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Stress/Strain Analysis of a Nitinol Self-Deploying Stent

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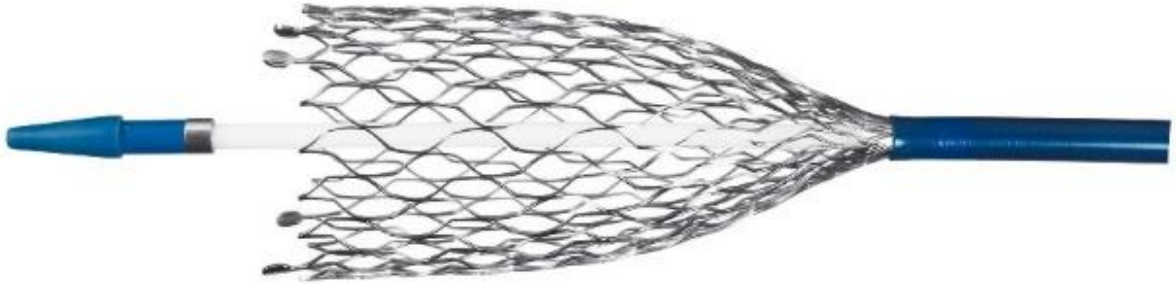
Background

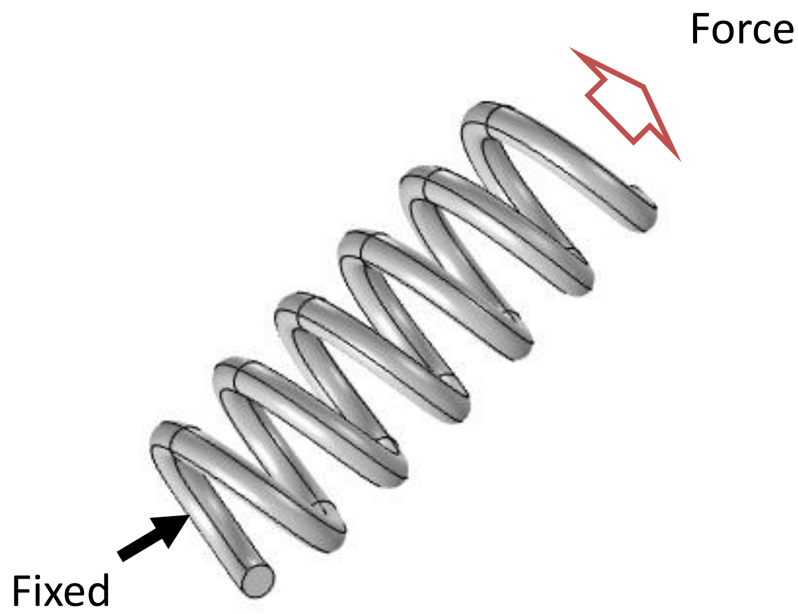
- Stents in general are used to expand constricted blood vessels
- Shape memory materials, such as Nitinol, are strong, flexible and lightweight alloys that can remember its original shape after excessive deformation
- Self-expanding nitinol stents are less rigid and can tolerate larger strains and therefore has a longer fatigue life than balloon-expandable stents
- FEA is a useful design tool to observe the stress and strain experienced by stents and its interaction with the artery



Self expandable stents [Photograph]. Retrieved from https://www.bemedical.be/products/vascular-surgery/self-expandable-stents.

