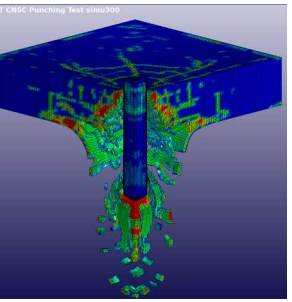

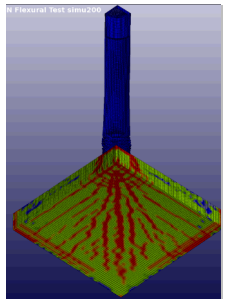

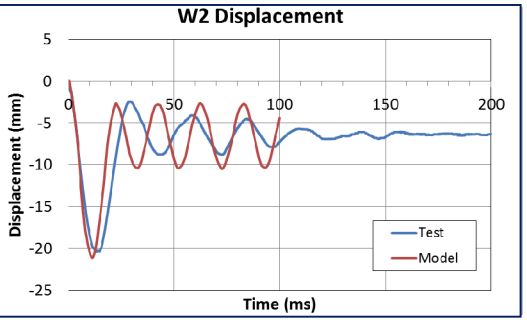

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SAND2012-8791P

IRIS 2012 Simulations Overview

OECD/NEA Workshop on Improving Robustness Assessment Methodologies for Structures Impacted by Missiles (IRIS)

Ottawa, Canada, 17-19 October 2012

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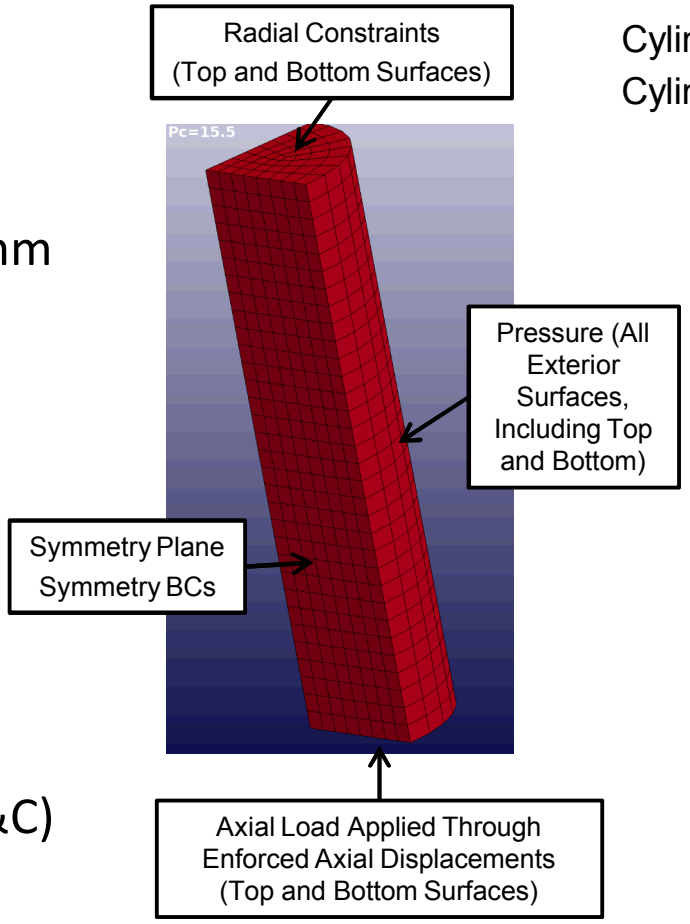
Outline

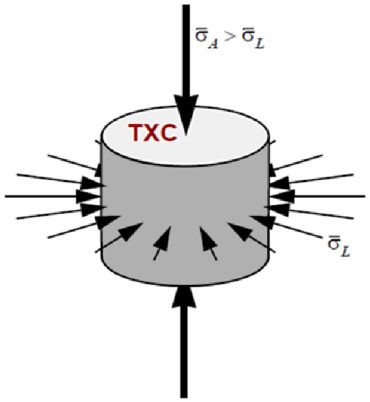
- Concrete Cylinder Test Modeling
  - Model, Results, Conclusions
- Detailed Missile Impact Modeling
  - Model, Results, Conclusions
- Simplified Missile Impact Modeling
  - Methodology Description
  - Model, Results, Conclusions

Concrete Cylinder Test Model

- Code: LS-DYNA
- Mesh: Quarter Sym.
  - 1536 Hex
  - Element Size ~4.375 mm
- Boundary Conditions
  - Quarter Symmetry
  - Radial at Ends
  - Pressure
  - Axial Displacement
- Material Model
  - Karagozian & Case (K&C)



Cylinder Length = 140 mm
Cylinder Diameter = 70 mm



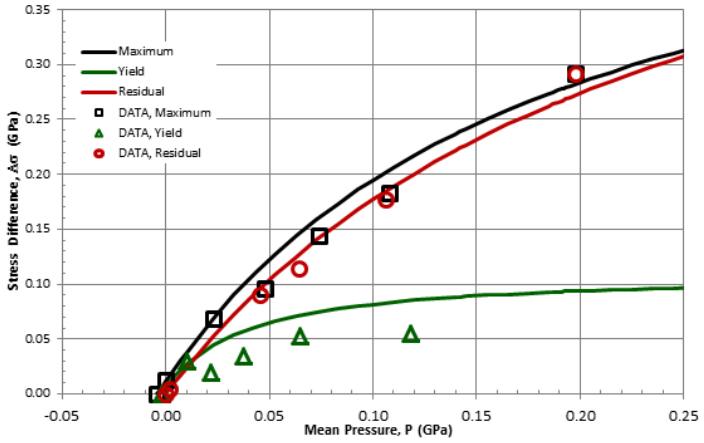
Triaxial Compression (TXC)

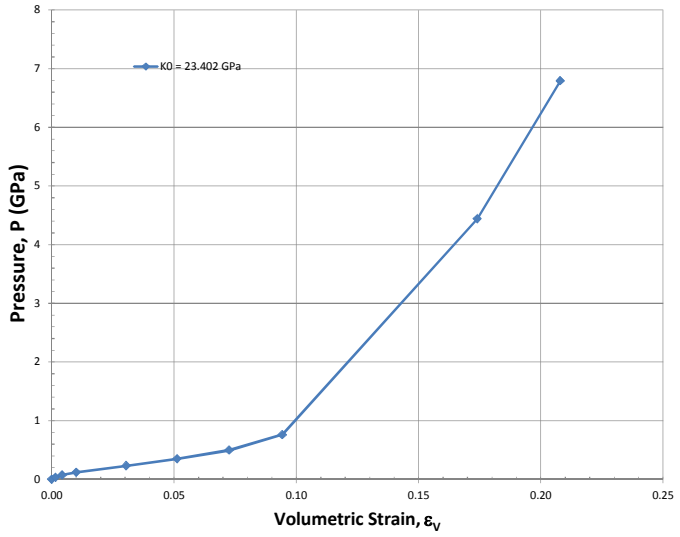
Typical Concrete Cylinder specimen:
Specimen Diameter = D
Length, L = 2*D
L/D = 2

σ_L = Confinement Pressure = P_C
σ_A = σ_L and then increase σ_A

Concrete Constitutive Model

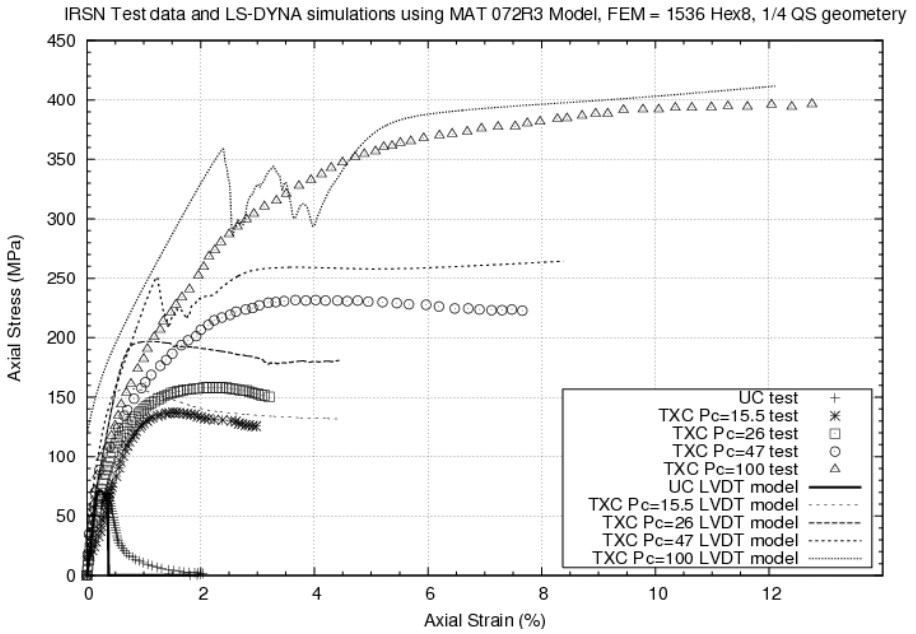
- K&C Model (MAT_072R3)
- Three Invariant Model
- Deviatoric Response
  - Strength vs. Pressure
  - Yield, Ultimate, Residual
- Volumetric Response
  - Volumetric Strain vs. Pressure
- Damage
  - Tensile, Compressive, Volumetric
- Strain Rate Dependence
- Material Erosion

