 0.05 seconds but still achieved stress results similar in magnitude to the results from the baseline simulation and the simulation that used a maximum time step of 0.001 seconds, see Figure 7.

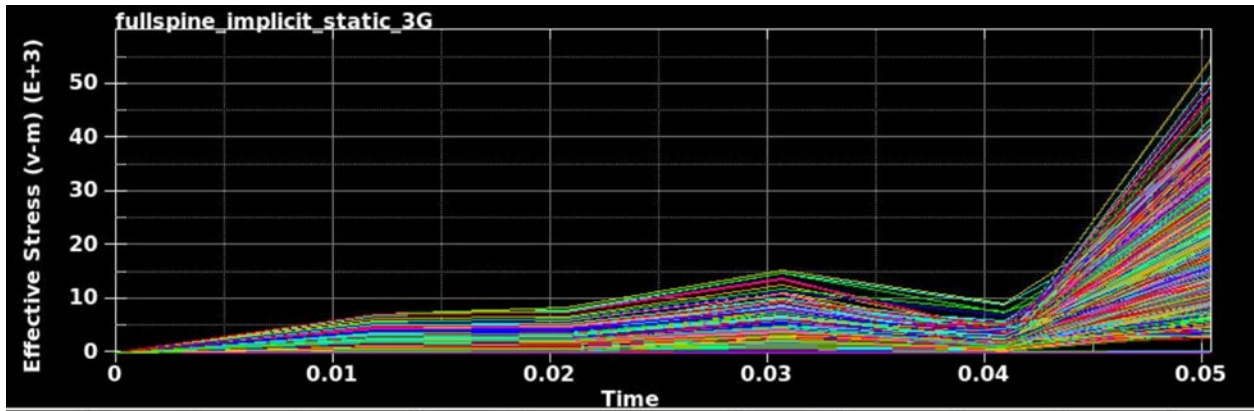


Figure 7. Static simulation with constant acceleration load of 3 G stress vs. time results

2.0 STATIC SIMULATION REFINEMENT

2.1 Displacement Based Implicit Static Simulation

In order to achieve the desired spinal loading conditions of pilots during centrifuge training, the spine simulation was changed from an implicit dynamic simulation, to an implicit static simulation. The main difference between the two simulation types is that static simulations are not time dependent, while dynamic simulations consider the effects of time. For the centrifuge simulation, this means that the static simulation does not account for loading rate, rather it simply depends on the maximum load achieved. The static simulation was run using a displacement load rather than an acceleration load. The full spine model was input into LS-DYNA and fully fixed at the sacrum, meaning every node in the sacrum was unable to rotate or displace. With the sacrum fixed, a displacement load was applied to the C1-2 vertebrae. The displacement of the C1-2 vertebrae was increased from 2mm (Millimeter) to 8mm in increments of 2mm. The displacement was applied to every node within the C1-2 vertebrae and was applied in the Y direction, this created a purely axial loading condition. Figure 8 illustrates the static simulation setup that was used.

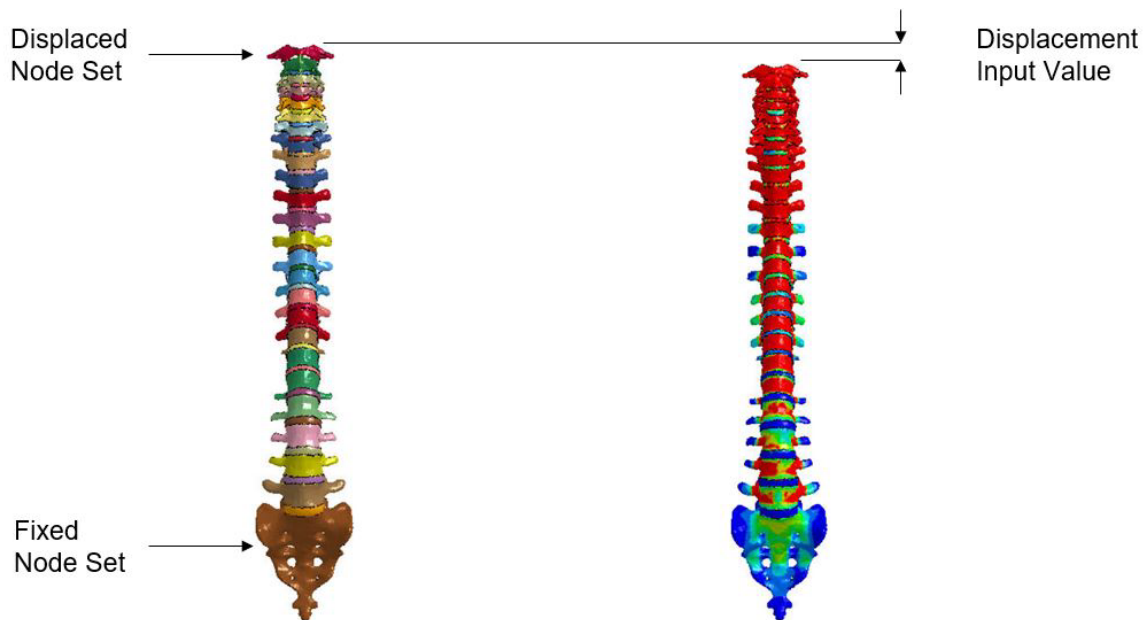


Figure 8. Static simulation setup used in centrifuge study

During centrifuge training, pilots experience large acceleration loads measured using the unit (g). To convert from an acceleration load measured in (g), to a displacement load measured in (mm), the graph in figure 2 was used. Figure 9 is just a preliminary linear approximation made by analyzing data from similar simulations, further literature review is required to validate the graph.