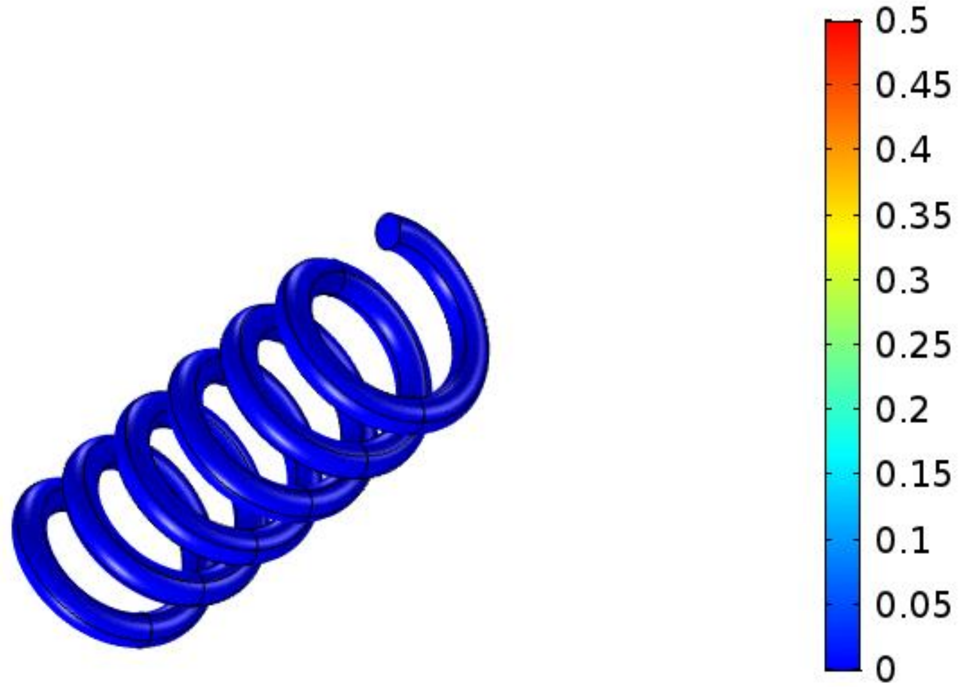
Shape Memory Alloy Example

- Nitinol spring pulled, released, and then gradually heated



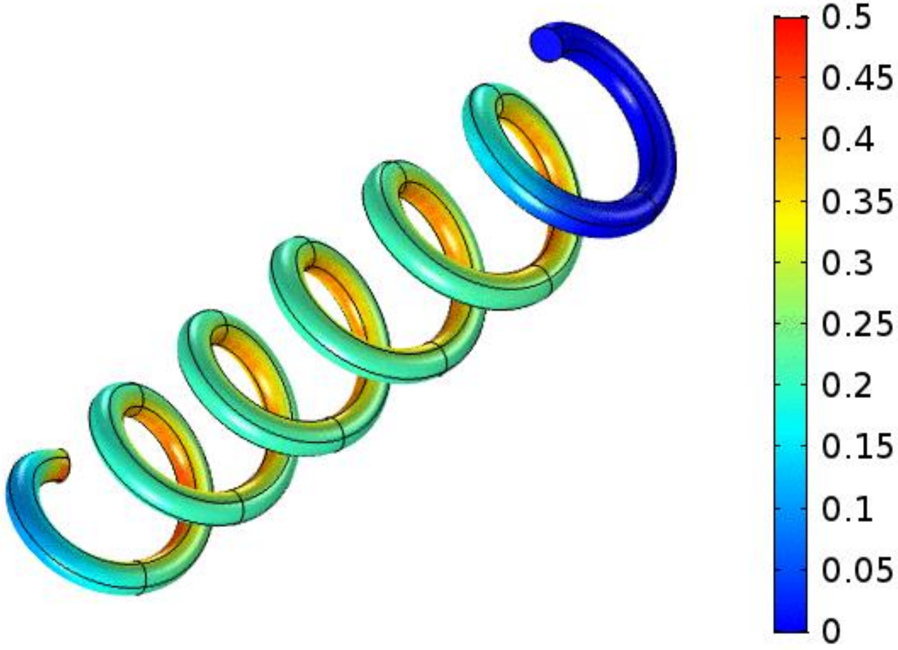
Shape Memory Alloy Example

- Martensite volume fraction in pull and release steps