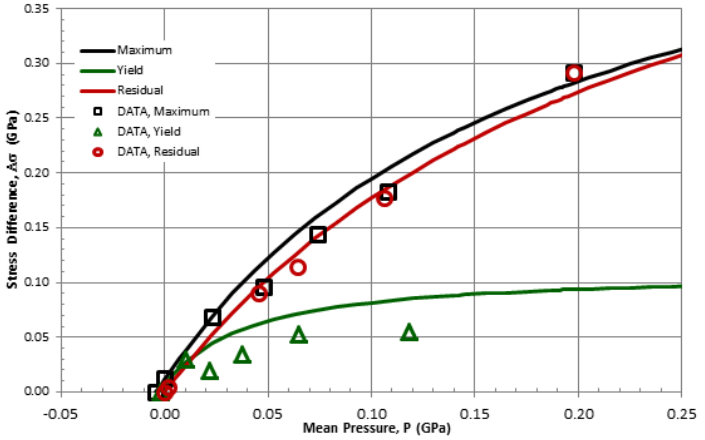




Simulation Results and Conclusions

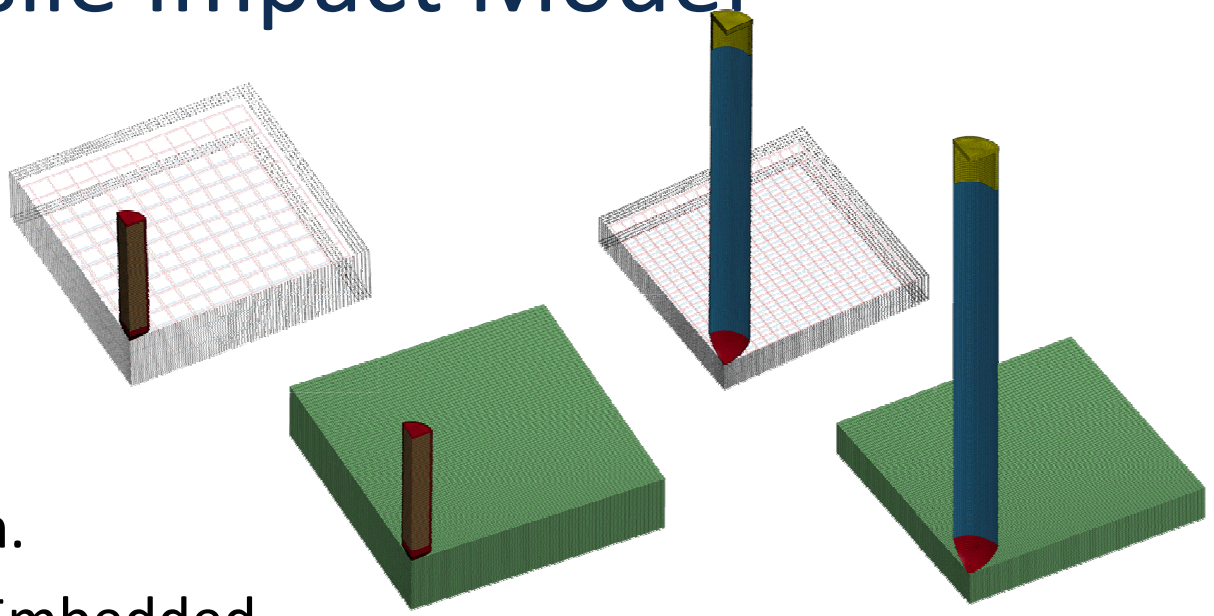
- Model does reasonable job of recreating concrete cylinder test.
- Non-smooth yield to ultimate transition at higher confining pressures.
  - Cracking?
  - Loading Rate (~0.1 s^{-1})?
- Overestimation of ultimate strength for mid-confining pressures.
  - Poor Failure Surface Fit.





Detailed Missile Impact Model

- Code: LS-DYNA
- Two Models
  - VTT Flexural
  - VTT Punching
- Mesh: Quarter Sym.
- Reinforcing Steel: Embedded
- Boundary Conditions
  - Quarter Symmetry
  - Target Edges
- Material Models
  - 3 Concrete Models

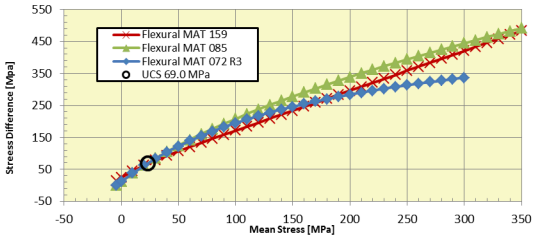


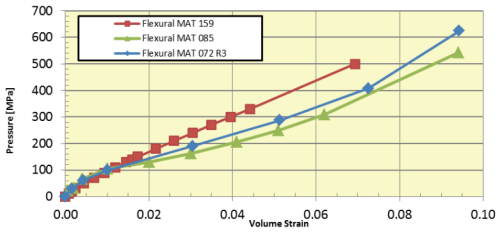
Attribute[1]	VTT Flexural	VTT Punching
Complete Model		
Number of Elements	180,632	290,085
Target – Concrete		
Number of Elements	162,000	267,300
Characteristic Element Dimension (mm)	8	8
Target – Steel Reinforcing		
Number of Element	3,112	1,104
Characteristic Element Dimension (mm)	30	43
Missile		
Number of Shell Elements	12,256	N/A
Characteristic Shell Element Dimension (mm)	6	N/A
Number of Hexahedral Elements	3,264	21,681
Characteristic Hexahedral Element Dimension (mm)	6	8

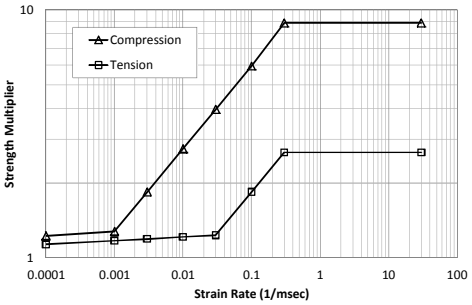
[1]Numbers of elements listed are for the quarter symmetric model.

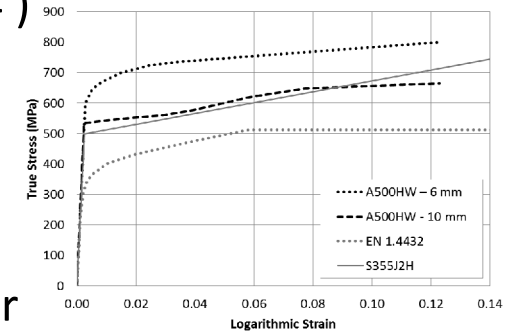
Detailed Model Materials

- Concrete (3 Models)
  - K&C (MAT_072R3)
    - w/ Rate Dependence
  - Winfrith (MAT_085)
  - Continuous Surface Cap (MAT_159)
- Reinforcing Steel
  - Elastic Plastic (MAT_024)
    - w/ Rate Dependence
- Missile Steel
  - Elastic Plastic (MAT_024)
    - w/ Rate Dependence
  - Bilinear (MAT_003)
    - w/ Rate Dependence
- Missile Concrete
  - MAT_016 Pseudo Tensor





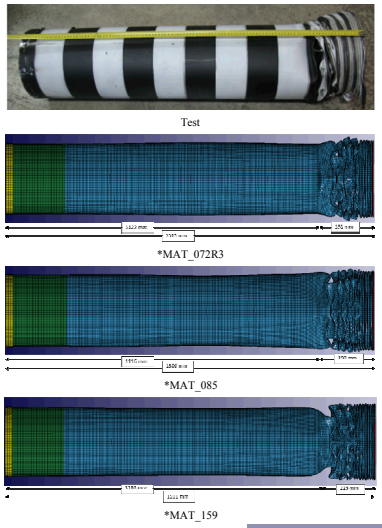




Material/Property	VTT Flexural		VTT Punching
Target Concrete			
Modulus of Elasticity [GPa]	39.3		39.3
Poisson's Ratio	0.22		0.22
Density [kg/m^3]	2260		2260
Compressive Strength [MPa]	69.0		69.0
Tensile Strength [MPa]	4.0		4.0
Target Reinforcing Steel			
Designation	A500HW – 6 mm		A500HW – 10 mm
Modulus of Elasticity [GPa]	219		210
Poisson's Ratio	0.29		0.29
Density [kg/m^3]	7843		7843
Yield Strength [MPa]	600[a]		535[a]
Ultimate Strength [MPa]	715[a]		605[a]
Elongation to Failure, [%]	12[a]		12[a]
Rate Multiplier Constant C [1/sec]	40		40
Rate Multiplier Constant P	5		5
Missile Steel			
Designation	EN 1.4432	S355J2H	S355J2H and Fe52[c]
Modulus of Elasticity [GPa]	200	200	200
Poisson's Ratio	0.29	0.29	0.29
Density [kg/m^3]	7850	7738	7850
Yield Strength [MPa]	231[a]	500	231[a]
Ultimate Strength [MPa]	484[a]	1940	484[a]
Elongation to Failure [%]	N/A[b]	120	N/A[b]
Rate Multiplier Constant C [1/sec]	100	40	100
Rate Multiplier Constant P	10	5	10

[a]Value given is engineering stress or engineering strain.
[b]Failure criterion not included for this material.
[c]Even though the steel portion of the missile iscomposed of these materials, EN1.4432 properties were assumed.

VTT Flexural Results

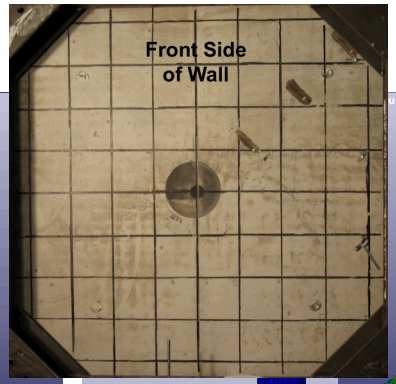


MAT_072R3 Model
- Rein. Steel Rate: Yes
- Concrete Rate: Yes

MAT_085 Model
- Rein. Steel Rate: Yes
- Concrete Rate: No

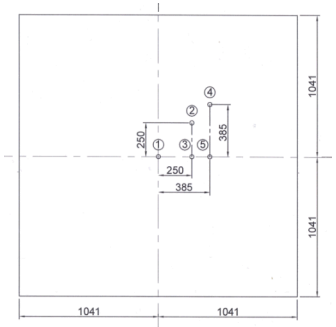
MAT_159 Model
- Rein. Steel Rate: Yes
- Concrete Rate: No

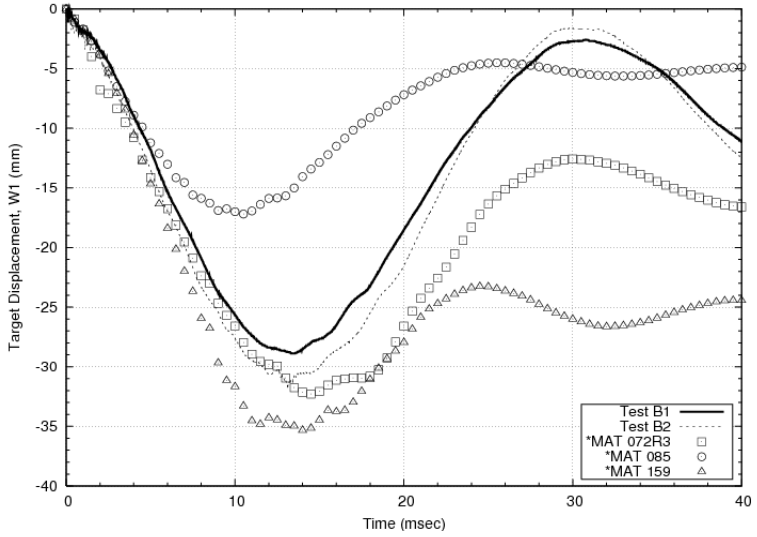
Response	Experiment B1	Experiment B2	*MAT_072R3	*MAT_085	*MAT_159
Rebound Velocity (m/sec)	N/A	N/A	6.5	7.1	6.9
tshock = Bounce/Shock Duration (msec)	N/A	N/A	15.75	17.00	14.75
L_T of Missile (mm)	955	930	1122	1116	1286
H_T of Missile (mm)	185	190	191	190	225
$L_T + H_T$ (mm)	1140	1120	1313	1306	1511
Shortening of Missile (mm)	971	991	798	805	600

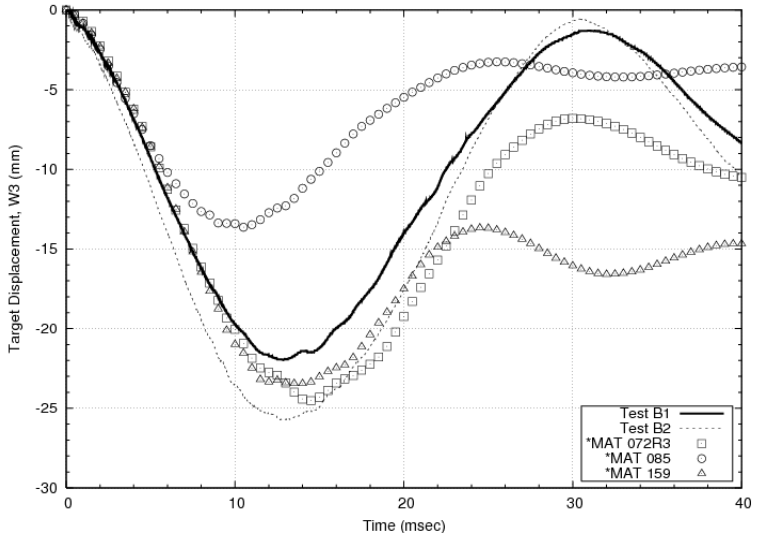


VTT Flexural – Target Disp.