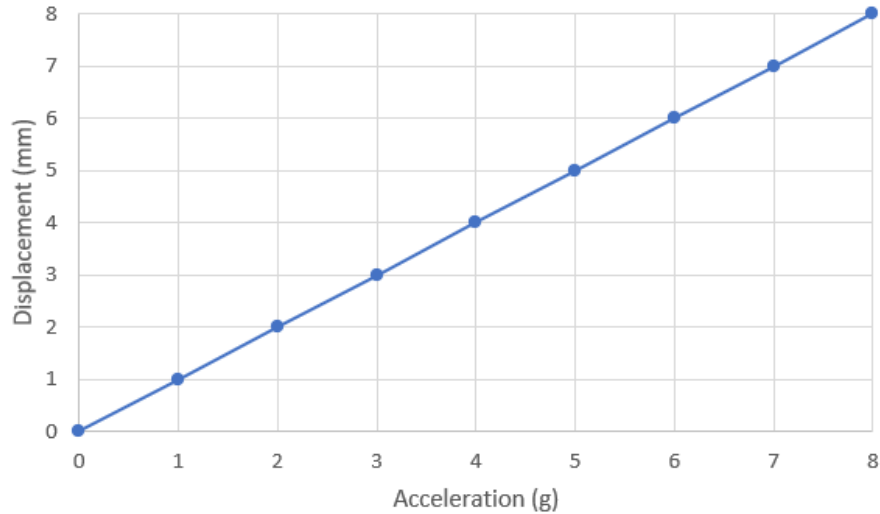


Figure 9. Graph used to convert from acceleration to displacement loading

2.2 Displacement Based Static Simulation Results

Upon analyzing the stress results from the 8mm displacement simulation, it was observed that the C2-3 disc had the largest stress values. Since the C2-3 disc had the highest stress values, Penn State decided to temporarily focus their damage and stress study on only the C2-3 disc. The stress results from the C2-3 disc under each loading condition were input into the MATLAB damage model. Figure 10.

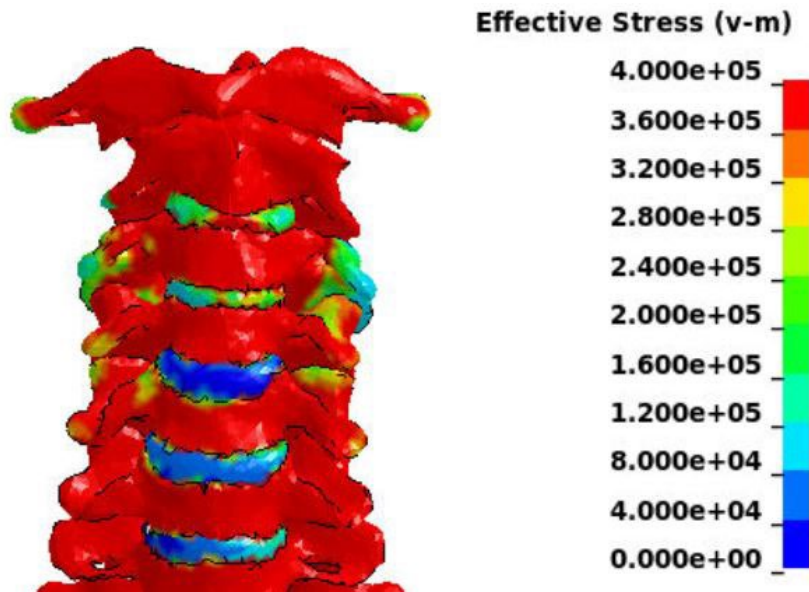


Figure 10. Stress results for the cervical spine with an 8mm displacement load

The centrifuge spine simulation produced element-wise von Mises stress for the entire spine model. As

stated above, the C2-3 disc was the focal point of this study. Figures 11-14 show the stress history for the C2-3 disc under displacement loads varying from 2mm to 8mm. Each line on the graphs represents the stress history of a single element.