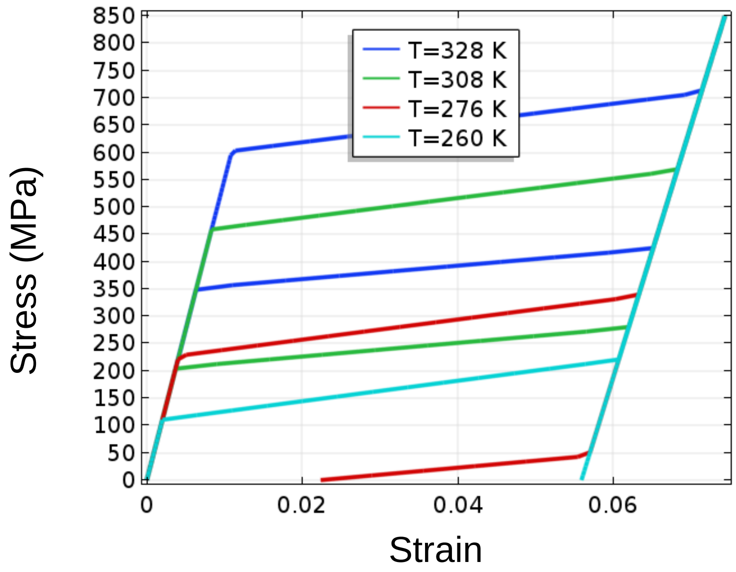
Shape Memory Alloy Example

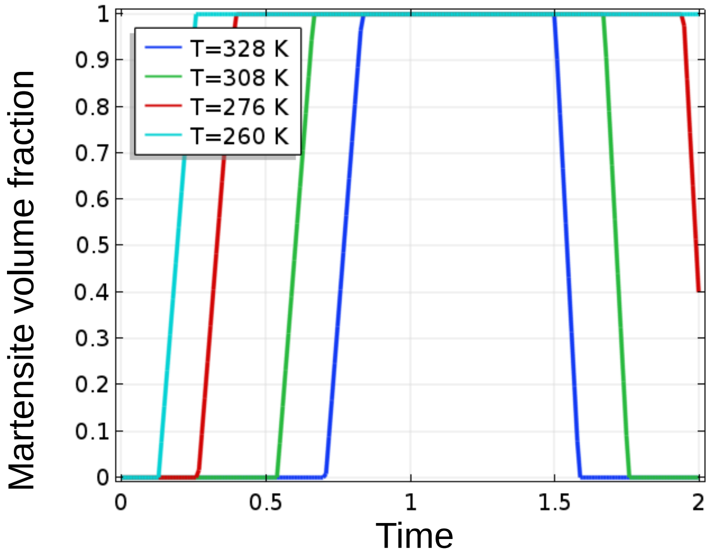
- Martensite volume fraction in heating step
- Temperature increase applied gradually from right to left