- MAT_072R3 and MAT_159 do a good job of matching amplitude and frequency.
- MAT_085 under predicts amplitude.
- MAT_159 over predicts residual displacement.
- MAT_072R3 does best over all job.

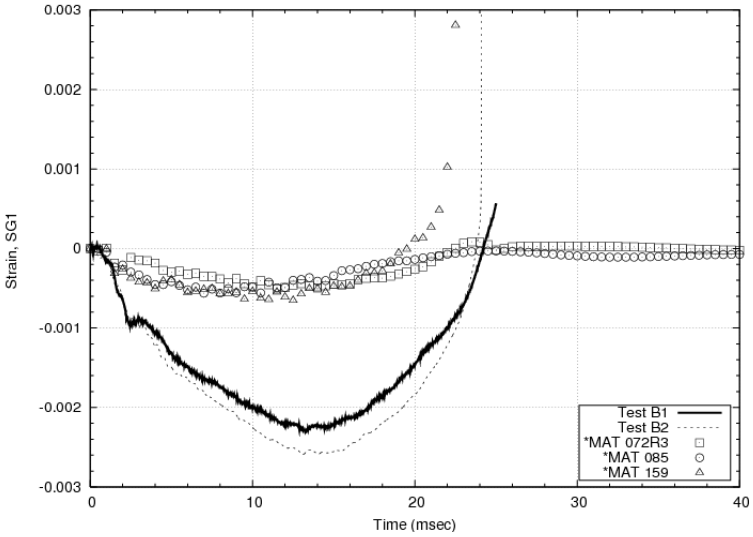


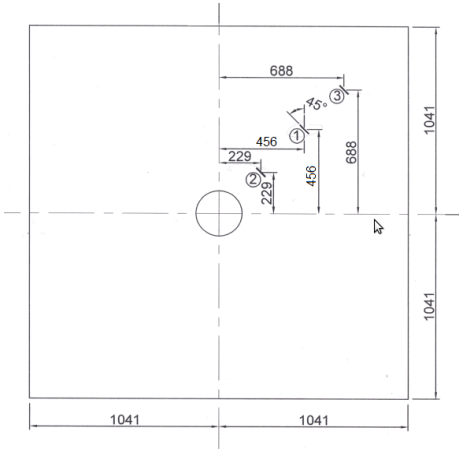


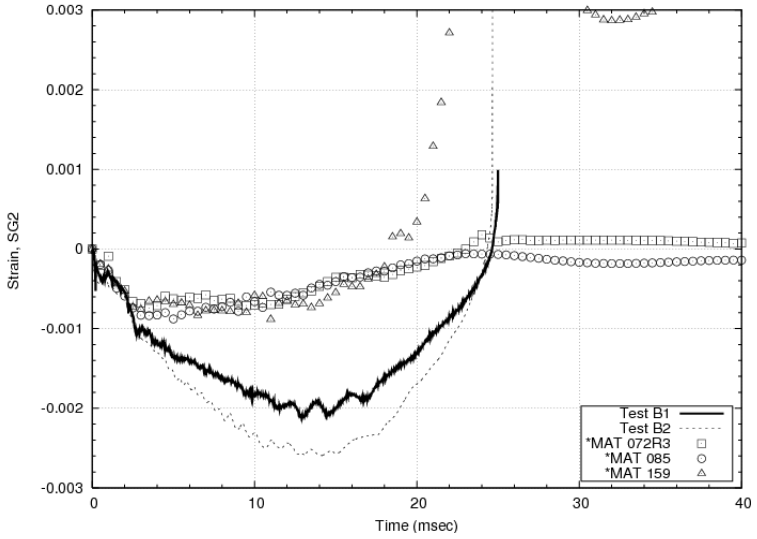


VTT Flexural – Concrete Strains

- Concrete strain predictions generally consistent between models.
- All of the models under predict concrete strains on target surface.
  - Measurement Details?

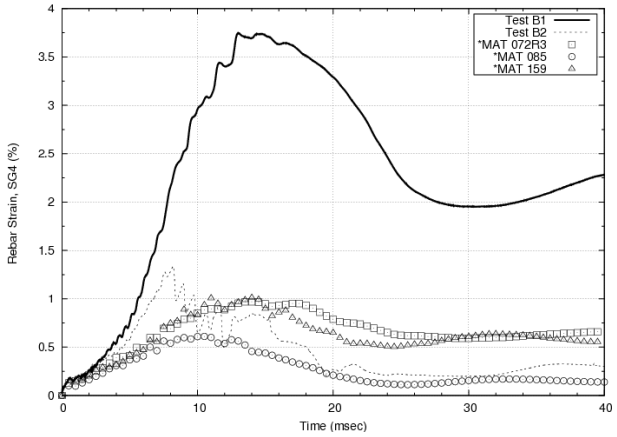


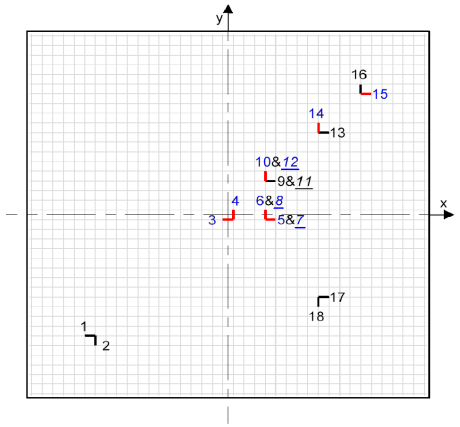


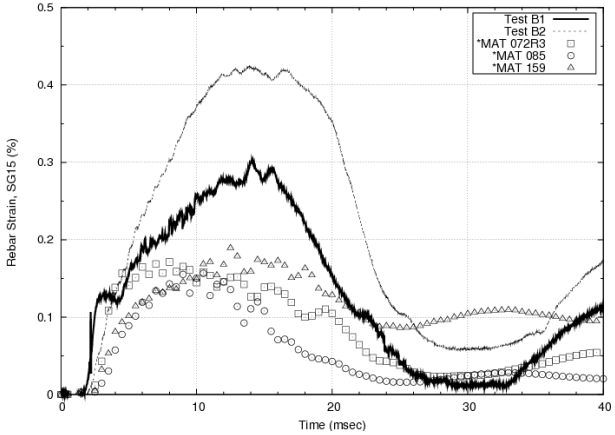


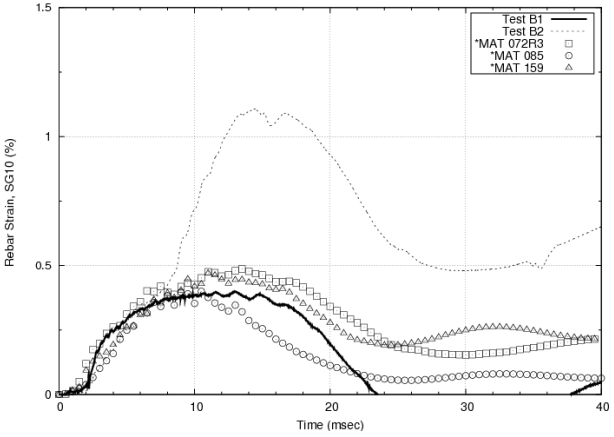
VTT Flexural – Rebar Strains

- Rebar strain predictions generally consistent between models.
- Degree of correlation with test measure values is variable
  - Within range of data measure from two tests.

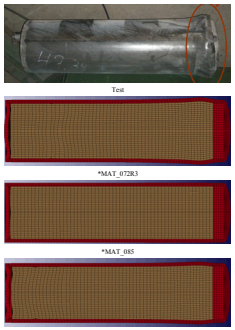








VTT Punching Results

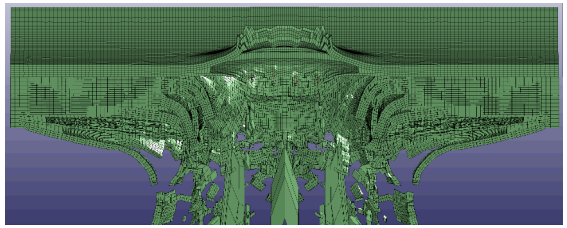


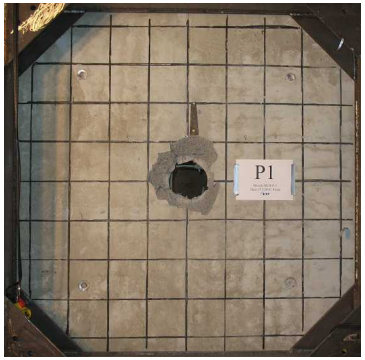
MAT_072R3 Model
- Rein. Steel Rate: No
- Concrete Rate: No

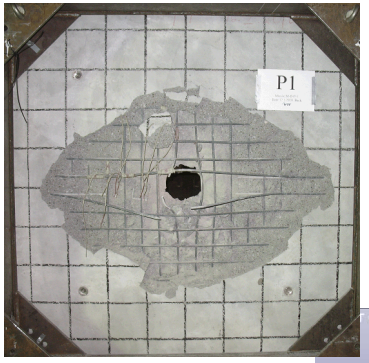
MAT_085 Model
- Rein. Steel Rate: Yes
- Concrete Rate: No

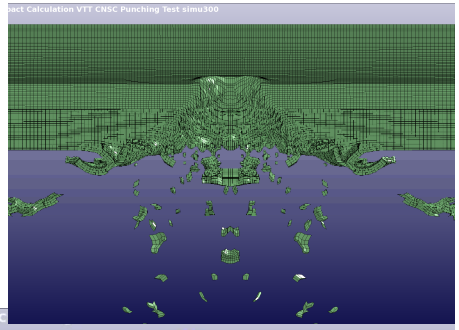
MAT_159 Model
- Rein. Steel Rate: No
- Concrete Rate: No

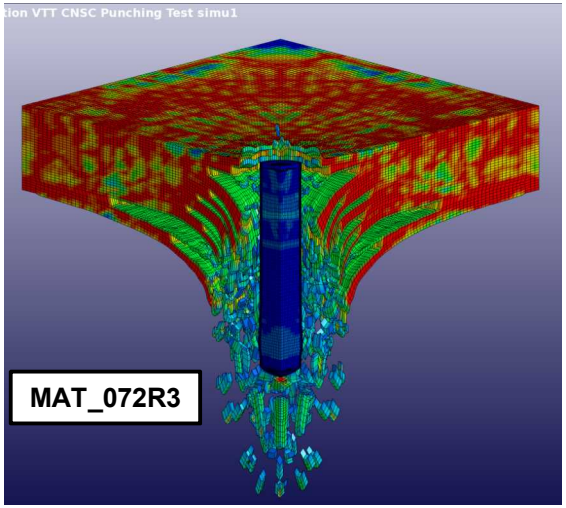
Response	Experiment			Simulations		
	P1	P2	P3	*MAT_072R3 (Baseline P1)	*MAT_085 (Baseline P2)	*MAT_159 (Baseline P3)
Exit Velocity (m/sec)	33.8	45.3	35.3	52	41	45
Missile Nose Bulging	YES	YES	YES	YES	NO	YES

