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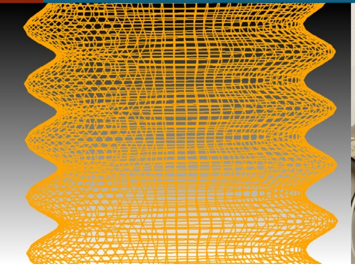
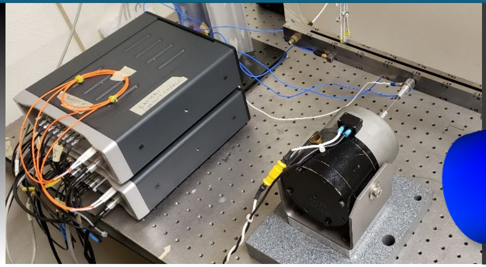
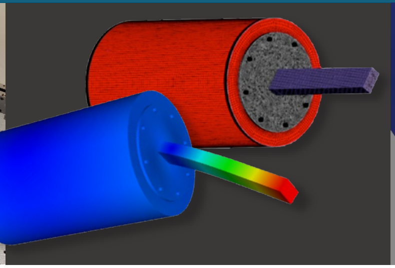
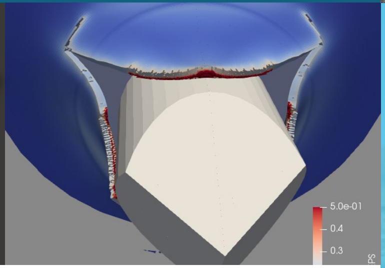
Mapping from Low Fidelity to High Fidelity Analysis for Failure Quantities of Interest









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SAND2021-8886 PE

U.S. DEPARTMENT OF ENERGY

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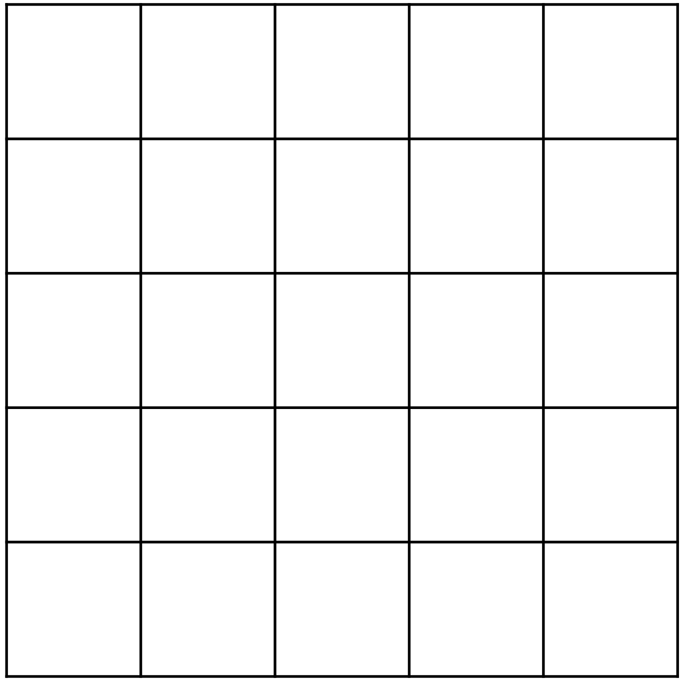
Motivation

Using a low fidelity model, can one predict failure seen in higher fidelity models?

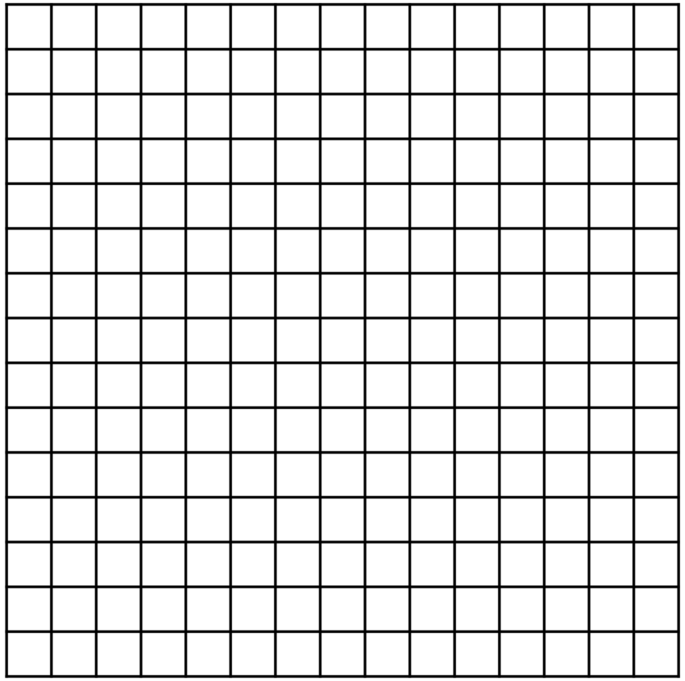
Lower Fidelity



shell element models

element death failure models

Higher Fidelity



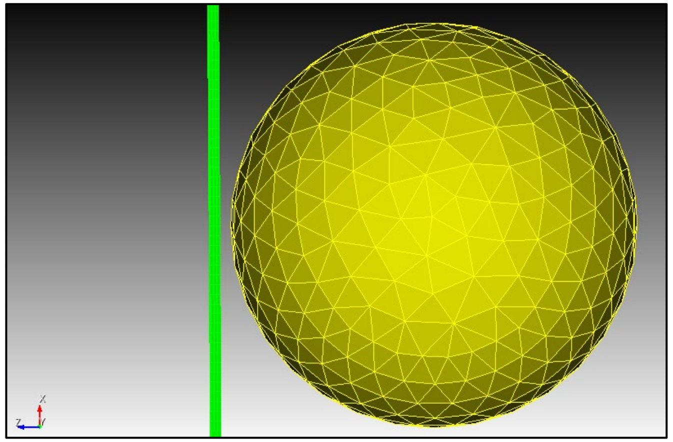
hexahedral element models

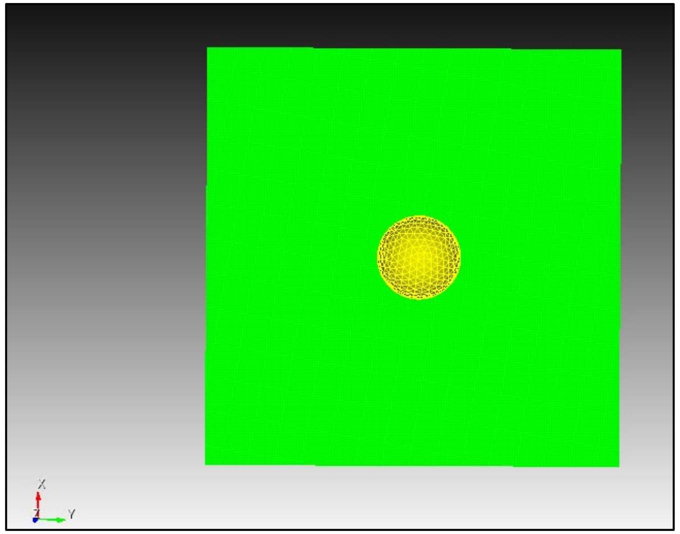
XFEM failure models

Outline

- Introduction
- Material Models
- Hexahedral (Hex) Model
- Shell Model
- Comparison of Hexahedral and Shell Models
- Neural Network
- Conclusions