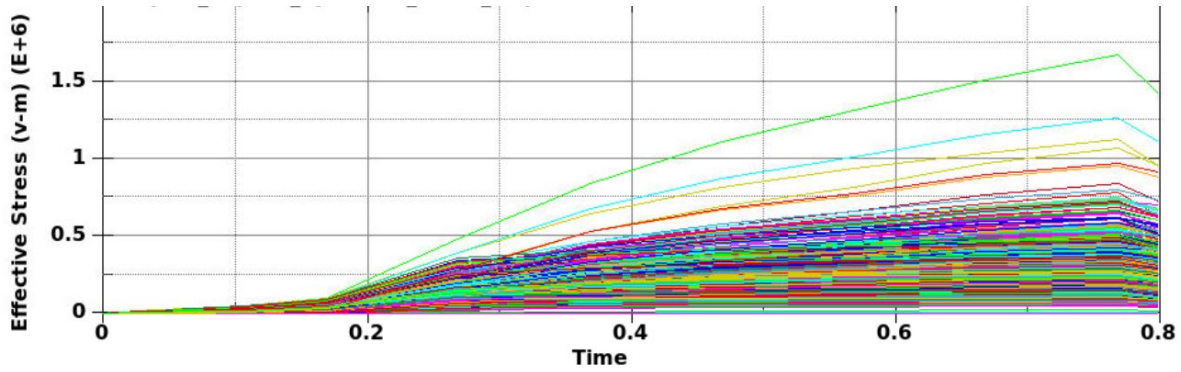


Figure 11. Stress history of C2-3 disc during 8mm displacement loading condition

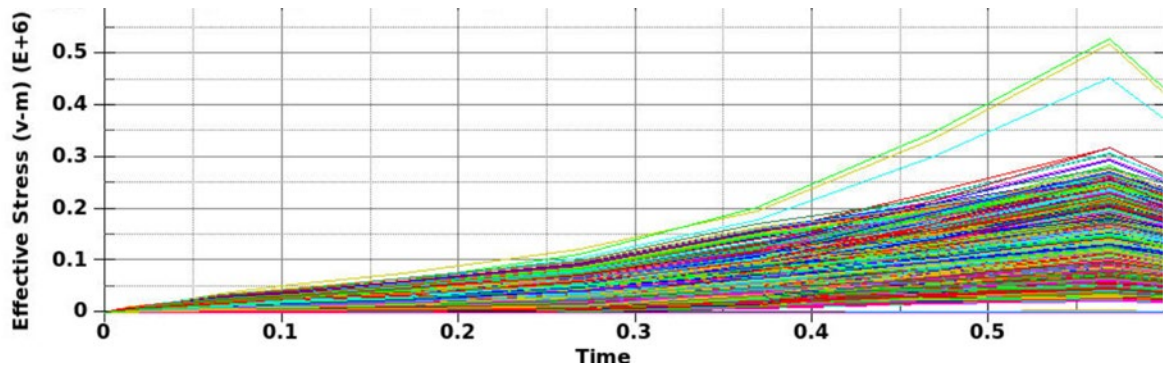


Figure 12. Stress history of C2-3 disc during 4mm displacement loading condition

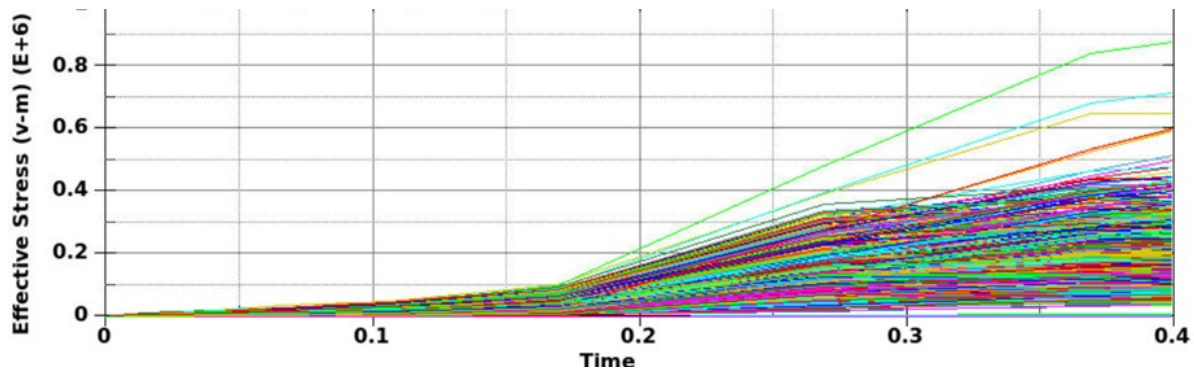


Figure 13. Stress history of C2-3 disc during 6mm displacement loading condition

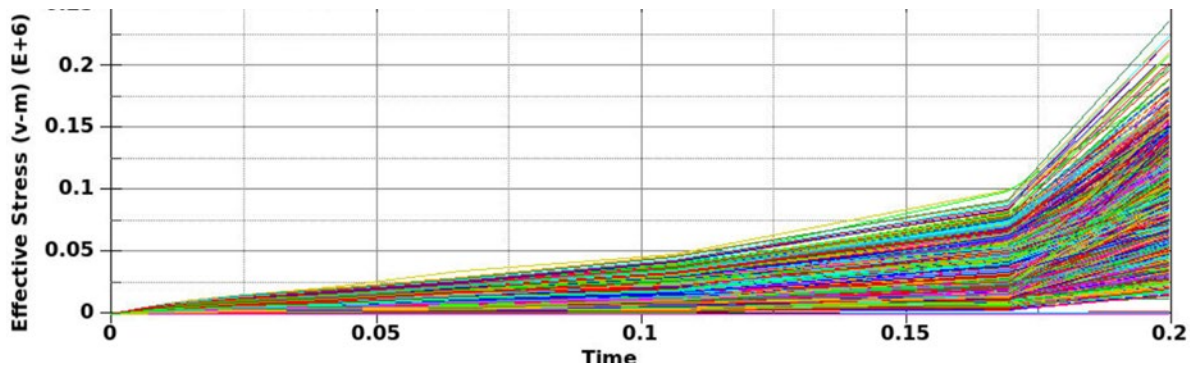


Figure 14. Stress history of C2-3 disc during 2mm displacement loading condition

The MATLAB damage model was run for every simulated loading condition using the effective stress plots shown in figures 11-14. The MATLAB damage model calculated the total damage accumulated in every element over a 30-year time period. For this study, the damage model was run assuming a pilot experienced 300 cycles per day of a single loading condition. The output of the damage model was a damage array that produced the graphs shown below in figures 15-18.