Response to Cyclic Uniaxial Loading

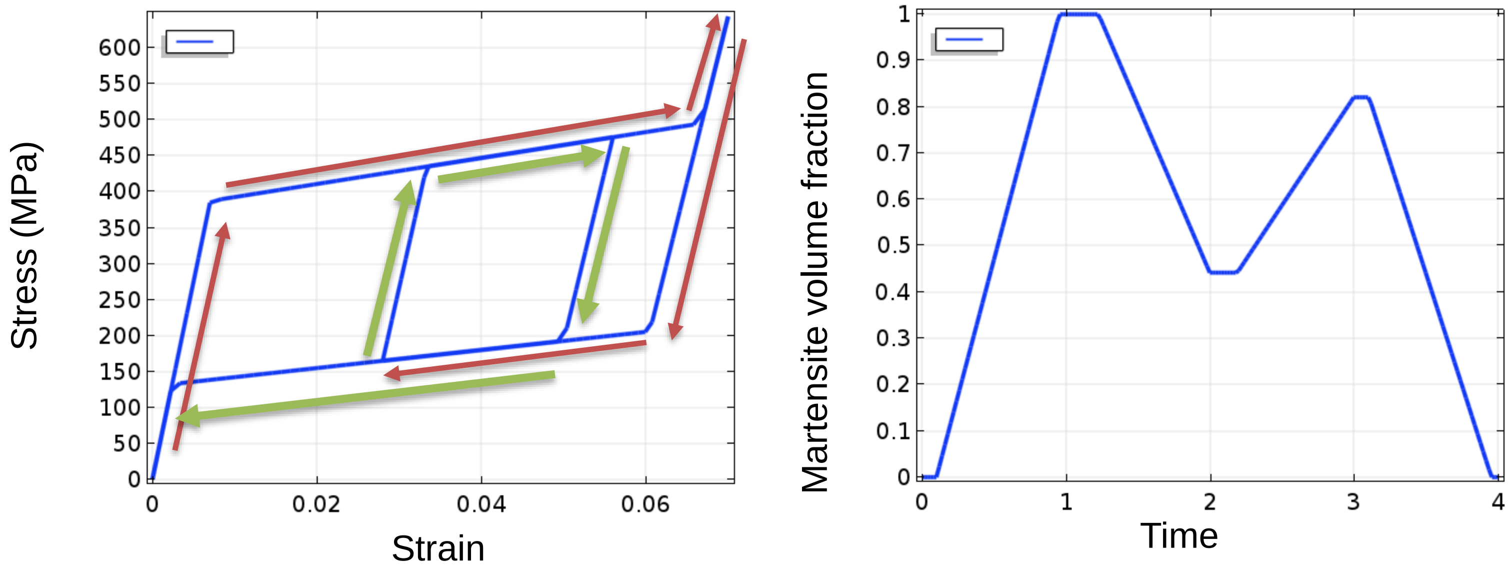
- Response of SMA to cyclic uniaxial loading
  - Showing full martensite transformation at different temperatures





Response to Cyclic Uniaxial Loading

- Response of SMA to cyclic uniaxial loading
  - Showing partial martensite transformation

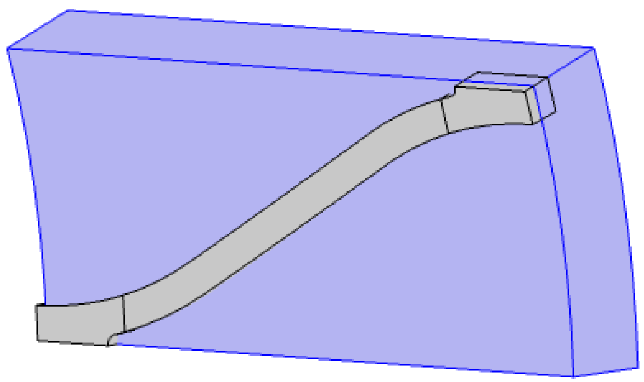


Simulation Steps

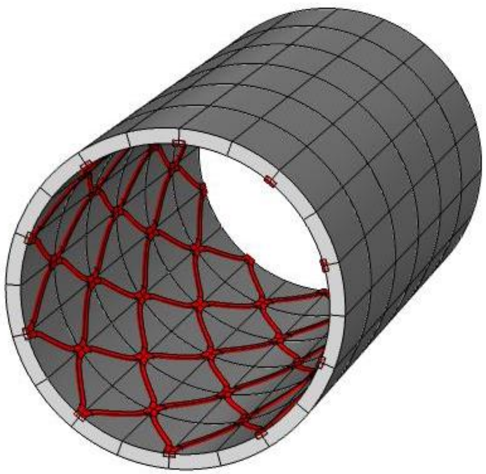
- For ease of insertion and placement of the stent into the artery, the stent is first crimped
- The crimped stent is then placed into a delivery catheter
- The catheter is delivered to the correct position in the blood vessel
- The catheter is retracted and the lack of a compression force allows the stent to deform back to its original shape – until it contacts the blood vessel
- After insertion of the stent, the stent experiences cyclic stresses and strains from the pressure variations of a cardiovascular cycle
  - Time varying load makes the stent susceptible to fatigue
  - Experimental fatigue failure data for Nitinol suggests that failure is primarily strain based