Problem Setup





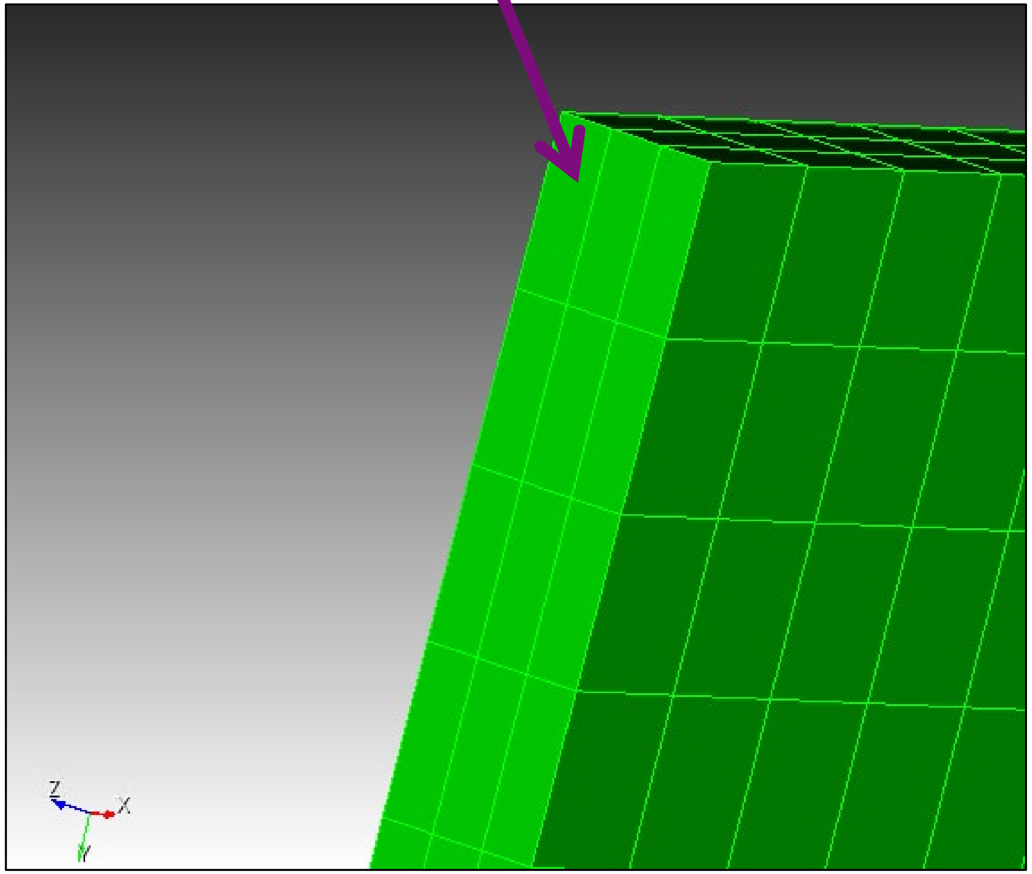
- Ball
  - 5" diameter
  - Made up of solid tetrahedral elements
  - Mesh size of 0.5"
  - 0.2" from plate in - z-direction
  - Initial velocity
- Plate
  - 25" x 25" x 0.12" square plate
  - Made up of either hexahedral (hex) or shell elements
  - Varying mesh sizes
  - Similar hex and shell models developed for comparison
  - Fixed on edges

Hexahedral and shell models developed at different levels of fidelity for comparison.

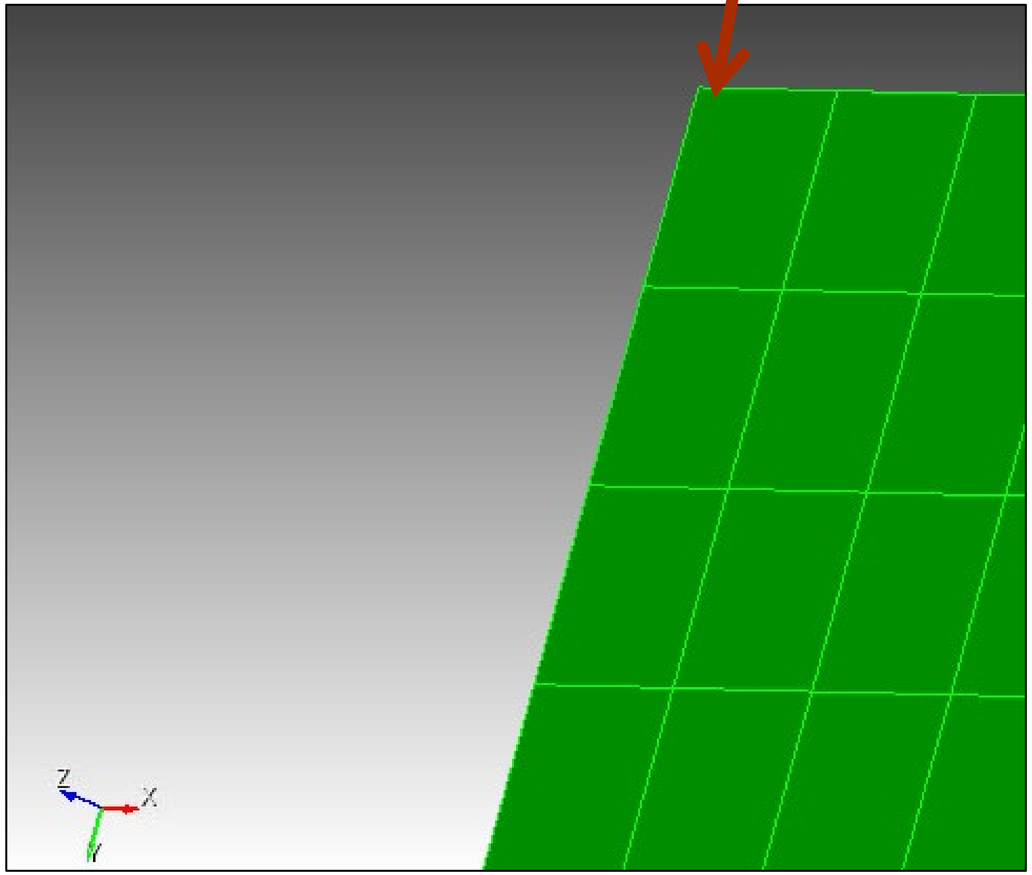
Hexahedral vs. Shell Elements

solid element

thickness stored as parameter



Hexahedral Plate



Shell Plate

Relating Hexahedral & Shell Elements

Relating hexahedral and shell elements will be achieved by comparing the following:

- Breakthrough velocity magnitude
  - How fast must the ball travel to break through the plate?
- Kinetic energy change
  - What is the change in energy of the projectile from the beginning time step to the end?
- Size of hole at ball speed of 5000 in/s
  - How much destruction is measured for each case?

Material Models

Plate: 6061-T651 Aluminum Alloy

Hex-Based Setup

J_2 Plasticity Model

Shell-Based Setup

Modular Plane Stress Plasticity Model

All components are set up with ductile failure models: J_2 plasticity for solid elements and modular plane stress plasticity for shell elements.