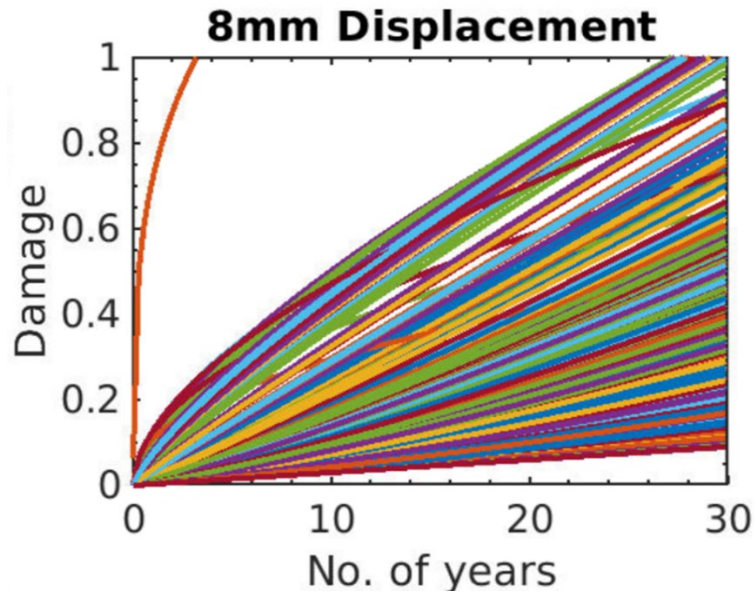


Figure 15. Element-wise total damage vs time

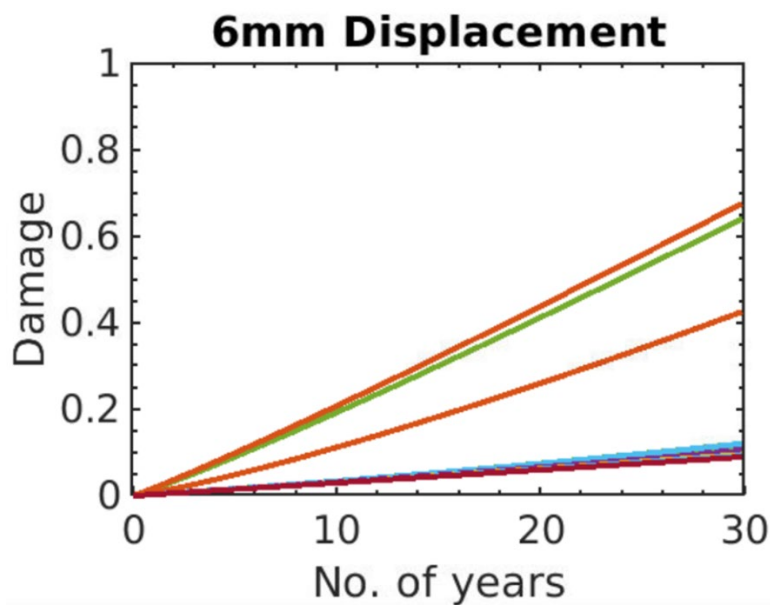


Figure 16. Element-wise total damage vs time

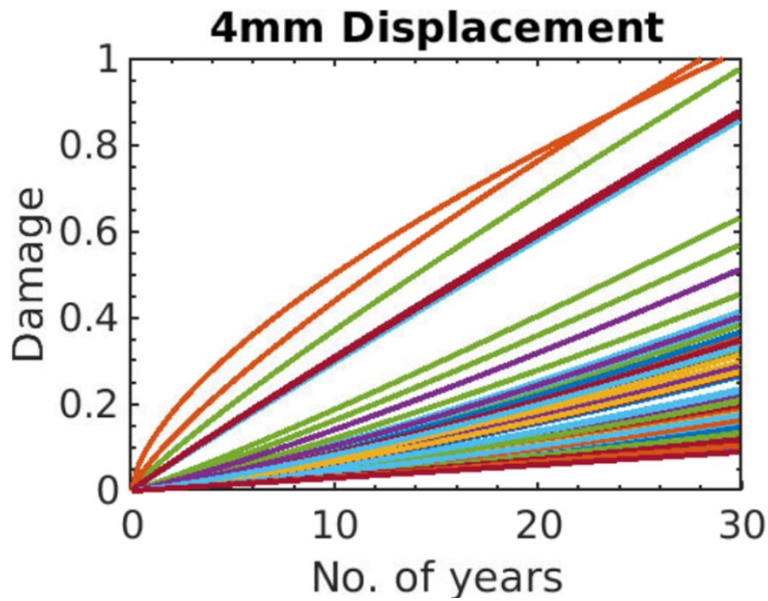


Figure 17. Element-wise total damage vs time

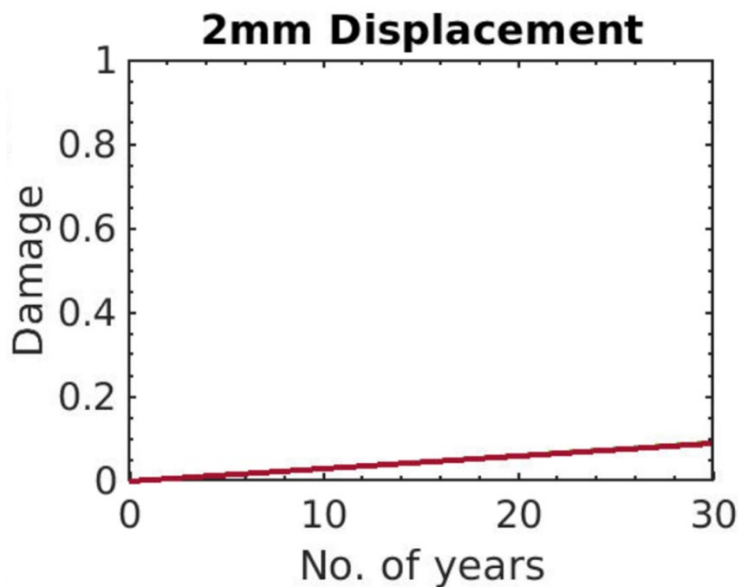


Figure 18. Element-wise total damage vs time

In order to visualize how the various displacement loads affected accumulated damage in the C2-3 disc, the graph shown in figure 19 was constructed. To create this graph, the total damage in every C2-3 disc element at a time of 30 years was averaged. The average damage value was then plotted against the loading condition.