Geometry

- For the model geometry, we assumed that the stent and artery are rotationally symmetric and modeled only 1/120 section of the stent and corresponding artery wall as portrayed to the left
- A full model, for visualization purposes, using a series of rotations, reflections, and arrays of the stent and artery is seen to the right



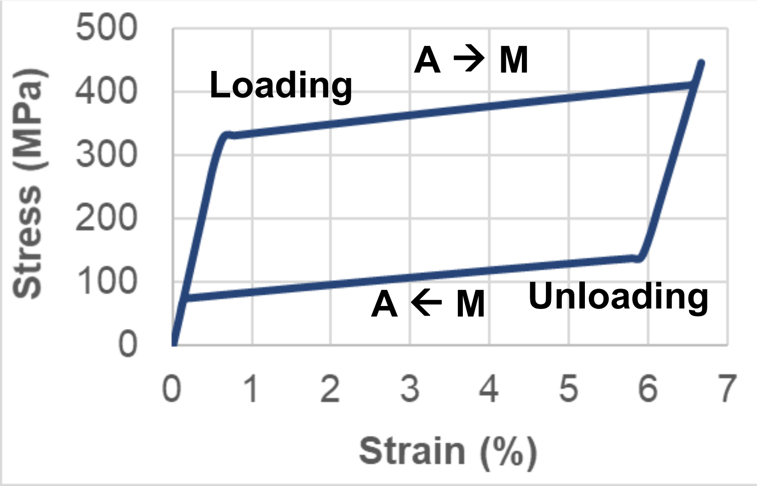
COMSOL Multiphyiscs model with stent (grey) and artery wall (blue)



Full model of stent (red) and artery (grey)

Materials

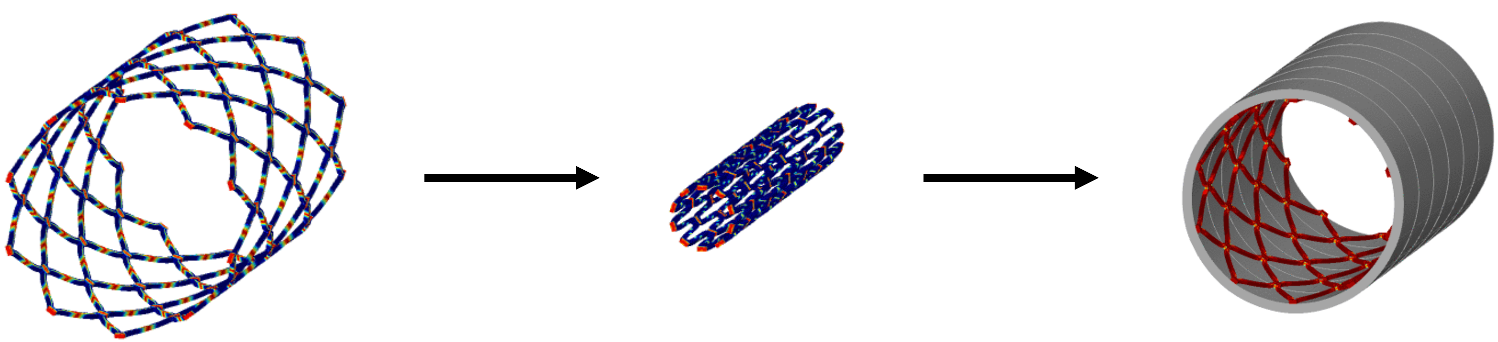
- We used a Lagoudas shape memory material model for the stent with nitinol material model parameters
  - The graph shows the material's superelasticity when subjected to a loading-unloading cycle at 17˚C
  - It illustrates the nitinol transformation between its austenite (A) and martensite (M) along with its deformation due to applied stress
- The blood vessel is modeled as a hyperelastic material to account for the large strain experienced due to stent expansion/compression