Ball: 304L Stainless Steel Alloy

All Setups

J_2 Plasticity Model

J_2 Plasticity

Fixed Parameters

Aluminum

Parameter	ρ (blob/in^3)	E (psi)	ν	c_p (in-lb/(blob °C))
Value	2.5×10^{-4}	10.4×10^{6}	0.33	1.36×10^{6}

Steel

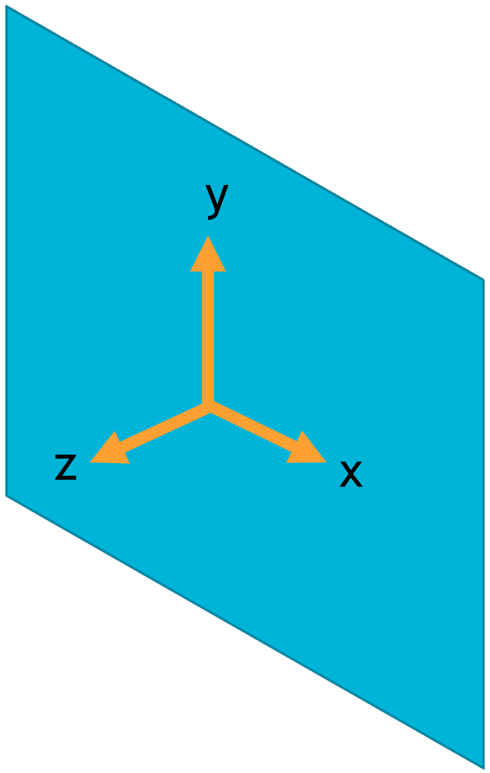
Parameter	ρ (blob/in^3)	E (psi)	ν	c_p (in-lb/(blob °C))
Value	7.49×10^{-4}	28×10^{6}	0.27	0.776×10^{6}

Fixed parameters do not vary with plastic deformation.

Modular Plane Stress Plasticity

- A J_2 plane-stress model with modified forms for hardening
- Uses the same values from the J_2 plasticity model
- Developed for use with shell elements

Only the plane stress state is allowed in shell elements.



Death Criterion in Ductile Failure

- Element death will be defined using the damage variable D

- Factors of the damage variable
  - Calculated such that material failure occurs when damage ≥ 1
  - Accumulates with plastic deformation
  - Functional dependency chosen to be on the stress, equivalent plastic strain rate, and temperature histories

$$D = \frac{1}{d_{crit}} \int_0^{\epsilon^p} f\left(\sigma, T, \dot{\epsilon^p}\right) d\epsilon^p$$

Element death occurs when the variable damage ≥ 1, which accumulates with plastic deformation.

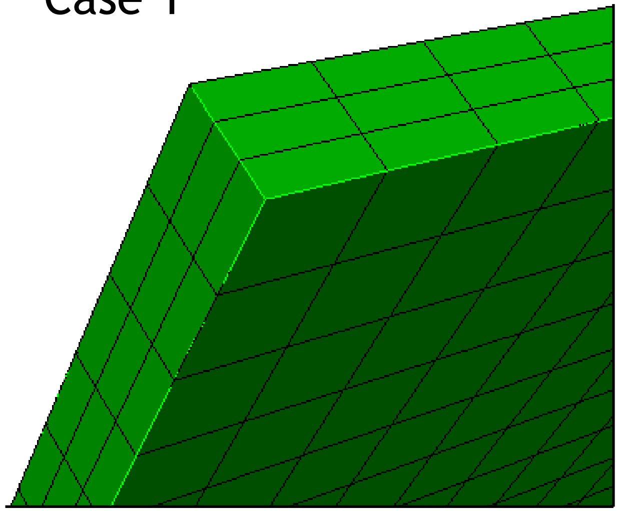
Hexahedral Model Development

Plate Mesh Sizes Considered

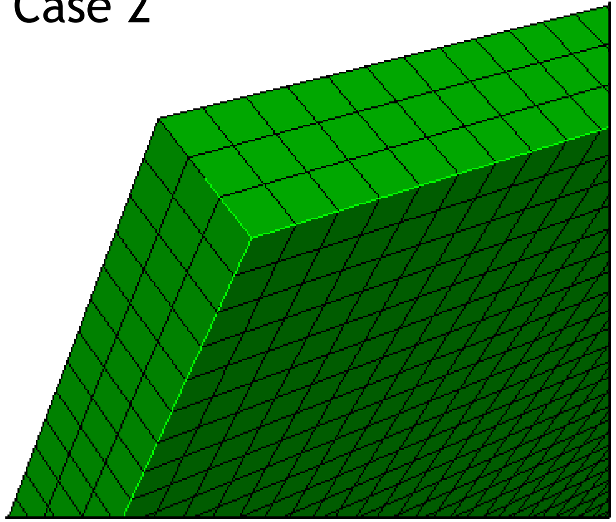
Case Number	Element Side Length Across Face (in)	Number of Elements Through Thickness	Total Number of Nodes	Aspect Ratio
1	0.12	3	175,848	3
2	0.04	3	1,568,268	1
3	0.02	6	10,956,131	1

Varied number of elements through the thickness and across faces of plate.