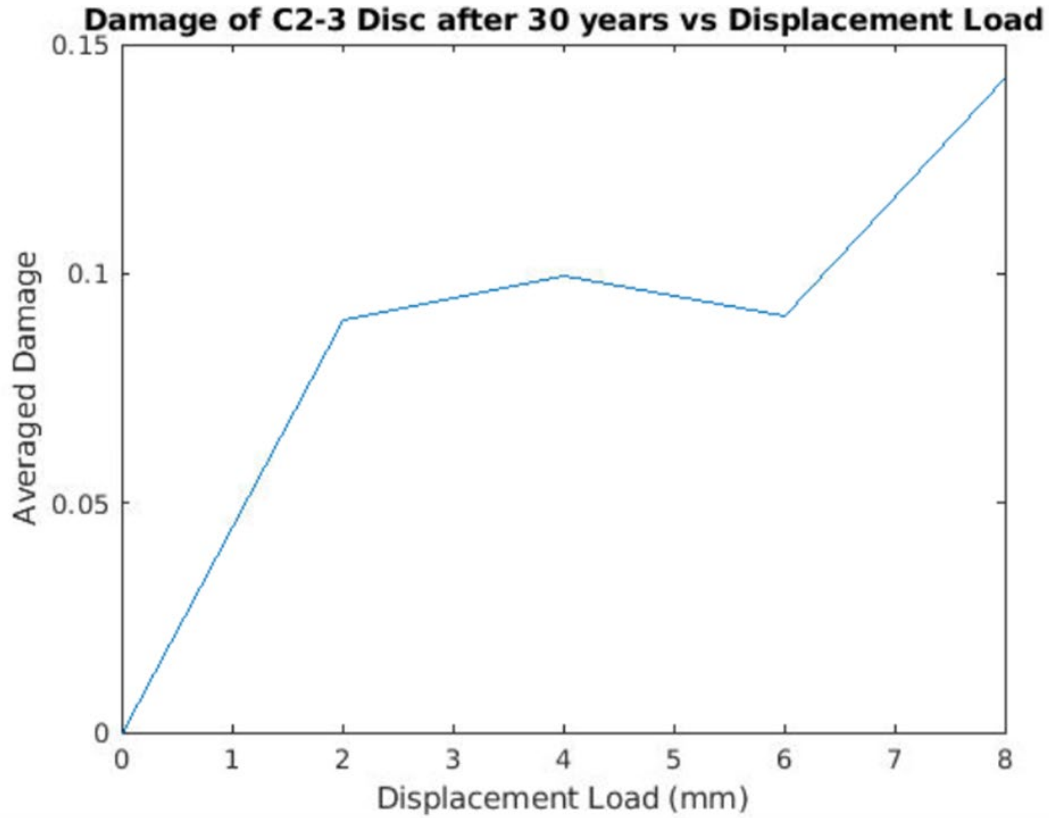


Figure 19. Averaged Damage vs. Displacement load

As can be seen in the graph above, the damage in the C2-3 disc tended to increase as the displacement load increased except from the 4mm loading condition to the 6mm loading condition. In addition to the average damage vs. displacement load plot, a graph plotting average element stress vs displacement load was also created (Figure 20).

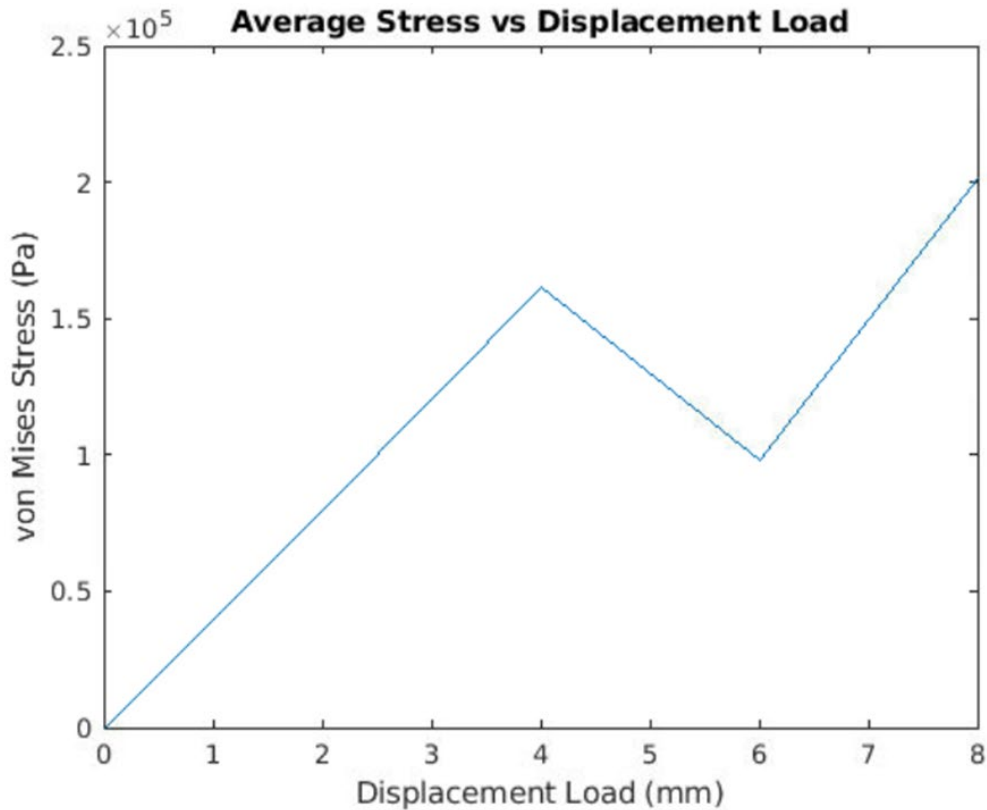


Figure 20. Averaged Stress vs. Displacement Load

As to be expected, the stress plot follows the exact trend as the damage plot. Average element stress increases as the displacement load increases except from a load of 4mm through 6mm. This trend demonstrates that there is a positive correlation between stress and total damage, meaning as stress increases, damage also increases. To further visualize the damage results on the C2-3 disc, the total damage of each element was plotted on the C2-3 disc mesh in Paraview. Figure 21 shows the damage progression in the C2-3 disc from 10 years through 30 years of centrifuge training using the 8mm displacement damage results.

Figures 21 and 22 show that the highest damage is concentrated in the lateral center of the anterior side of the C2-3 disc. The section views of the damage results also indicate that damage is highest on the surface of the disc and propagates from the surface to the interior of the disc.