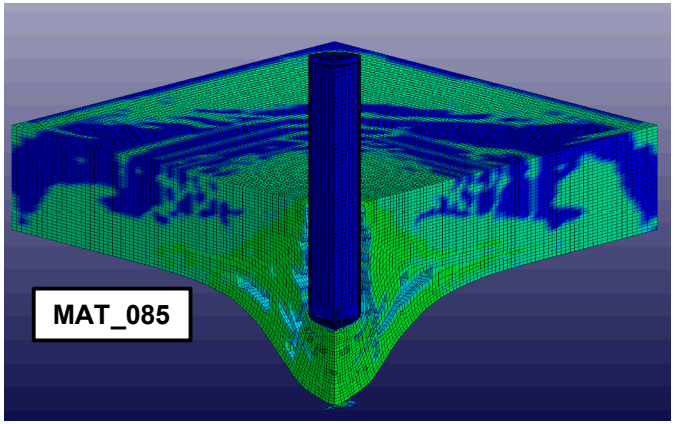


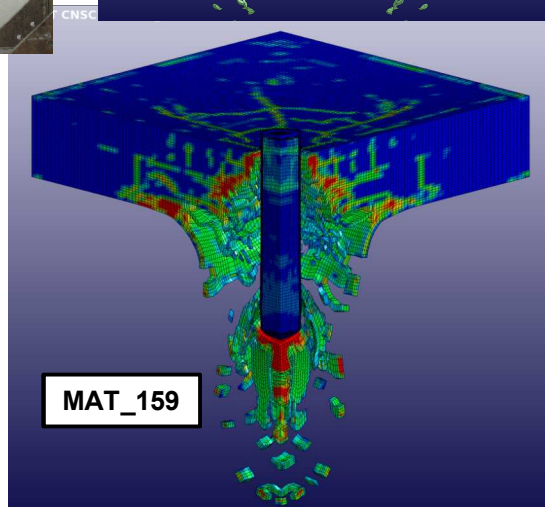








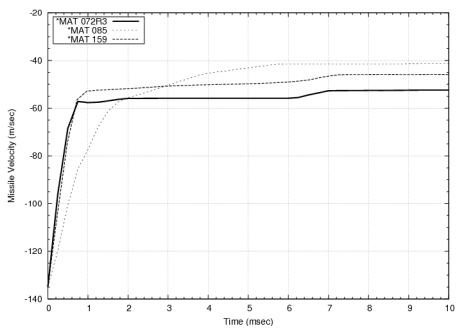


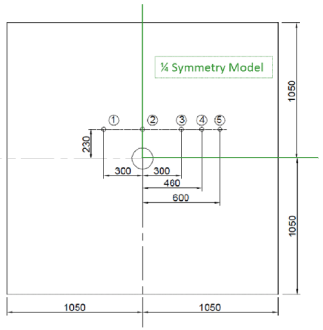


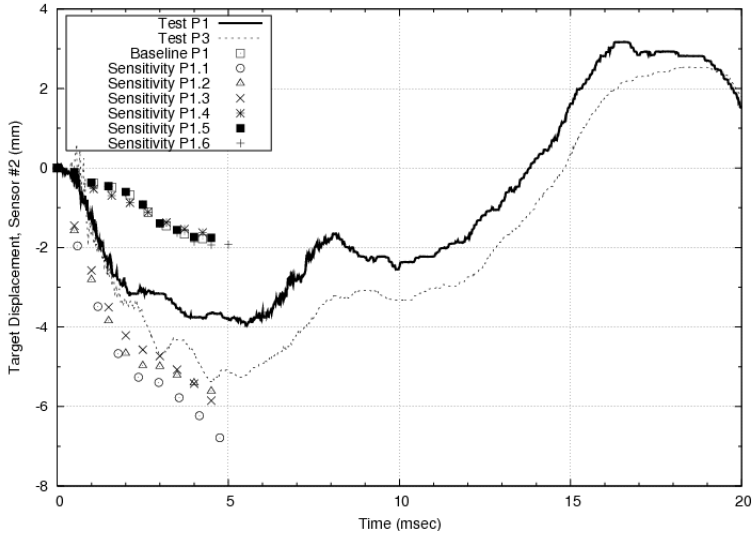
VTT Punching – Target Disp.

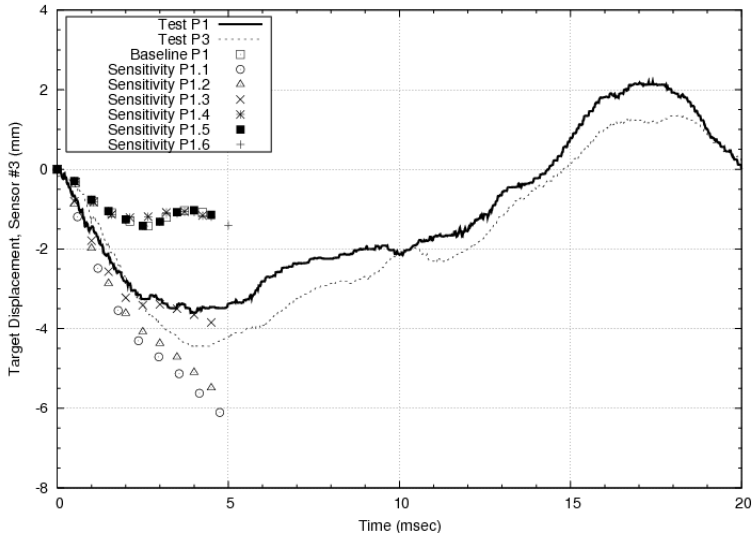
- All of the baseline models under predict the displacements.
  - They also over predict missile exit velocity.
- Including some strain rate effects in the concrete material response improves the model predictions.

Target Concrete Model *MAT_072R3 (K & C)	Target Concrete Erosion (epssh)	Target Concrete Dynamic Increase Factor (DIF)	Reinforcing Steel Bar Strain Rate Cowper-Symons	S-Lambda (Stretch Parameter on DIF of MAT_72R3, %)
Baseline P1	0.60	1.0	OFF	N/A
Sensitivity P1.1	0.60	Strain Rate Dependent	OFF	100
Sensitivity P1.2	0.60	Strain Rate Dependent	OFF	75
Sensitivity P1.3	0.60	Strain Rate Dependent	OFF	50
Sensitivity P1.4	0.60	1.0	ON	N/A
Sensitivity P1.5	0.61	1.0	OFF	N/A
Sensitivity P1.6	0.62	1.0	OFF	N/A



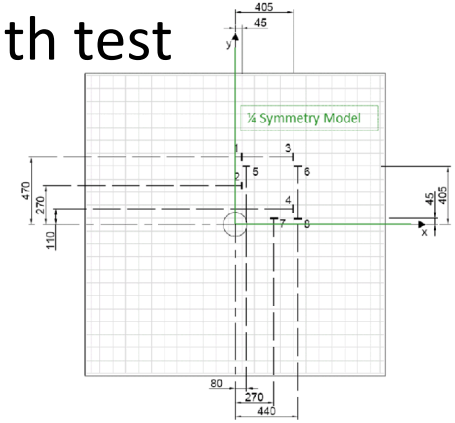


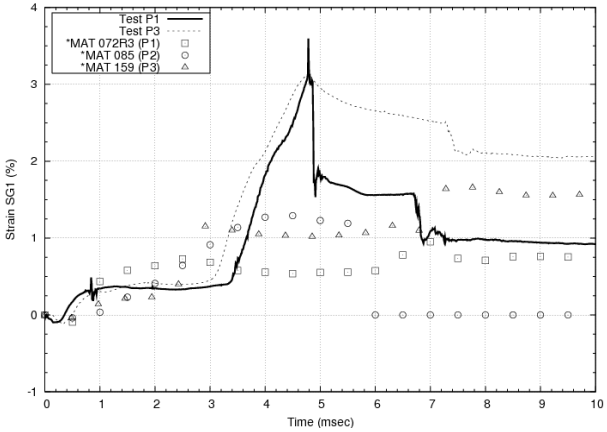


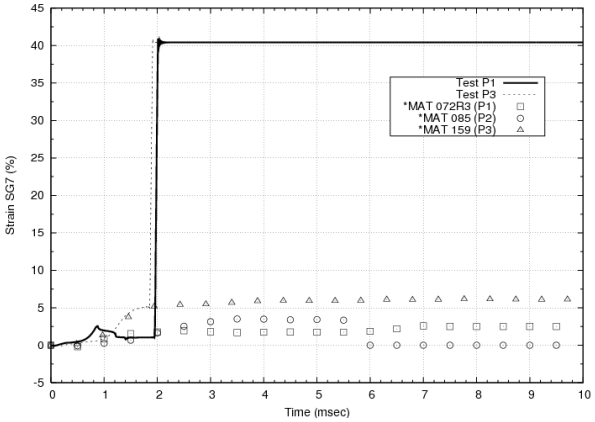


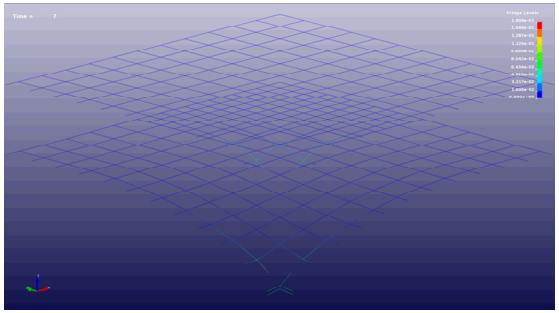
VTT Punching – Rebar Strains

- Rebar strain predictions generally consistent between models.
- Degree of correlation with test measure values is “o.k.”