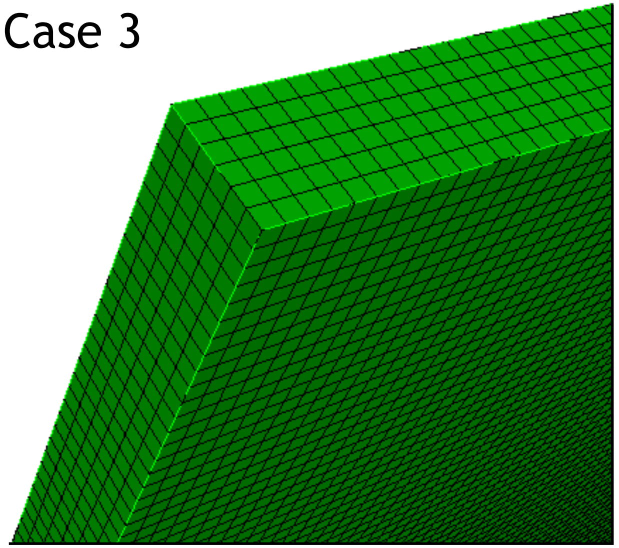
Case 1



Case 2



Case 3



Hexahedral Fidelity Comparisons

Case 3 - Most Refined

Case 1 - Least Refined

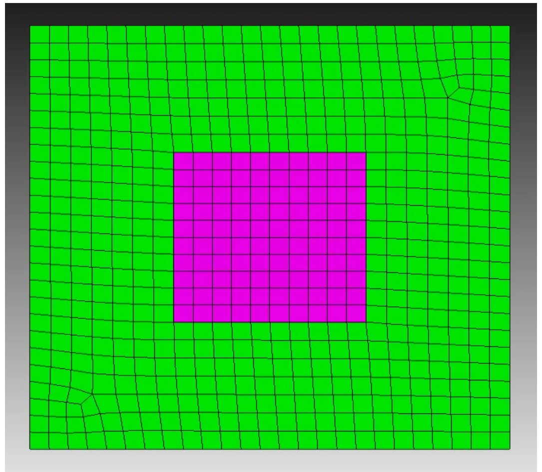
Hexahedral Velocity Threshold

Case Number	Breakthrough Velocity (in/s)
1	1388
2	1363
3	1187-1250

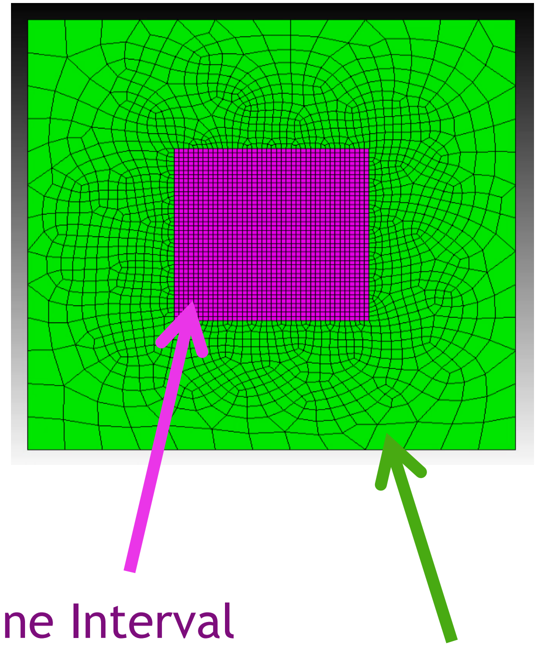
Breakthrough velocity decreases with mesh refinement.

Shell Development

Case 1



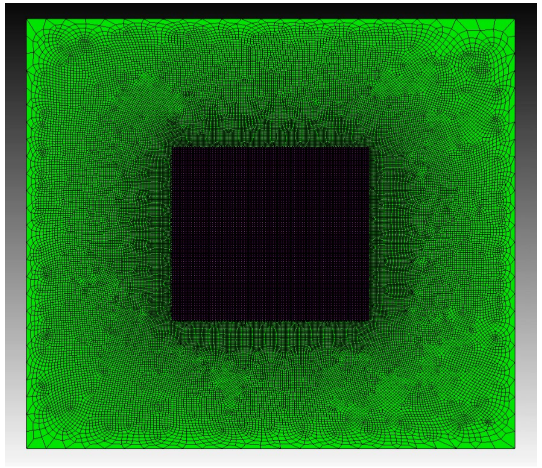
Case 3



Fine Interval Mesh

Graded Pave Mesh

Case 5



Shell Intervals Evaluated

Case	Element Interval (in)	Outer Interval Pave (in)	Total Number of Nodes
1	1	1	1764
2	0.5	2	2,006
3	0.25	2	4,193
4	0.12	1	14,627
5	.04	1	110,920
6	.02	N/A	1,566,125

Shell Models have greater utility in lower fidelity schemes, as they can be localized, and do not have to adhere to aspect ratio limitations

Shell Fidelity Comparisons

Case 1 - 1” Mesh

Case 4 - 0.04” Mesh

Case 6 - 0.02” Mesh

Shell Velocity Threshold

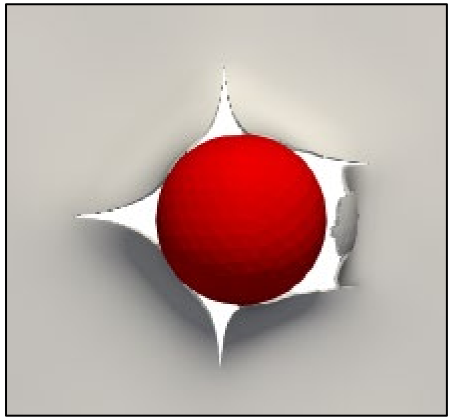
Breakthrough Velocity

Mesh Size (in)	Breakthrough Velocity (in/s)
1	1083
.5	844
.25	795
.12	765
.04	516

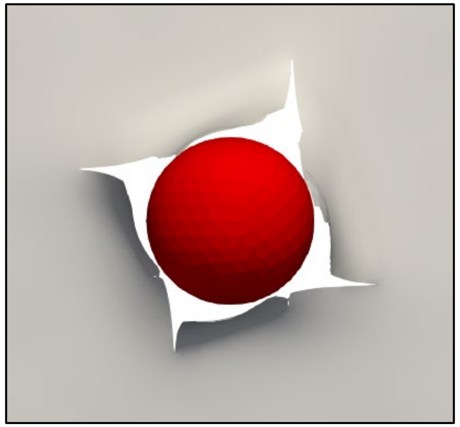
Disparity in Velocity Threshold is greater relative to Hex models, but all thresholds are underestimated relative to hex models

Comparison of Shell and Hex

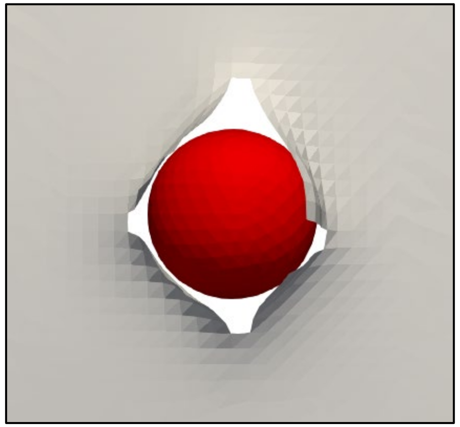
	Hex Model (.04)	Shell (.04)	Shell (0.5)
Computation Time (hour : minutes : seconds)	96:05:40	11:53:52	00:04:04
Projectile Kinetic Energy Loss (J)	7.02	7.80	12.67



Hex Model (.04)

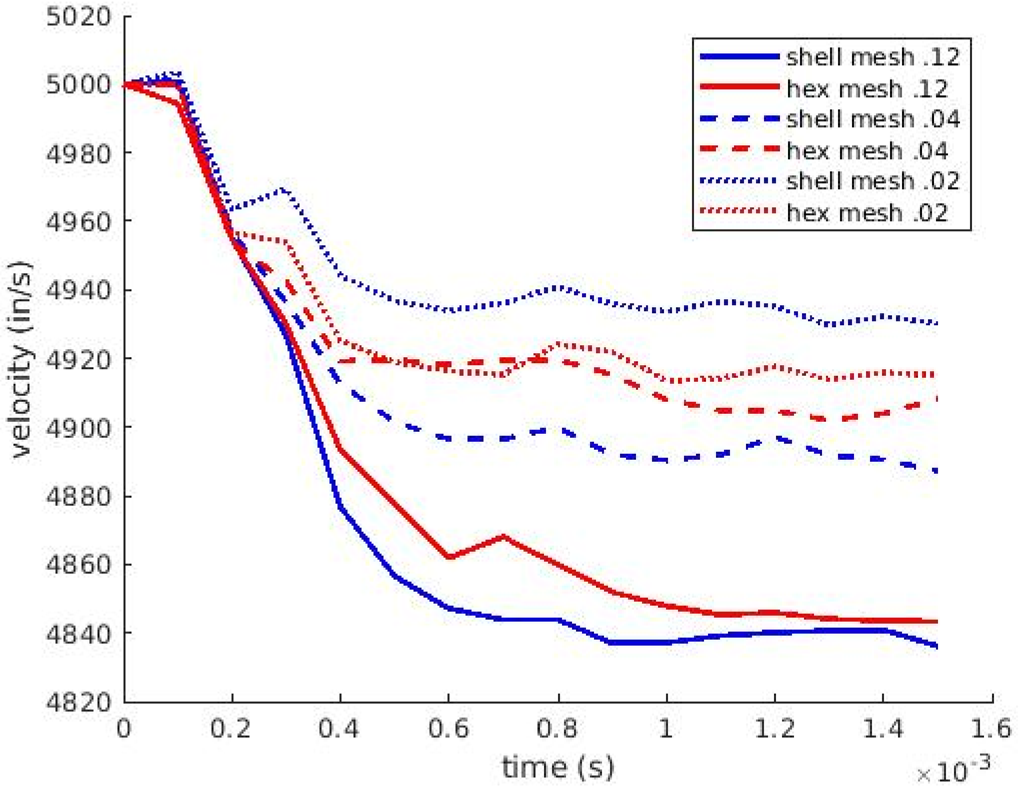


Shell Model (.04)