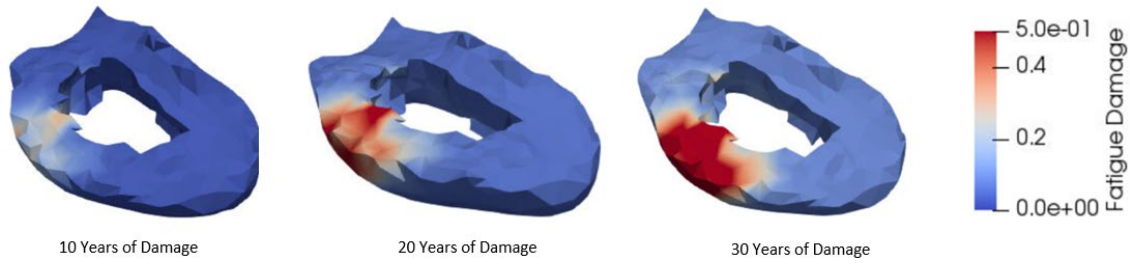


Figure 21. Damage progression in the C2-3 disc over a 30-year time span with 8mm loading condition

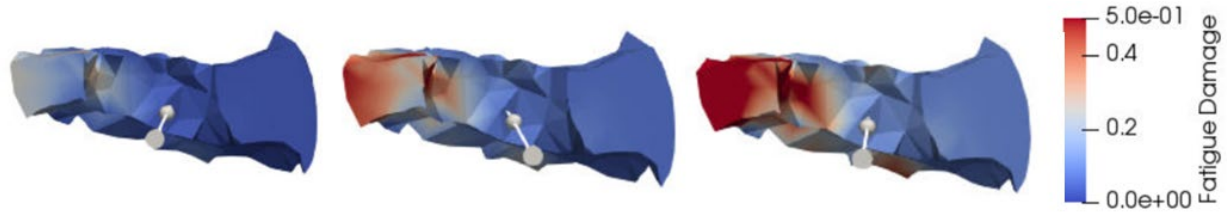


Figure 22. Section view of damage progression in the C2-3 disc over a 30-year time span with 8mm loading condition

3.0 FULL SPINE DAMAGE STUDY

3.1 Implicit Static Simulation Parameter Changes

Improvements were made to the static simulation to increase the accuracy of the results. Additionally, damage results were collected for the full spine, rather than just the cervical region. The damage results were visualized in ParaView and showed that the majority of spinal damage appears in the cervical discs.

Initially the simulation was run using a variety of displacement loads that ranged from 2mm-8mm. When the element stress history plots were generated for these simulations, it was clear that the results were not consistent. Since the displacement rate was constant at 1mm/s (Millimeters/Per Second) across all simulations, the element stress histories should have been the same across all simulations, the only difference being that simulations with higher displacement values would have additional results. Unfortunately, the stress histories were not the same across the simulations with different displacement loads. In an attempt to get more accurate results with matching stress histories, a smaller convergence tolerance of $1e-7$ and timestep of .001 were used. These two refinements significantly increased the accuracy of the results, this increase in accuracy can be seen below in figures 23 and 24.

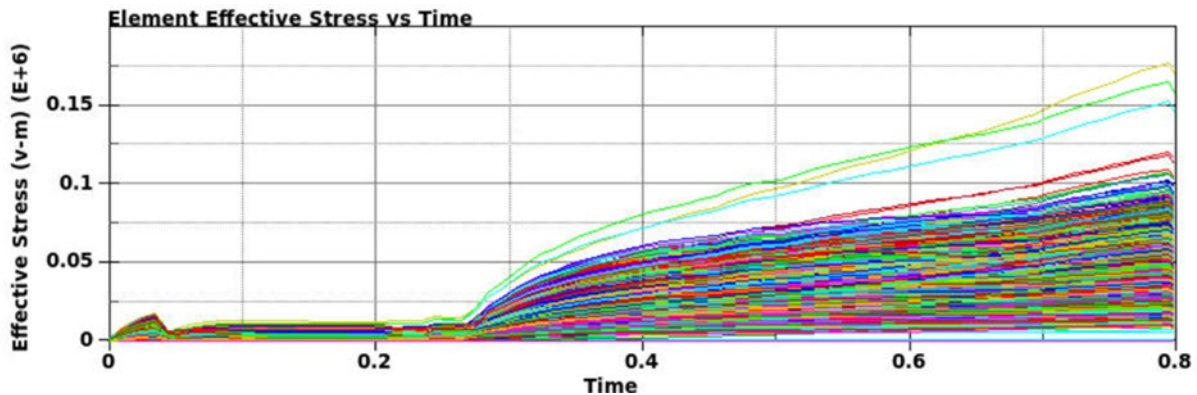


Figure 23. Element stress-history plot of C2-3 disc from 8mm displacement load

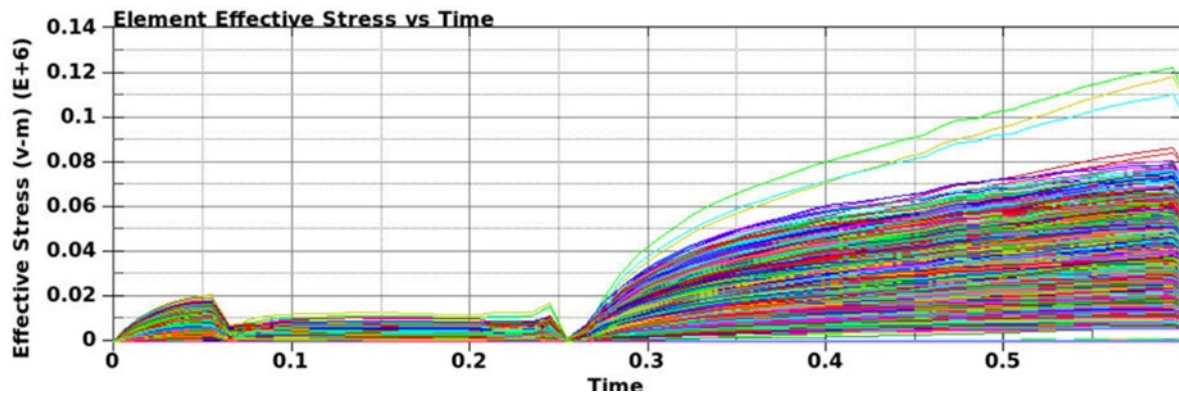


Figure 24. Element stress-history plot of C2-3 disc from 6mm displacement load

The two plots shown in figures 23 and 24 show that the element stress histories from the 6mm displacement simulation and 8mm displacement simulation are very similar. This means that the stress value at a given time will be approximately the same on both graphs. The simulation results showed that stress is the highest in the cervical discs, while stress is relatively low in the thoracic and lumbar discs. The low stress in these regions meant that there was little damage in the thoracic and lumbar discs.