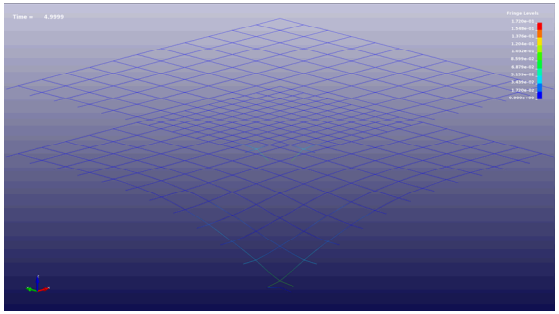




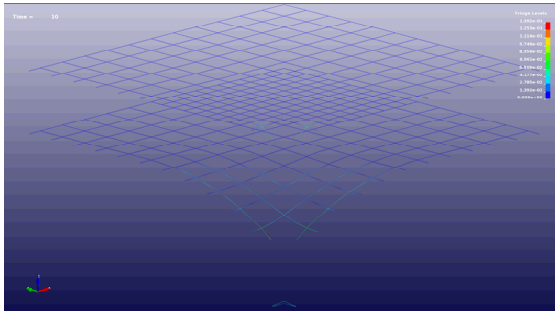




*MAT_072R3 (t = 7 msec)



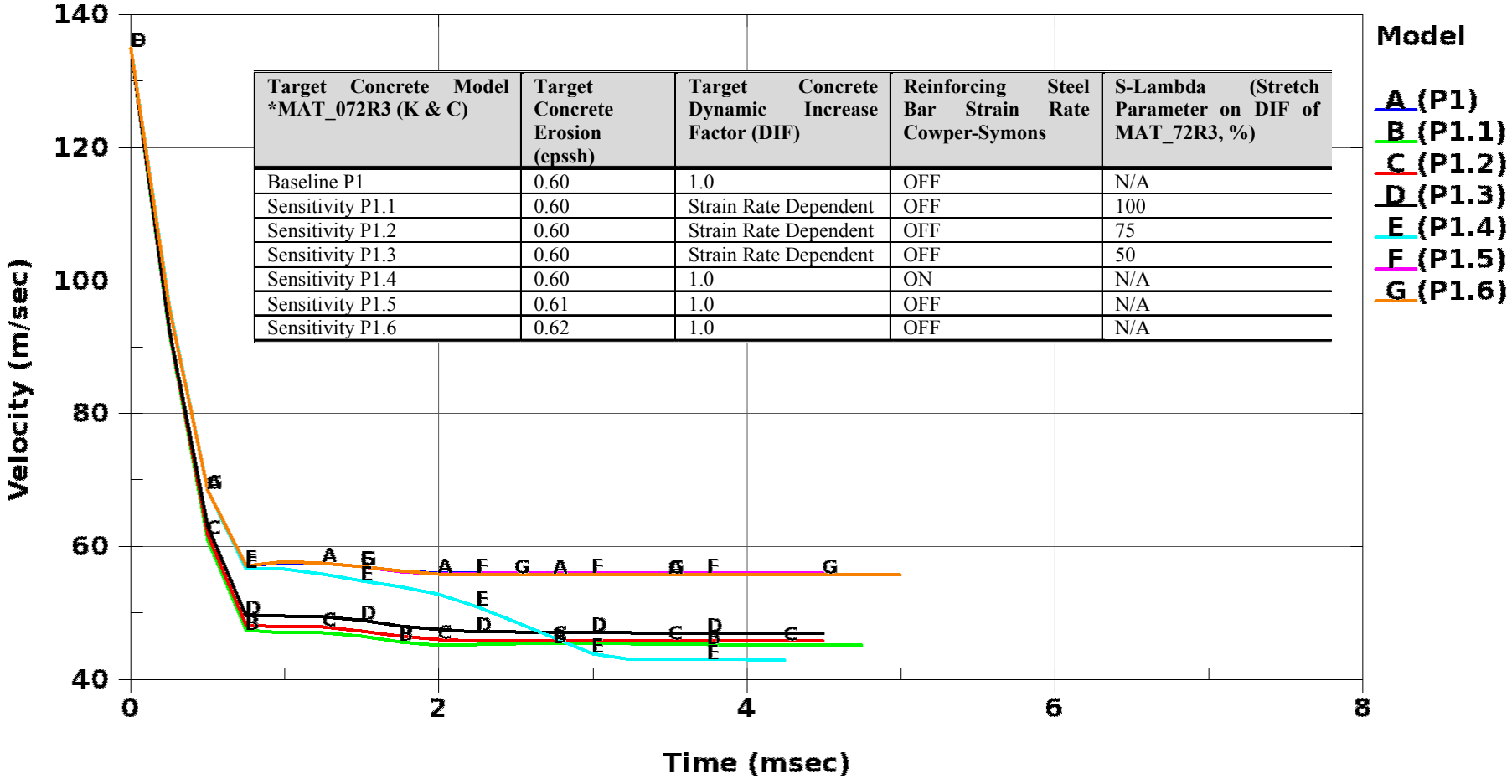
*MAT_085 (t = 5 msec)



*MAT_159 (t = 7 msec)

VTT Punching - Sensitivity

Target Concrete Model *MAT_072R3 (K & C)	Target Concrete Erosion (epssh)	Target Concrete Dynamic Increase Factor (DIF)	Reinforcing Steel Bar Strain Rate Cowper-Symons	S-Lambda (Stretch Parameter on DIF of MAT_72R3, %)
Baseline P1	0.60	1.0	OFF	N/A
Sensitivity P1.1	0.60	Strain Rate Dependent	OFF	100
Sensitivity P1.2	0.60	Strain Rate Dependent	OFF	75
Sensitivity P1.3	0.60	Strain Rate Dependent	OFF	50
Sensitivity P1.4	0.60	1.0	ON	N/A
Sensitivity P1.5	0.61	1.0	OFF	N/A
Sensitivity P1.6	0.62	1.0	OFF	N/A



Detailed Model Conclusions

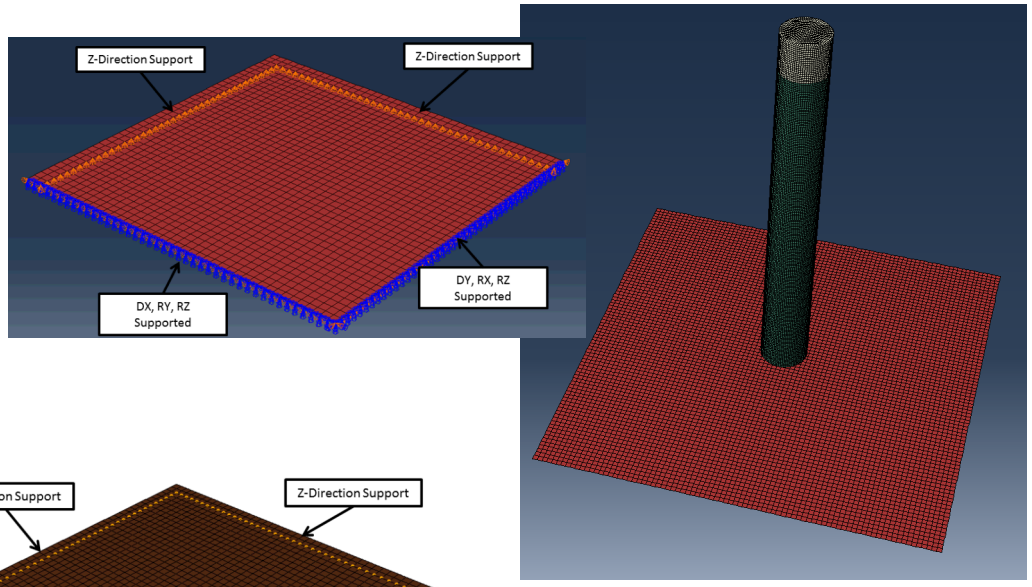
- In many instances, detailed response parameters were not precisely reproduced by the analytical models.
- However, general response characteristics (max target displacements and target response frequency, fail/no-fail, missile response) were predicted relatively accurately.
  - Without having full knowledge of all required input parameter sets.
- Areas of Uncertainty
  - Material Degradation and Failure
  - Material Response Characterization
    - Full Coverage of Applicable Regimes of Material Response.
- Conclusion: Method does seem able to produce reasonably accurate and useful predictions despite input uncertainties.

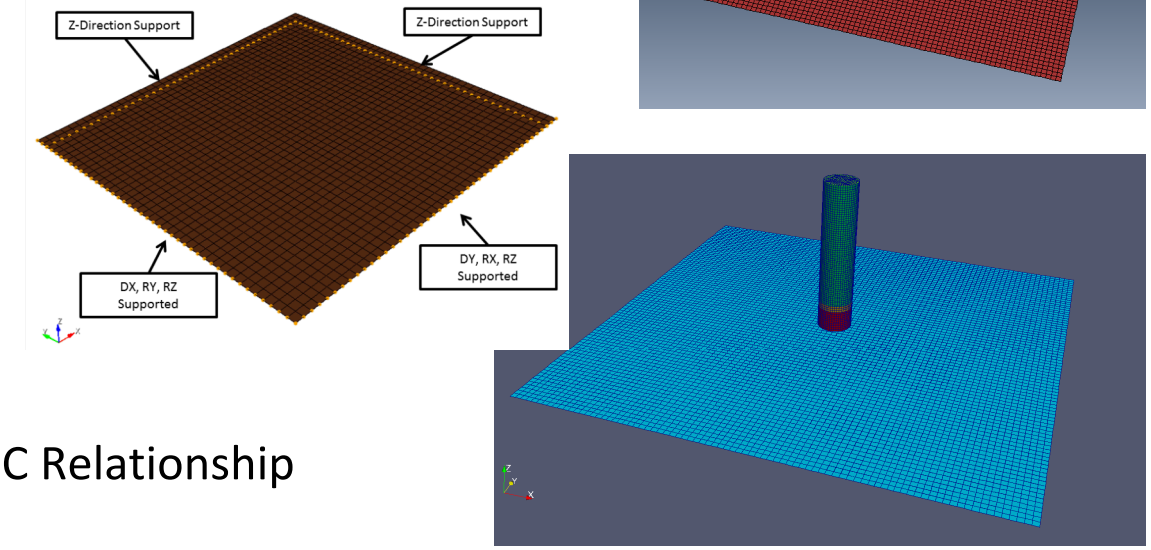
Simplified Methodology

- Simplified Methodology is Required
  - Complex Structures
  - Sensitivity Studies
- Proposed Methodology
  - Determine moment-curvature (M-C) relationship.
  - Establish bi-linear M-C material parameters for target.
  - Create a simplified model of target (shell elements & bi-linear material).
  - Define bending failure criteria.
  - Calculate punching failure load and force versus missile penetration depth.
    - Empirical equations of Li and Tong (1994) and Forrestal et. al. (2003).
  - Define shear failure criteria.
  - Create an analytical representation of the impacting missile.
  - Run the analysis.