Shell Model (0.5)

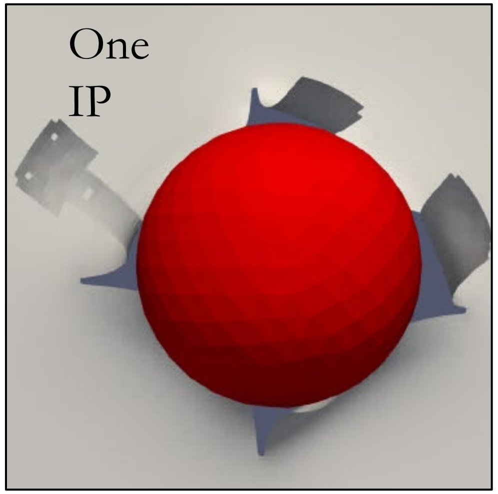
Comparison of Shell and Hex

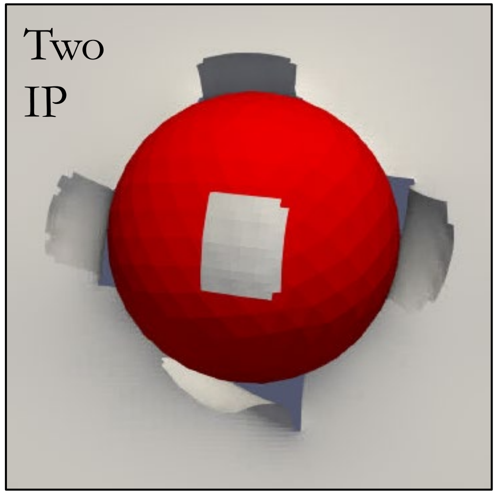


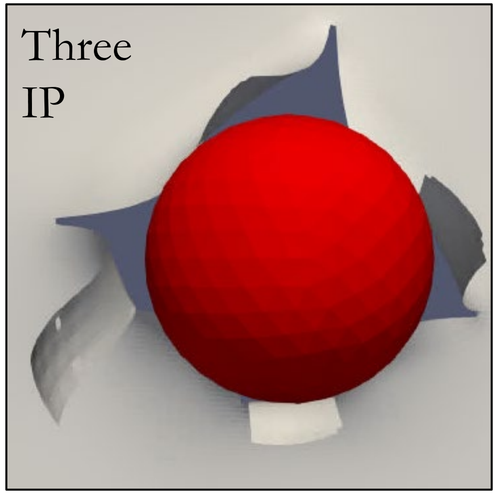
Velocity of the ball vs. time for different levels of fidelity.

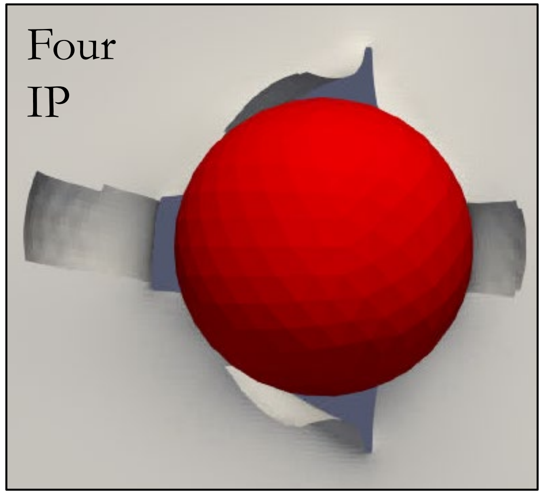
Shell – Varying Integration Point Thresholds

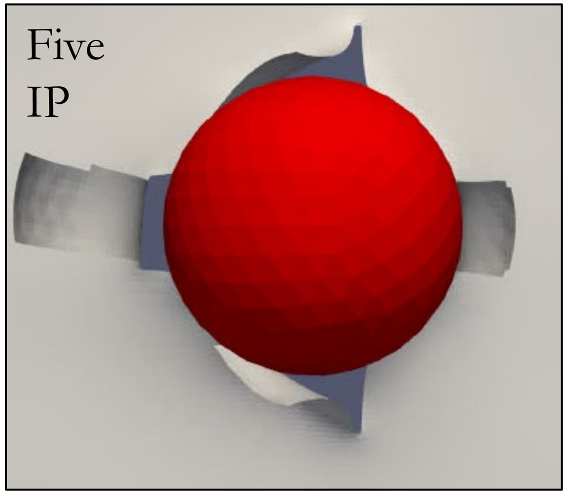
Number of Integration Points (IP) to Reach Death Criterion Before Element Killed