The element stress history data for every disc in the spine was imported into the long-term damage model. The damage model was initially run assuming 300 cycles of the 7mm displacement loading condition per day for thirty years. As stated above, the stress was relatively low in the thoracic and lumbar spine. In fact, the stress in the thoracic and lumbar discs was low enough that no fatigue damage accumulated in these regions. The only component of the damage model that contributed to damage in these discs was aging, this can be seen in figure 25.



Figure 25. Full spine disc damage after 30yrs of repeated 7mm displacement load

Figure 26 shows the damage progression of every element in the T1-2 disc. The T1-2 disc consists of 2,871 elements, but notice there is only a single line on the damage plot. This signifies that every element had the exact same damage progression. Every element had the same damage progression because there was no fatigue damage and damage due to aging is constant across every element. In contrast, the element-wise damage progression of the C2-3 disc can be seen below in figure 27. The C2-3 disc experienced high stress which caused many elements to accumulate mechanical damage from fatigue

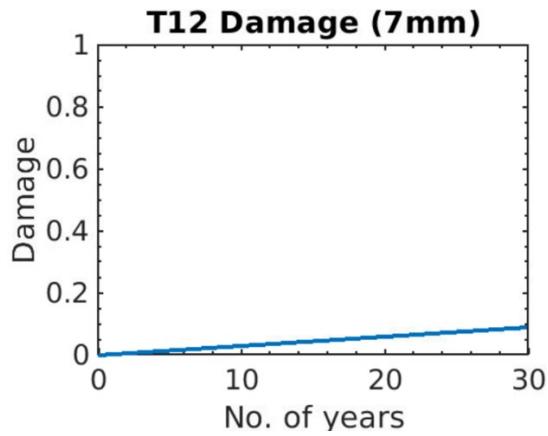


Figure 26. Damage progression of T1-2 disc under 7mm displacement load

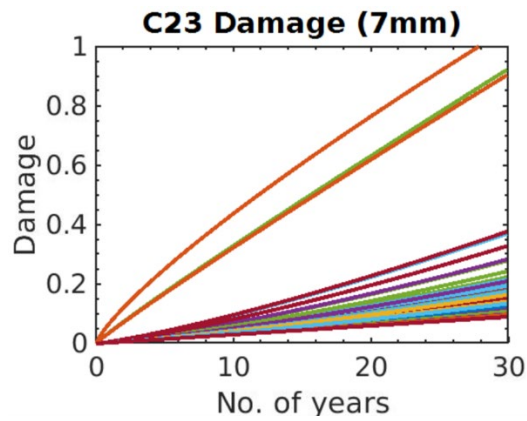


Figure 27. Damage progression of C2-3 disc under 7mm displacement load

Since the thoracic and lumbar spine experienced no mechanical damage from fatigue, only the cervical discs were closely analyzed. The plots shown below in figures 28-32 show the damage distribution for each disc within the cervical spine.