Stress strain curve for nitinol material used in our model

Boundary Conditions

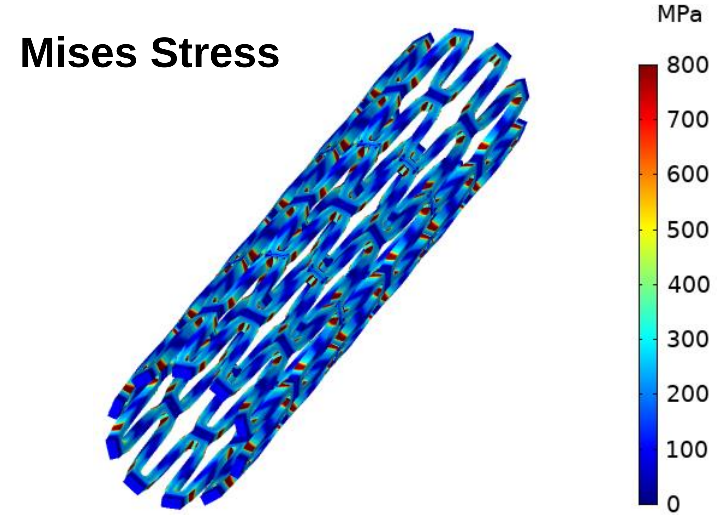
- The stent starts in the configuration at the left
- Contact with an external shrinking virtual cylinder on the outer walls of the stent reduces it size as seen in the middle image
- After compression, the stent is placed in the artery and the compression pressure on the outer walls of the stent is decreased
- The stent attempts to spring back to its original state
- The varying pressure due to the blood flow is finally applied to the inner walls of the stent and artery wall