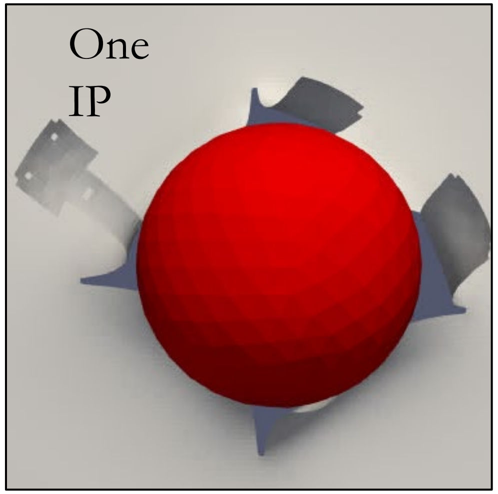








Shell – Varying Integration Point Thresholds

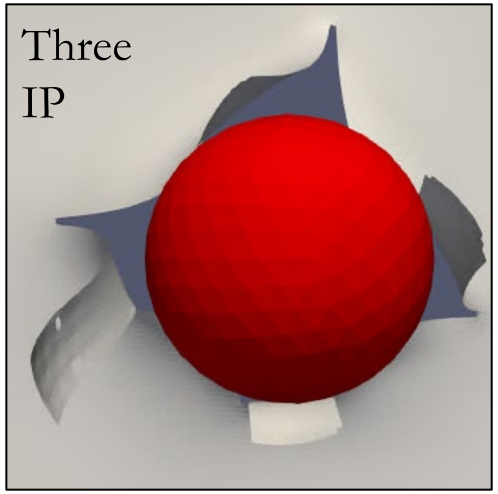


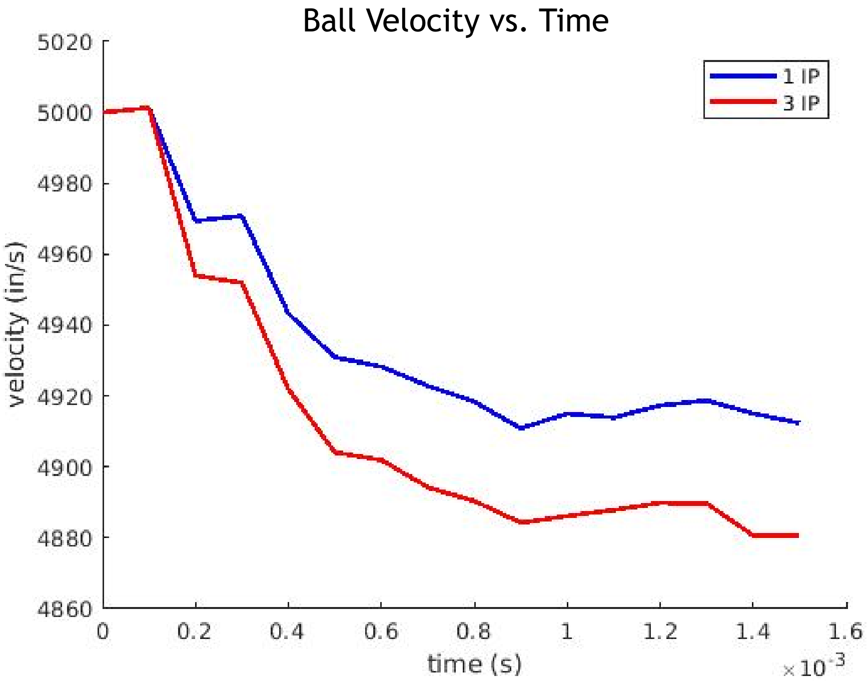
Number of Elements Killed

198

Number of Elements Killed

196



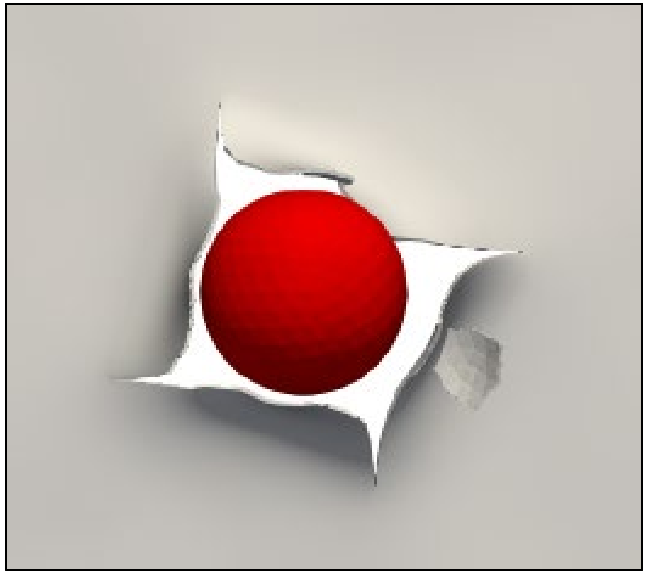


Comparison of Hexahedral Element Death vs Shell XFEM

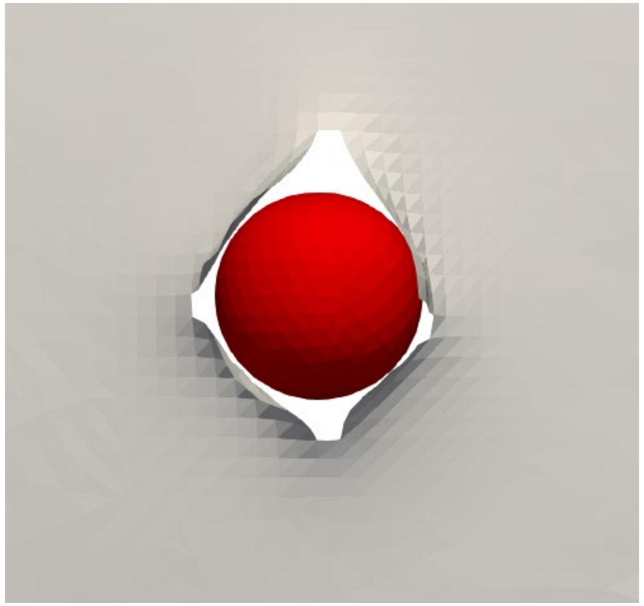
Mass Lost

- Shell with XFEM - 0 lb
- Shell with Element Death - 2.1×10^{-5} lb
- Hex with Element Death – 2.076×10^{-5} lb (0.1% of starting mass)

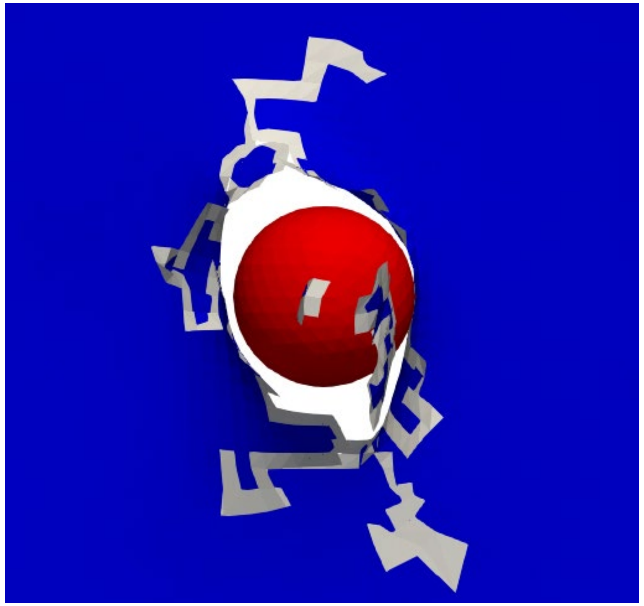
Case 3 Hex Model (Most Refined)



Case 2 Shell Model

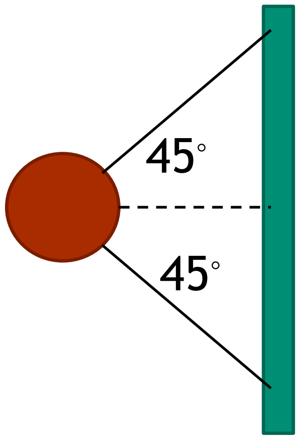


Case 2 Shell Model XFEM



Neural Network problem

- A fully connected neural network is used to determine if there is a break in a plate given the initial velocity of the projectile.
- To train the neural network, data was gathered from simulations where the initial velocities magnitude and directions varied. This simulation was then used to determine if there was a break in the plate or not.
- With this neural network, we can run lower fidelity simulations and predict if there was break in the plate or not.