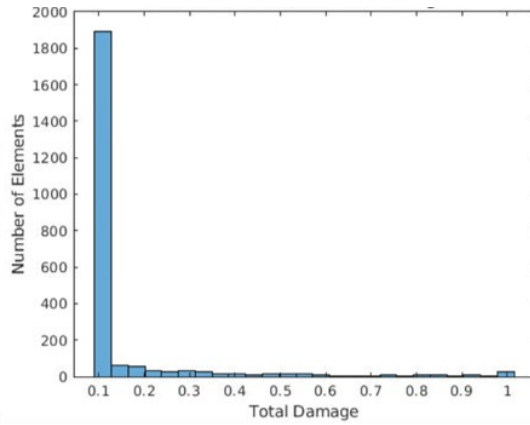


Figure 28. C2-3 element damage distribution under 8mm displacement load

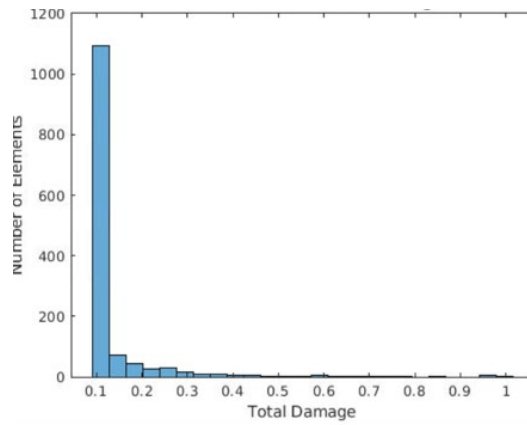


Figure 29. C3-4 element damage distribution under 8mm displacement load

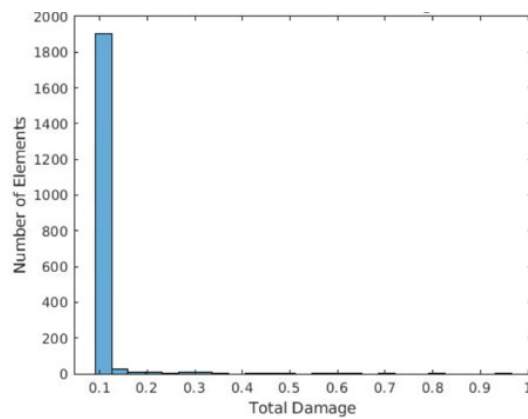


Figure 30. C5-6 element damage distribution under 8mm displacement load

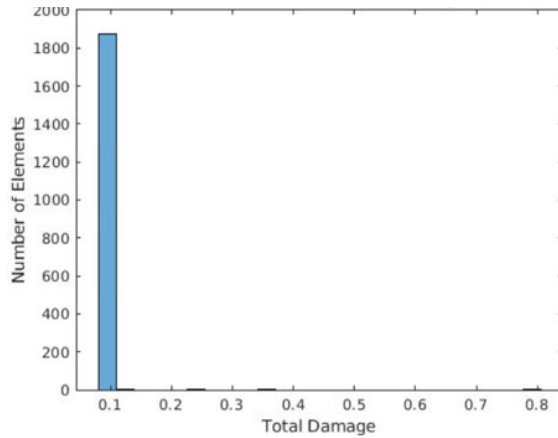


Figure 31. C6-7 element damage distribution under 8mm displacement load

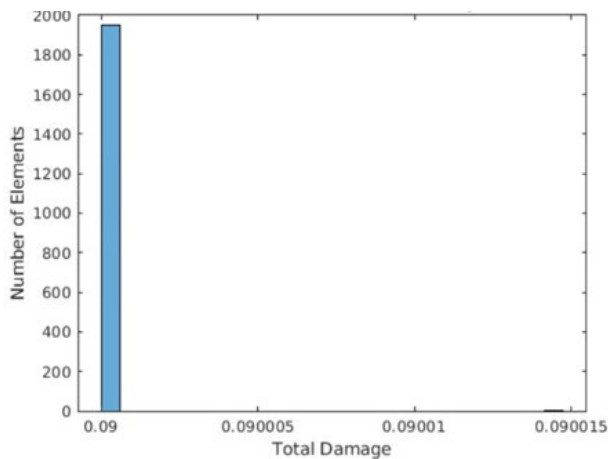


Figure 32. C4-5 element damage distribution under 8mm displacement load

The damage distribution charts above show that the majority of the elements in the cervical discs have a damage value of 0.09 which is the damage caused by thirty years of aging. Although most elements are not affected by mechanical fatigue, there are still many elements that have a high final damage value due to fatigue from cyclic loading. To better understand where the damage is most prominent and how the damage progresses, the damage results and cervical disc meshes was inserted into ParaView.

Figure 33 shows that the C2-3 disc experienced the most damage from the 8mm displacement load. The majority of the damage was centered on the posterior side of the C2-3 disc. Figure 34 shows a section view the damage progression within the cervical discs over a 30-year time frame. The damage originates on the posterior surface of the C2-3 disc and propagates towards the center of the disc. The C3-4 disc experienced the second highest amount of damage. Unlike the C2-3 disc, the C3-4 disc damage is not laterally centered. The damage of the C3-4 disc originates at the surface and intensifies with very little propagation towards the center of the disc, see figure 35 below.

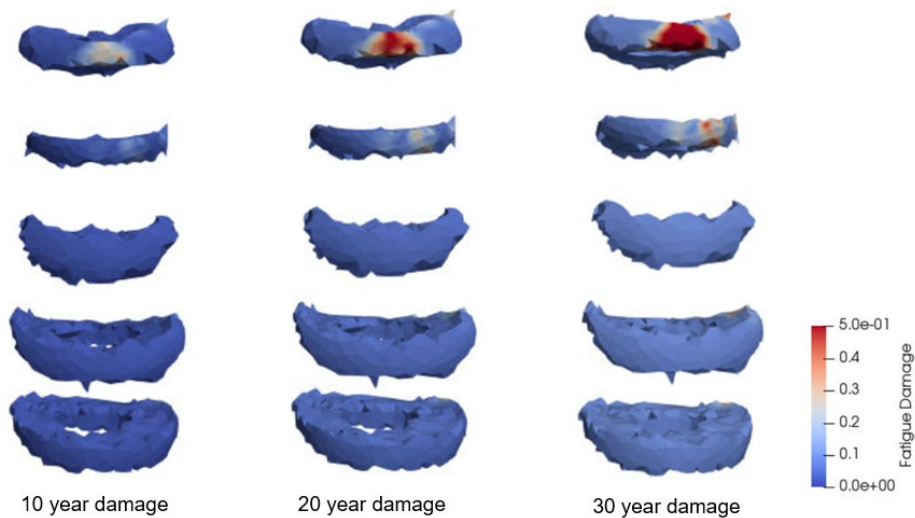


Figure 33. Cervical disc damage progression



Figure 34. Cervical disc damage progression section view

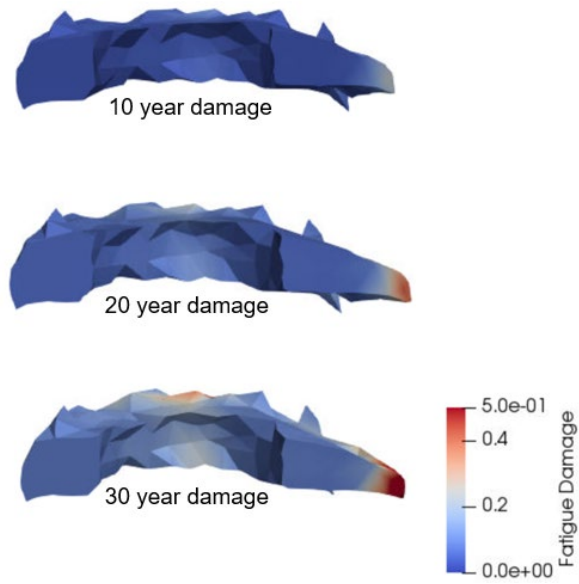


Figure 35. C3-4 disc damage progression

4.0 FUTURE WORK AND GOALS

The static simulation is running well and is ready to be used to investigate how a pilot's seat angle affects long term damage in the spine. For this investigation, the angle of the displacement load will be varied to replicate the effects of seat angle on the spinal loading path. Multiple seat angles will be simulated in LS-DYNA. The stress results from these simulations will be input into the MATLAB damage model and analyzed.

LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

G/s	Acceleration of Gravity, Per Second
G	Gravitational Force
mm	Millimeter
mm/s	Millimeters/Per Second