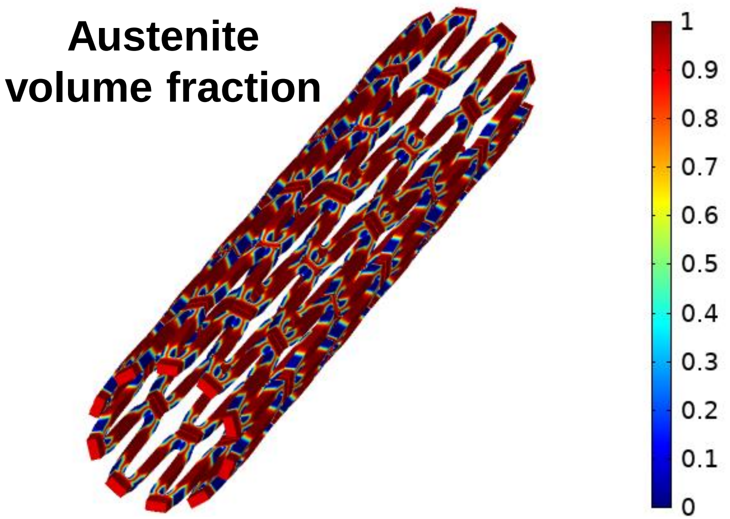


Initial Stent **Stent Compression** **Blood Pressure Variation**

Phase Transformation

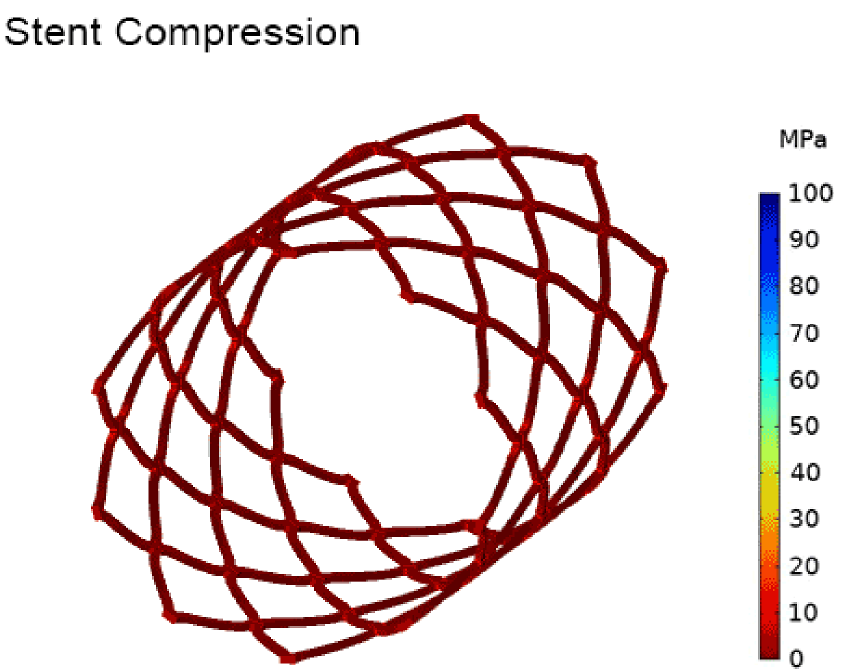
- The nitinol stent is initially at its austenite phase
- As it is compressed, stress increases, most prominently at the inner peaks of the stent
- The portions of the stent experiencing the highest stress, seen in the top figure, transforms to martensite by the end of the compression stage as seen in blue at the bottom figure
- Once expanded, the material shifts back to its austenite phase
- It remains in this phase throughout the cardiovascular cycle as the pressure due to blood flow is not large enough to trigger transformation