Left: Mesh size = .5
Runtime = 130 sec

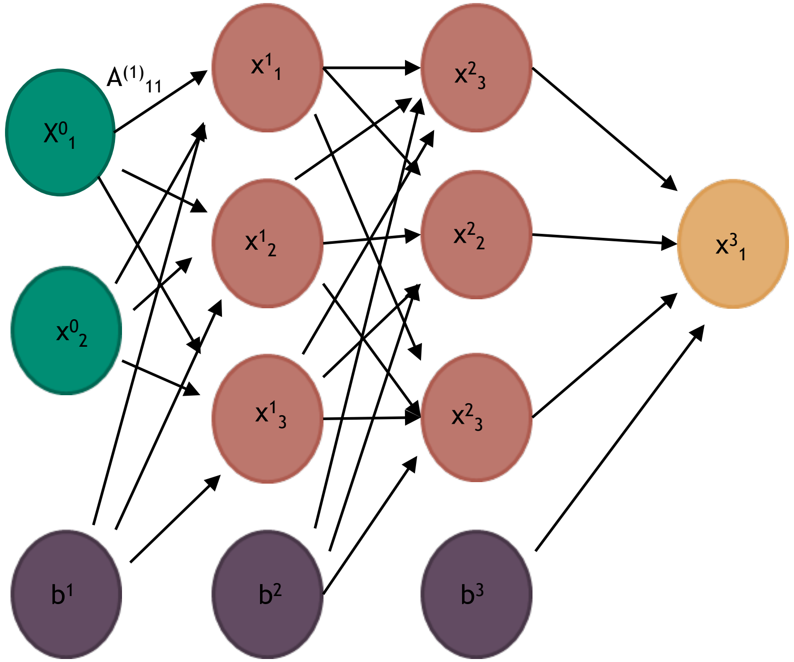
Right: Mesh size = 2
Runtime = 21 sec

Fully Connected Neural Network

- For a fully connected neural network each connection between layers can be represented as

$$\varphi^i(A^i x^{i-1} + b^i) = x^i$$

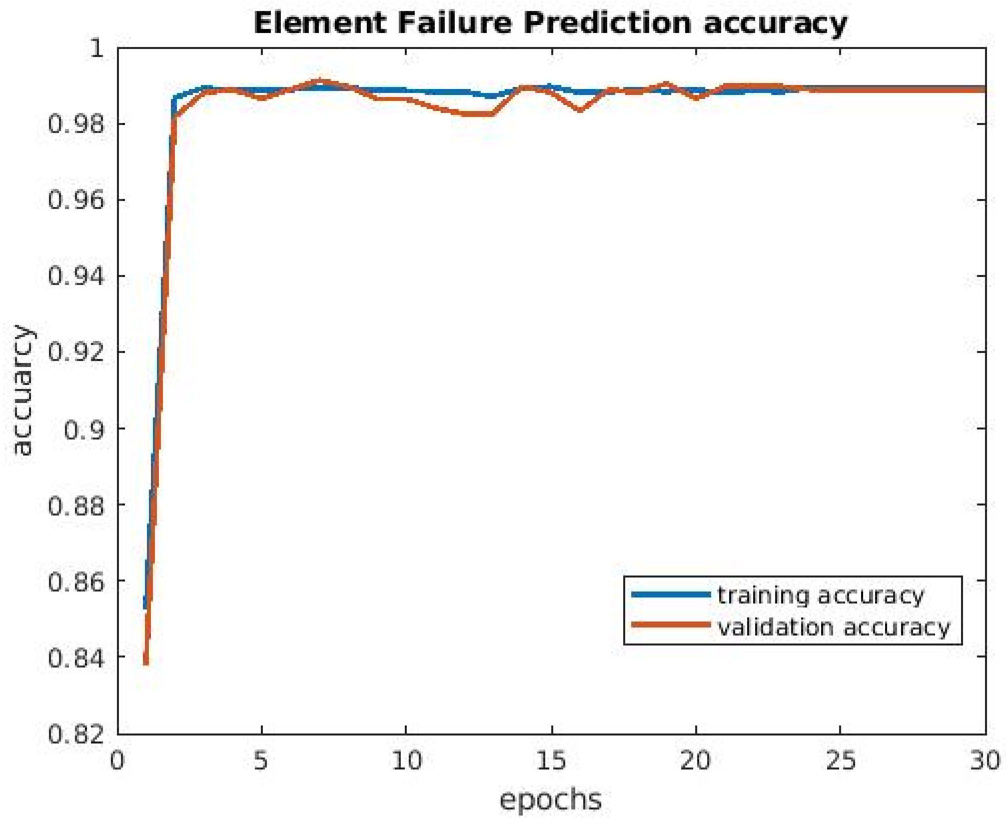
- Here **i=1,2,…,n**, where **n-1** is the number of hidden layers.
- The vectors $\mathbf{x}^{i-1}$ are the inputs into the **i**th layer of the neural network.
- $\mathbf{A}^i$ and $\mathbf{b}^i$ are the weight matrix and bias vectors respectively..
- The function $\boldsymbol{\varphi}^i$ is a an element wise function known as the activation function. This is used to add nonlinearity to the neural network.



Neural Network Training

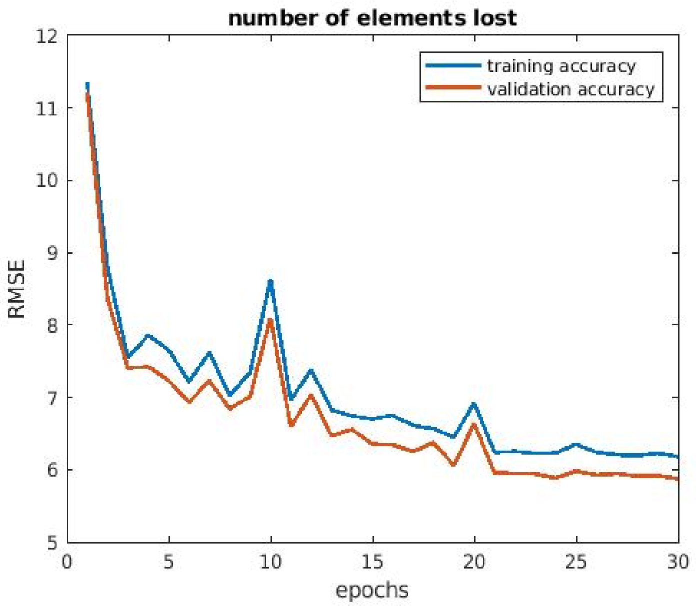
- Trained the network using 30 epochs.
- Use the adam optimization algorithm.
- Total training time approximately 20 secs.