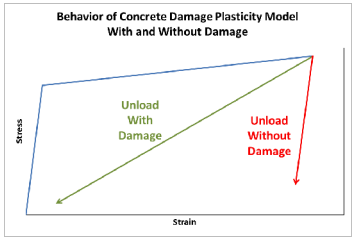
Simple Missile Impact Model

- Code
  - ABAQUS (VTT Flexural)
  - SIERRA/SM (VTT Punching)
- Elements
  - VTT Flexural
    - 6184 Shell
  - VTT Punching
    - 3300 Shell & Hex
- Mesh: Quarter Sym.
- Boundary Conditions
  - Quarter Symmetry
  - Target Edges
- Material Models
  - Bi-Linear Based on M-C Relationship





Simple Model - Materials



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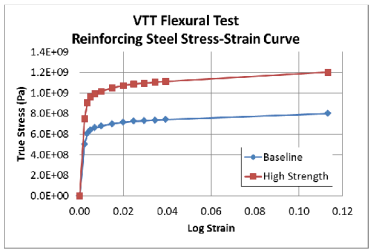
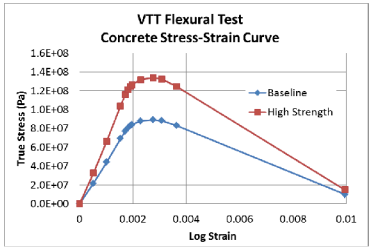
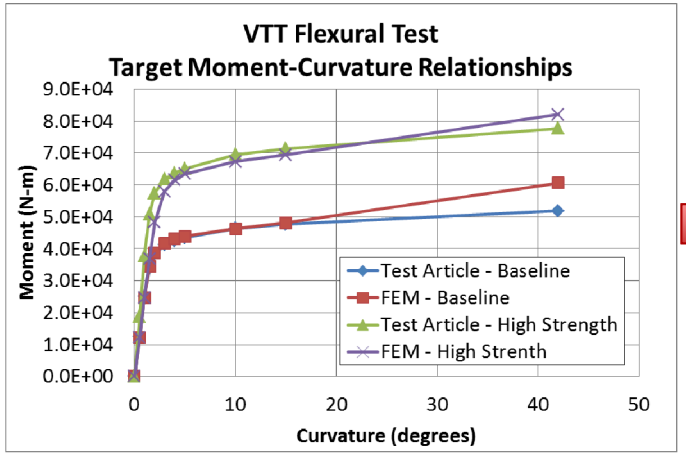
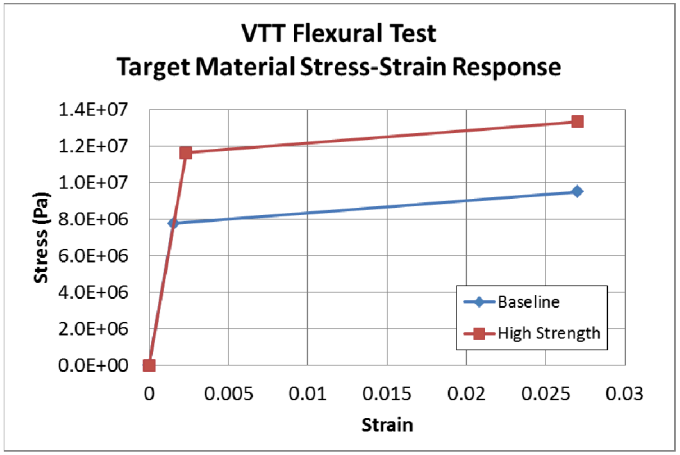
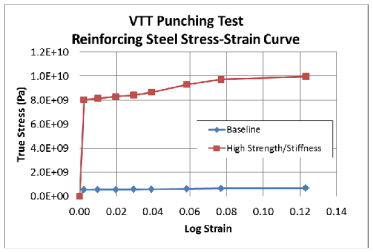
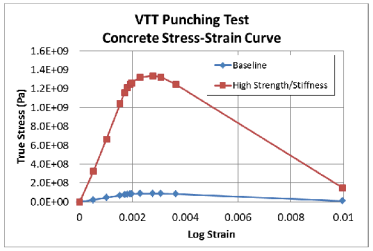


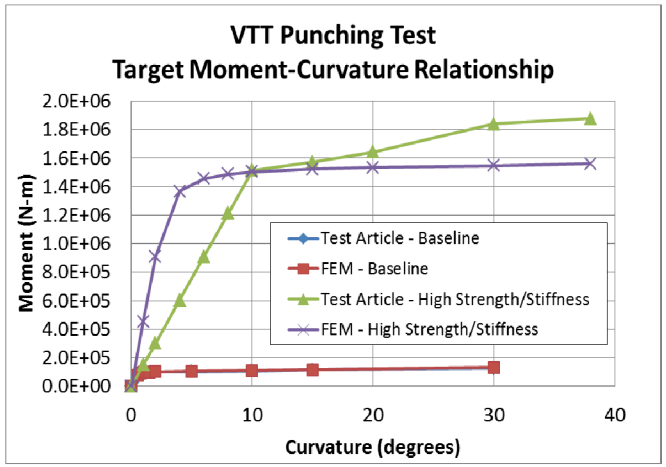


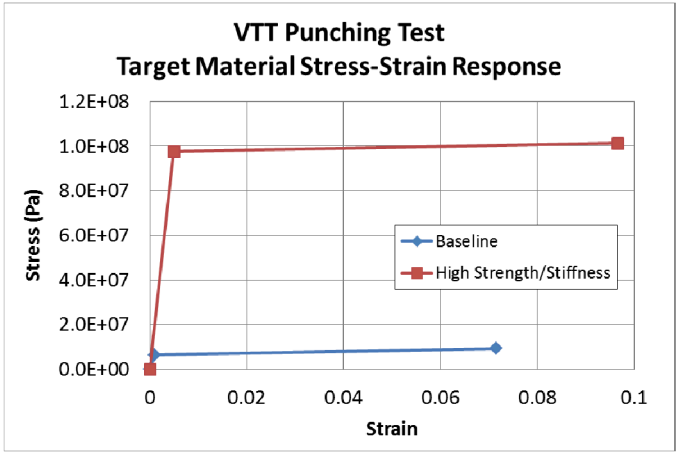






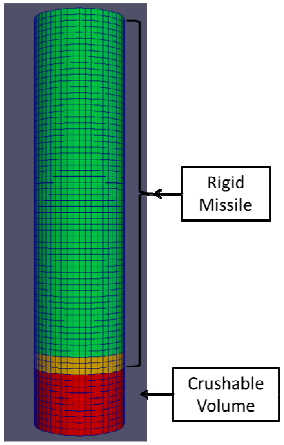


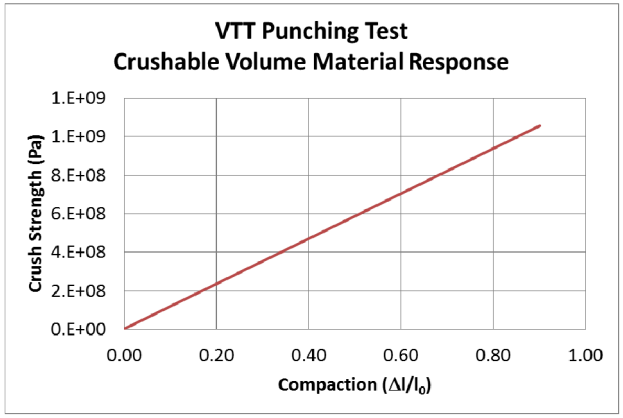


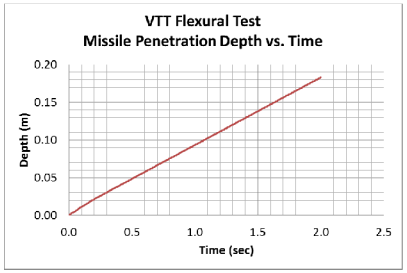


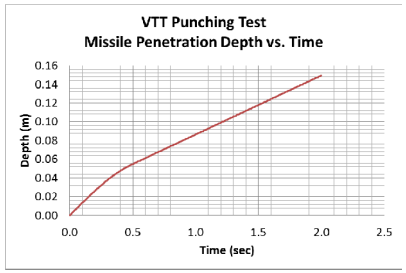
Simple Model - Punching Failure

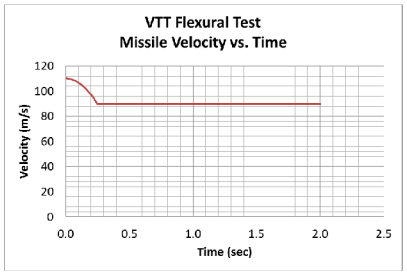
- Assume rigid missile.
- Calculate penetration depth versus resisting load.
  - Equations: Li and Tong (1994) and Forrestal et. al. (2003).
- Calculate through thickness failure criteria for punching.
- Create energy absorbing material for rigid missile.

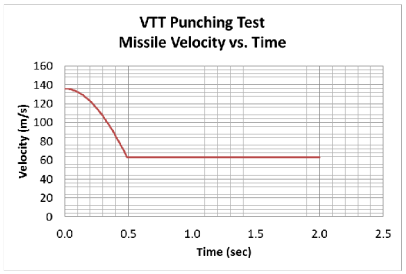


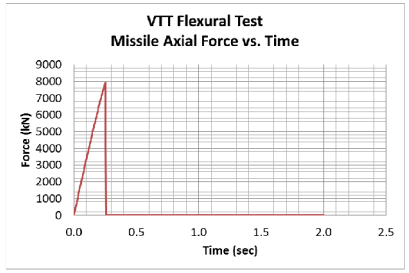


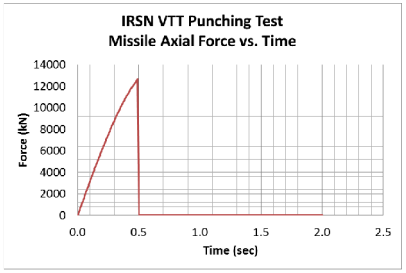


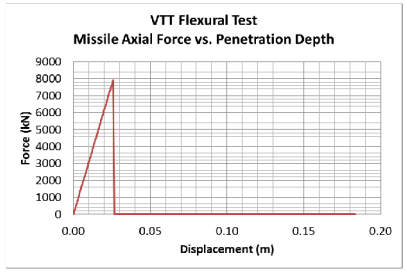


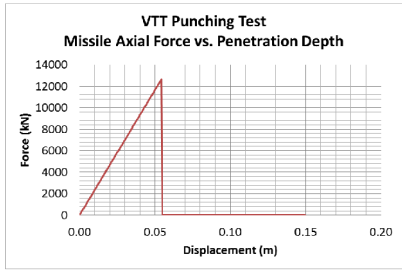




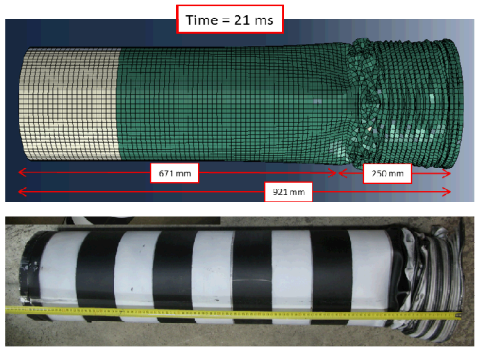


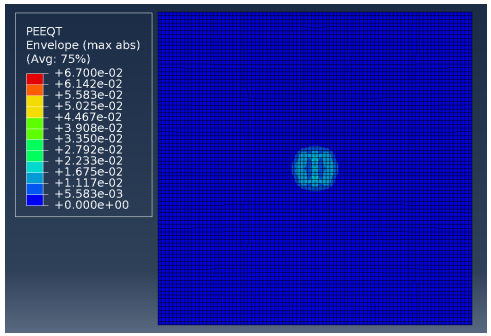


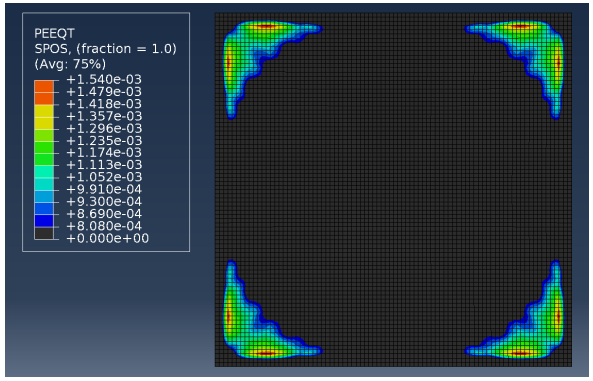


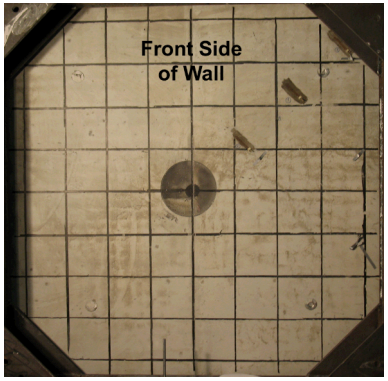


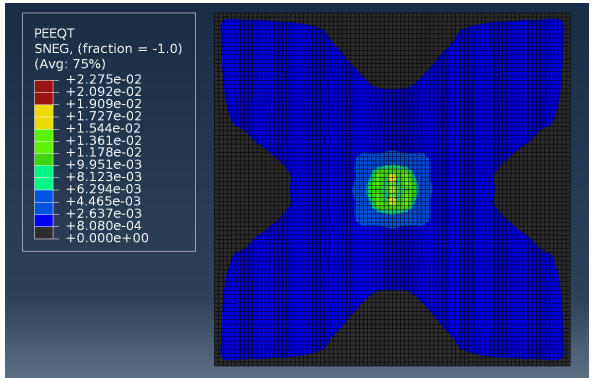
VTT Flexural Results (BL)