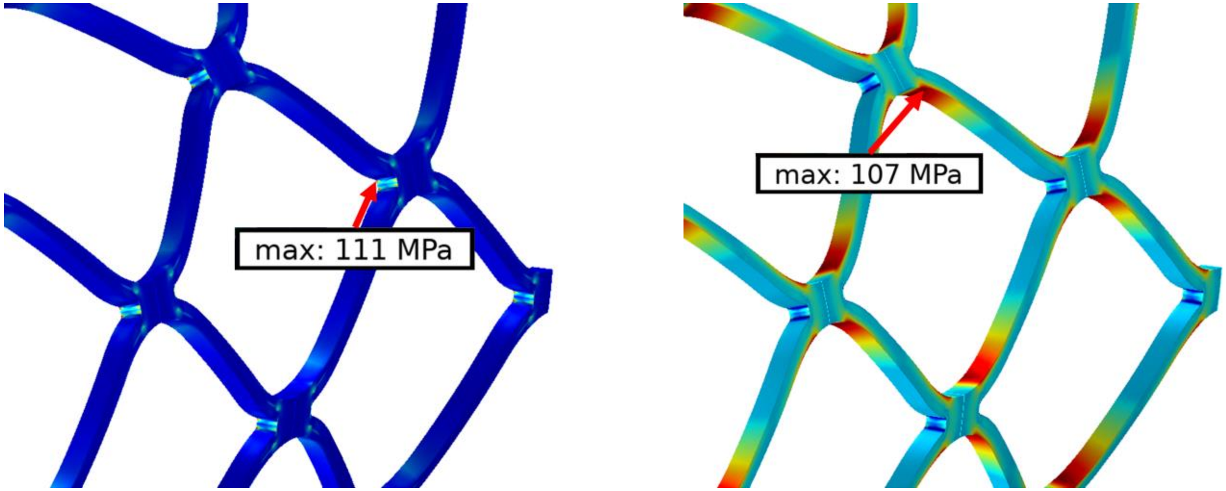
Stent Deformation and Stress State

- Animation of different stages of stent deployment showing Mises stress



Location of Max Stress

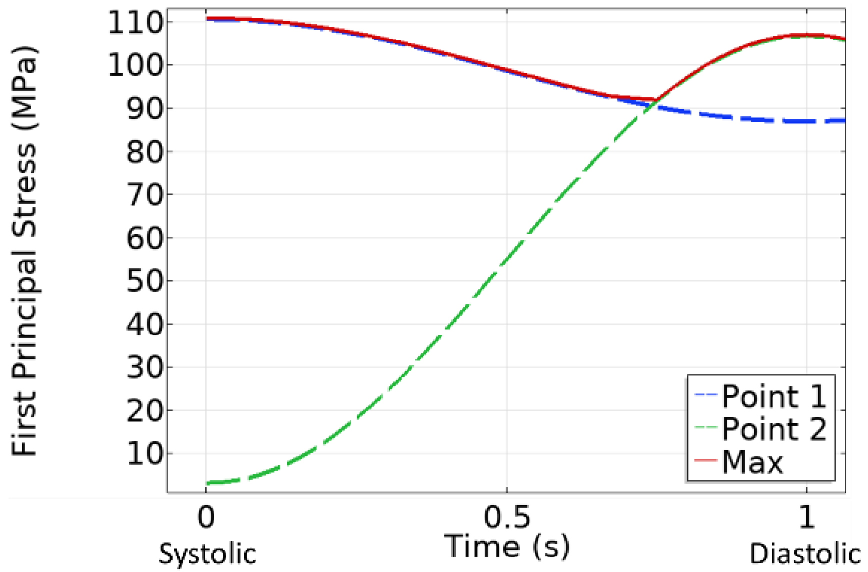
- Figures shows the stress states experienced by the stent at systolic and diastolic pressures
- The stent consistently experiences max stress near the connection between struts



Stress contours showing maximum first principal stresses in systolic (left) and diastolic (right) states

Stress Variation

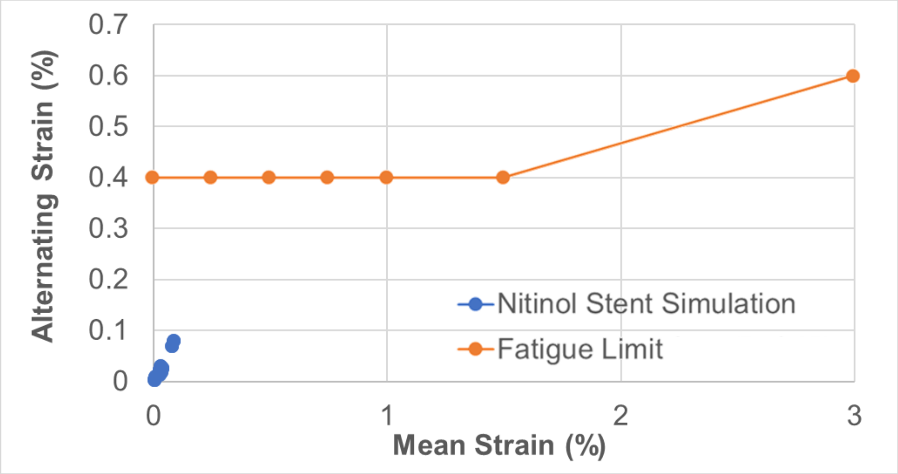
- The location of maximum first principal stress experienced by the stent changes over a cardiovascular cycle
- The graph shows the stress at two extreme points along with the maximum principal stress throughout a cycle
- This stress variation is important for fatigue life prediction



Max tensile principal stress experienced by stent over a cycle

Fatigue Life

- The constant life diagram compares the alternating and mean strains between the calculated results and experimental data
  - Alternating strain is calculated as half the difference between the max and min strains over a cycle
  - Mean strain is calculated as the average strain over a cycle
- Based on the diagram, all points from the modeled stent are below the fatigue limit line meaning this specific stent will not fail from 10^7 cycles



Constant Life Diagram for several points on stent

Summary

- We used COMSOL Multiphysics to account for the nitinol's shape memory behavior and predict the stresses and deformation typically experienced by a shape memory material stent
- We confirmed the low risk of fatigue when the stent is deployed in this healthy blood vessel configuration!
- This will be a starting model for evaluating stent behavior in diseased blood vessels and multiphysics issues related to the the stent such as fluid flow around stent, drug delivery, and plaque formation