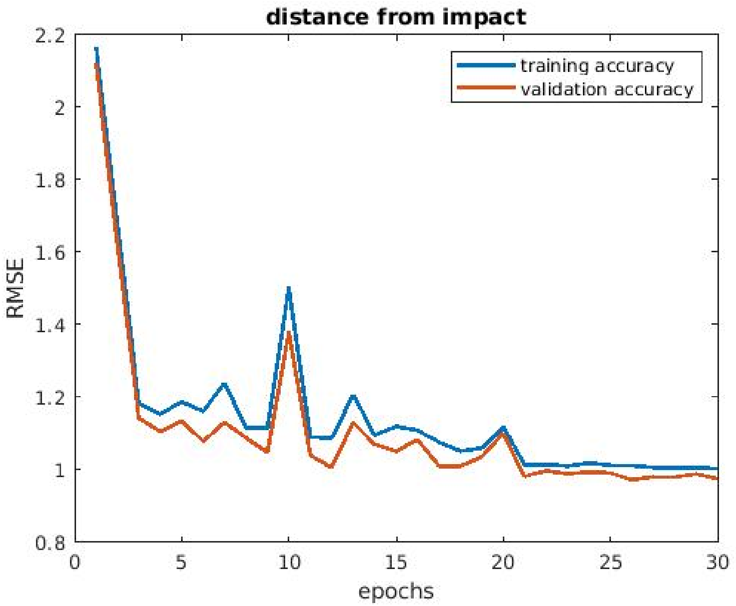
Prediction Accuracy ≈ 99%

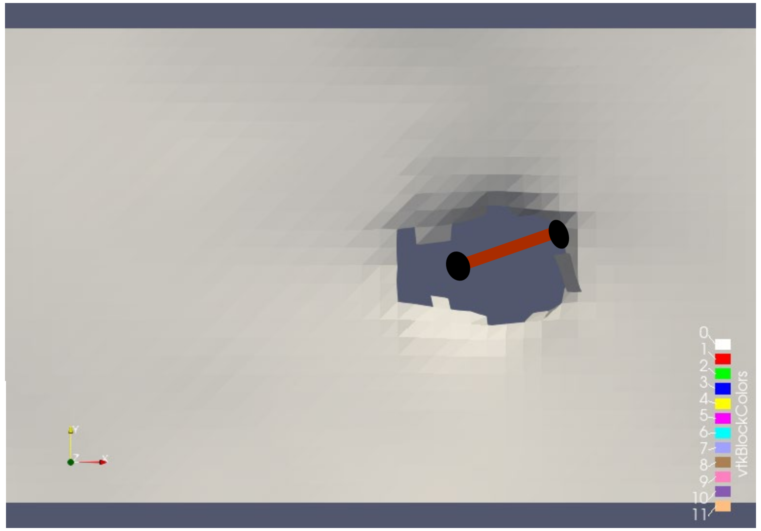


Impact Predictions

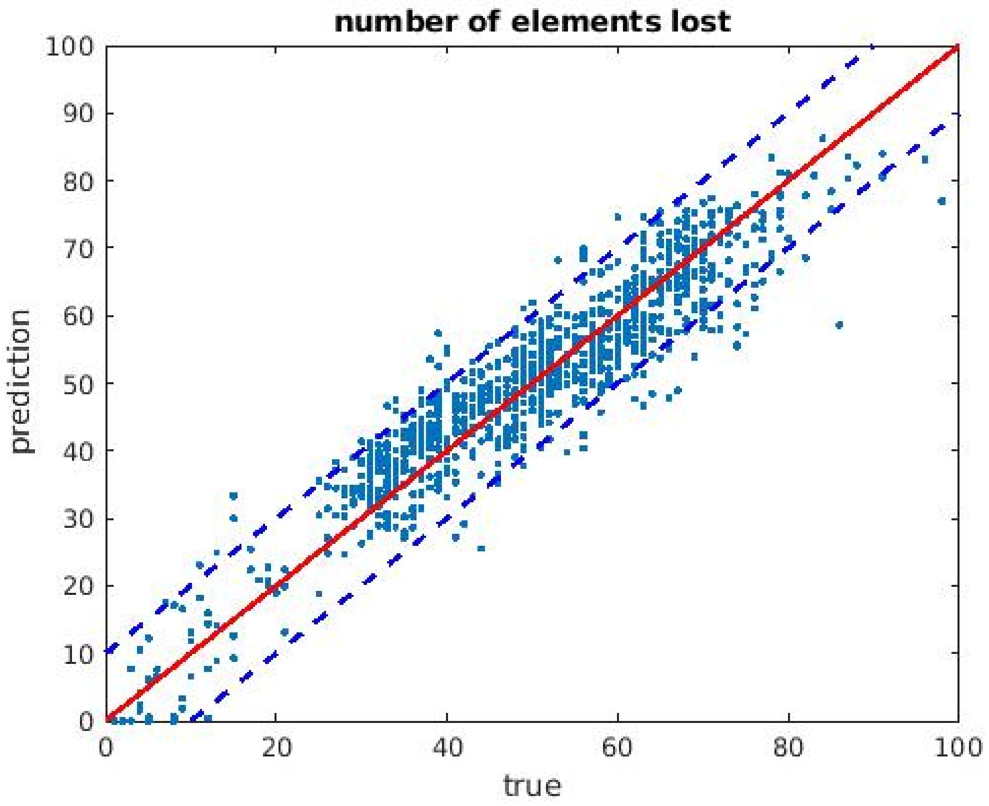
- Here, simulations are run to predict how large a tear there will be when there is element failure in the model.
- One fully connected neural network was used to make predictions on how wide the hole is and the total number of elements destroyed.

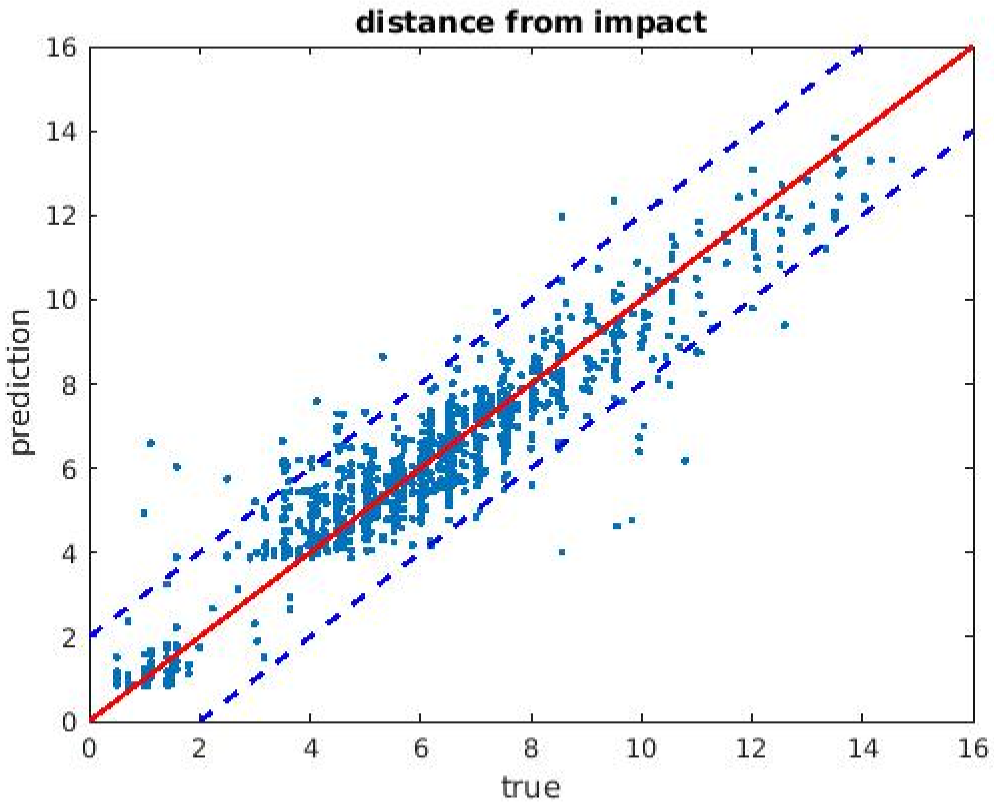






Impact Predictions on the Validation Set





62.59% of |y_true-y_pred|<5 elements lost
92.29% of |y_true-y_pred|<10 elements lost

77.44% of |y_true-y_pred|<1inch
94.92% of |y_true-y_pred|<2 inches

Results

- Developed quantitative and qualitative comparison of shell and hex models
- Looked at the usefulness of XFEM in coarse shell models for crack propagation compared to a refined hex model
- Quantified disparity in model behavior dependent on mesh resolution
- Able to accurately predict if there will be a tear in the plate given the projectiles velocity and give an estimate on how large the tear will be.

Looking into the Future

- Predict shape of the hole
- Train neural networks with other inputs, such as stress, strain, contact force, etc.
- Train neural network with higher fidelity model
- Study the differences in kinetic energy of the plate loss in element death vs. XFEM

Acknowledgements

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