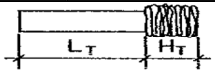






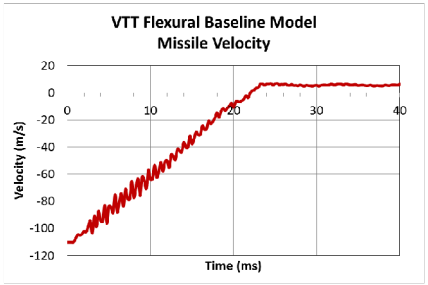


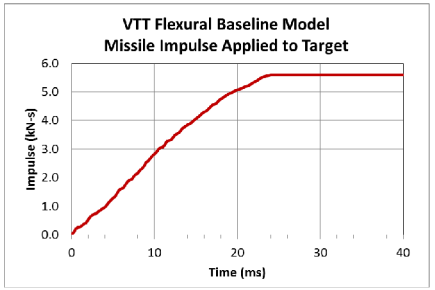
Missile Results	Baseline Model	Test Measured Value
Shock Duration	21 ms	Not Reported
Peak Load	842 kN	Not Reported
Total Impulse	5.59 kN-s	Not Reported
Missile Residual Velocity	-6.0 m/s (Rebound)	Rebound
LT at Shock Termination	671 mm	955 mm
HT at Shock Termination	250 mm	185 mm



Target Results	Baseline Model	Test Measured Value
Initial Max W1 Displacement	38.6 mm at 14.0 ms	28.9 mm at 13.5 ms
Initial Max W2 Displacement	29.9 mm at 14.5 ms	20.4 mm at 13.3 ms
Initial Max W3 Displacement	33.2 mm at 14.0 ms	22.0 mm at 12.9 ms
Initial Max W4 Displacement	19.9 mm at 15.0 ms	15.3 mm at 12.0 ms
Initial Max W5 Displacement	25.6 mm at 14.5 ms	19.5 mm at 13.1 ms
Total Max Support Force	1,783 kN at 9.0 ms	862 kN at 13.7 ms
Total Max Support Impulse	~12.0[a] kN-s	~6.5[b] kN-s
Target Failure (Yes/No)?	No	No
Target Failure Mode	N/A	N/A

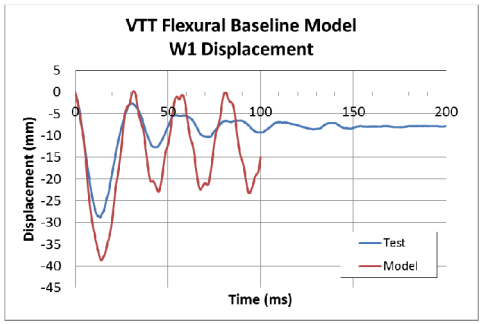
[a] Approximate average of min and max value in 50 to 100 ms range.
[b] Approximate average of min and max value in 20 to 40 ms range.

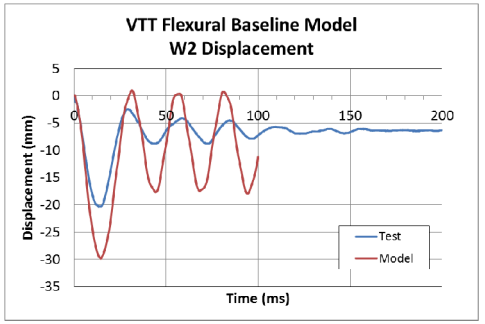


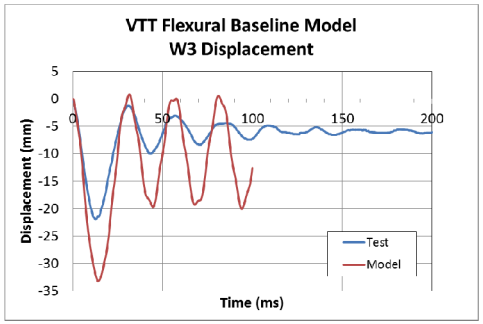


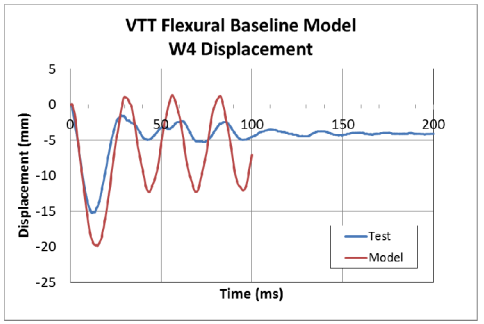
VTT Flexural – Target Disp. (BL)

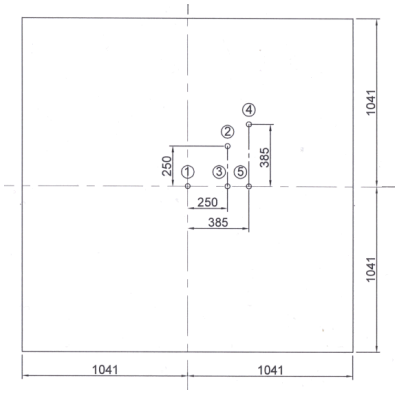
- BL simple model does good job of predicting general response.
  - Missile Rebound
  - No Bending Failure
- Amplitude of target displacements are over predicted, but frequency of response is about right.
- Missile crush-up is significantly over predicted.
  - No Strain Rate Effects in Missile Model?

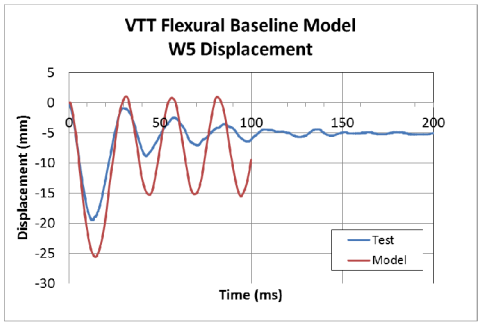




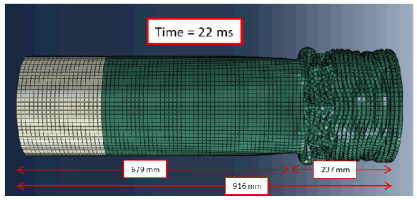


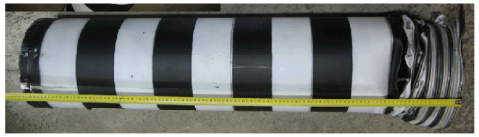


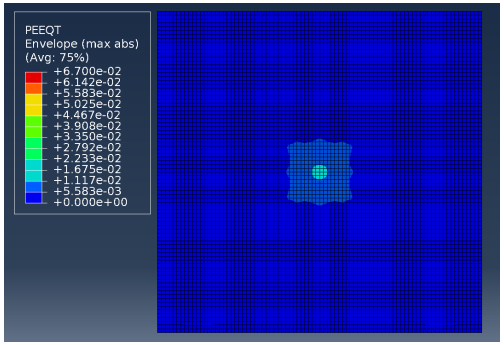


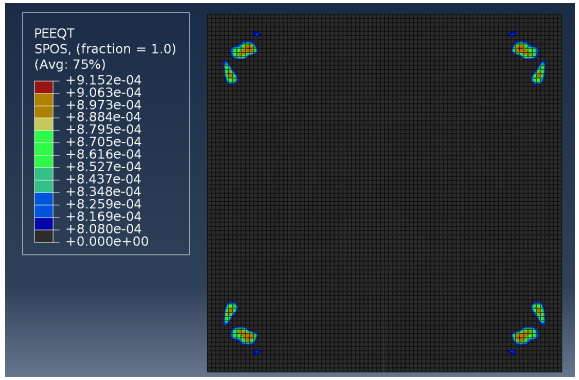


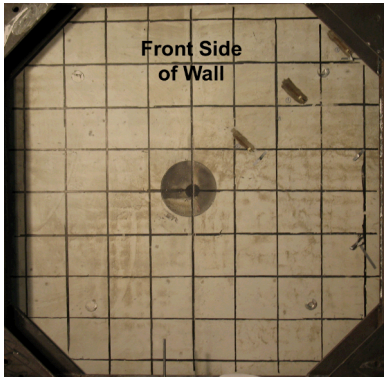
VTT Flexural Results (HS)

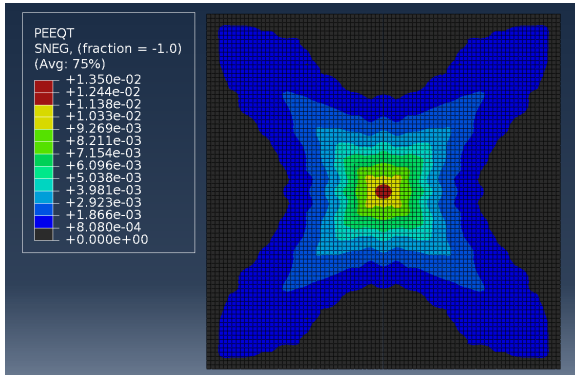




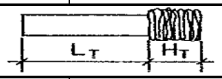








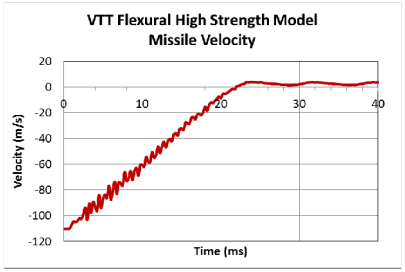
Missile Results	Baseline Model	Test Measured Value
Shock Duration	22 ms	Not Reported
Peak Load	822 kN	Not Reported
Total Impulse	5.29 kN-s	Not Reported
Missile Residual Velocity	-4.0 m/s (Rebound)	Rebound
LT at Shock Termination	679 mm	955 mm
HT at Shock Termination	237 mm	185 mm

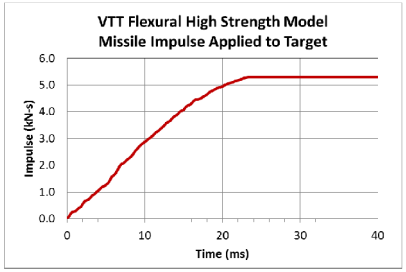


Target Results	Baseline Model	Test Measured Value
Initial Max W1 Displacement	26.5 mm at 11.5 ms	28.9 mm at 13.5 ms
Initial Max W2 Displacement	21.1 mm at 11.5 ms	20.4 mm at 13.3 ms
Initial Max W3 Displacement	23.3 mm at 11.5 ms	22.0 mm at 12.9 ms
Initial Max W4 Displacement	14.3 mm at 10.5 ms	15.3 mm at 12.0 ms
Initial Max W5 Displacement	18.4 mm at 11.0 ms	19.5 mm at 13.1 ms
Total Max Support Force	1,684 kN at 9.0 ms	862 kN at 13.7 ms
Total Max Support Impulse	~11.0[a] kN-s	~6.5[b] kN-s
Target Failure (Yes/No)?	No	No
Target Failure Mode	N/A	N/A

[a] Approximate average of min and max value in 50 to 100 ms range.

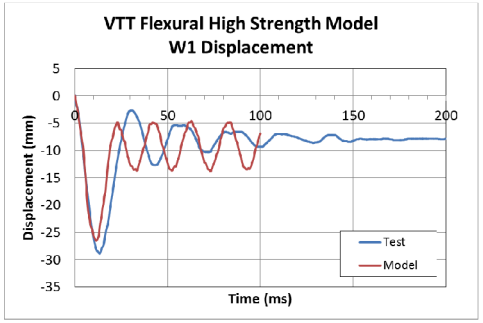
[b] Approximate average of min and max value in 20 to 40 ms range.

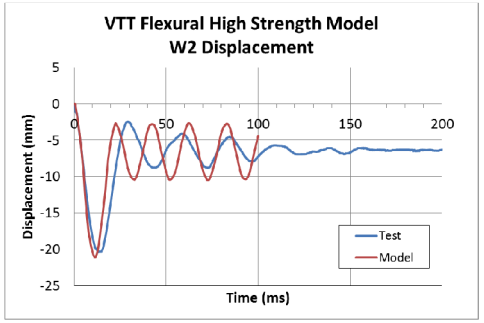


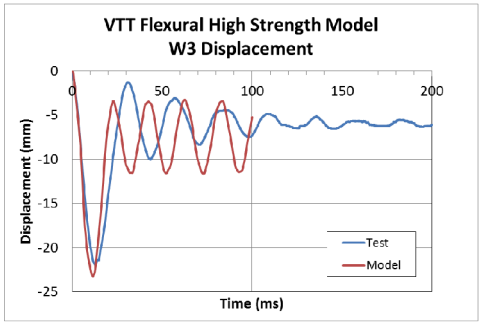


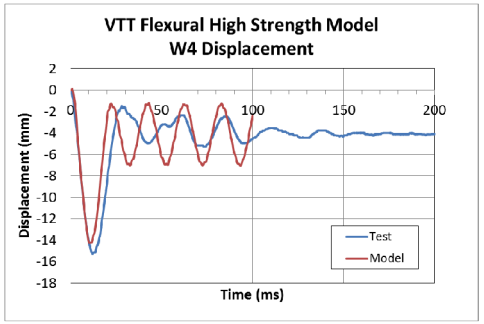
VTT Flexural – Target Disp. (HS)

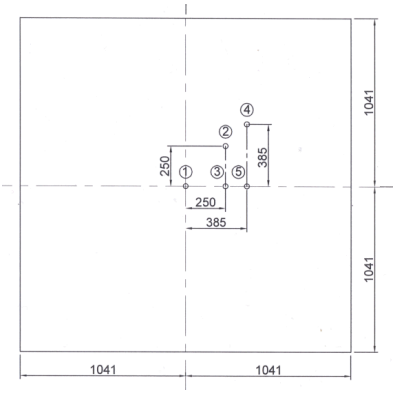
- HS simple model does good job of predicting general response.
  - Missile Rebound
  - No Bending Failure
- Amplitude of target displacements are predicted well, but frequency of response is slightly wrong.
- Missile crush-up is significantly over predicted.
  - No Strain Rate Effects in Missile Model?

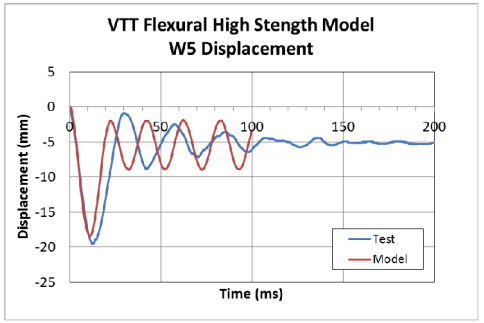




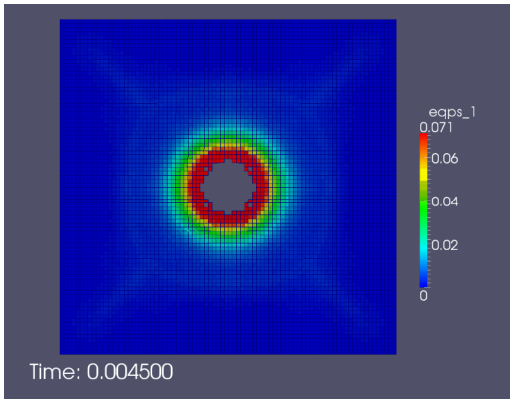


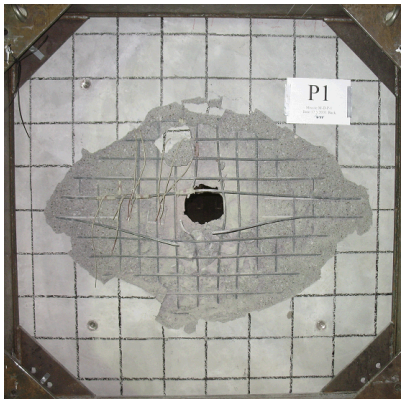


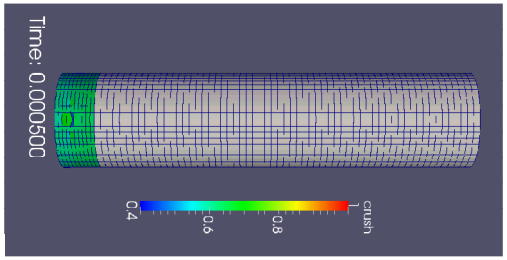


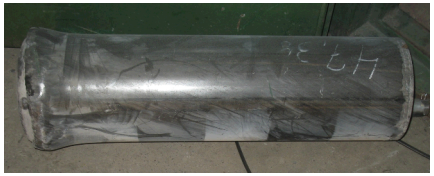


VTT Punching Results (BL)

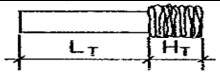






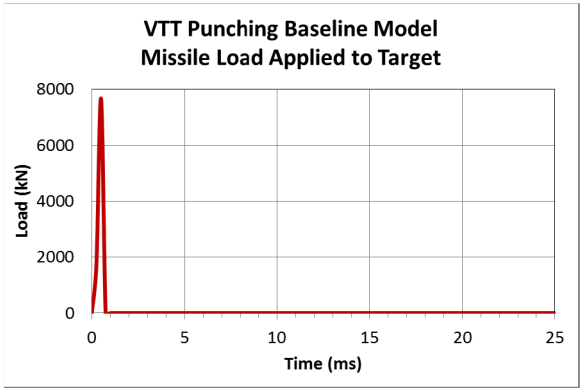


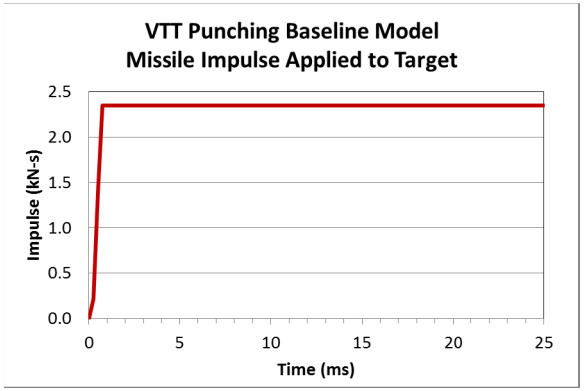
Missile Results	Baseline Model	Test Measured Value
Shock Duration	0.5 ms	Not Reported
Peak Load	7,669 kN	Not Reported
Total Impulse	2.35 kN-s	Not Reported
Missile Residual Velocity	77.7 m/s	33.8m/s
LT at Shock Termination	N/A – Rigid Missile	Not Reported
HT at Shock Termination	N/A – Rigid Missile	Not Reported

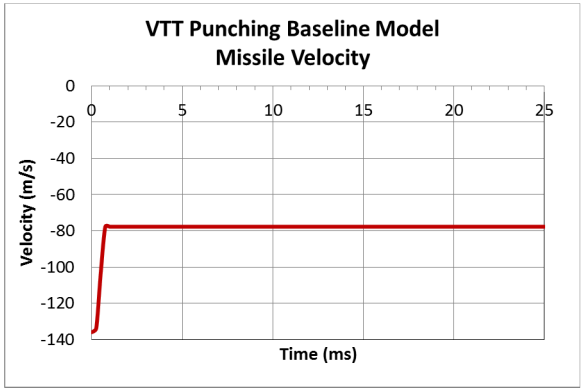


Target Results	Baseline Model	Test Measured Value
Initial Max W1 and W3 Displacement	5.99 mm at 4.5 ms	3.60 mm at 3.6 ms
Initial Max W2 Displacement	10.97 mm at 4.5 ms	3.96 mm at 5.5 ms
Initial Max W4 Displacement	4.19 mm at 5.0 ms	3.31 mm at 4.1 ms
Initial Max W5 Displacement	3.10 mm at 5.0 ms	2.50 mm at 3.3 ms
Total Max Support Force	2,446 kN at 3.0 ms	1,095 kN at 8.5 ms
Total Max Support Impulse	~2.0[a] kN-s	~4.0 kN-s
Target Failure (Yes/No)?	Yes	Yes
Target Failure Mode	Bending	Punching

[a] Value based on impulse at 7.5 ms.

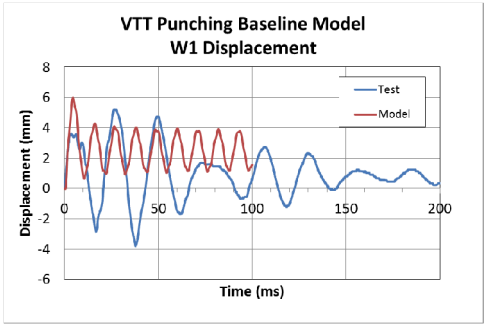


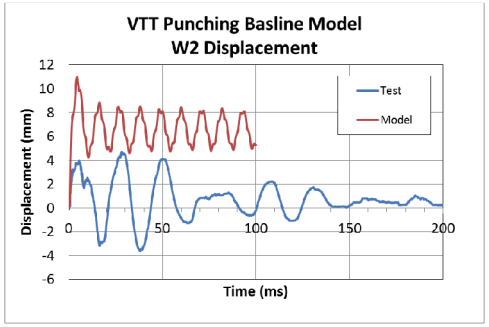


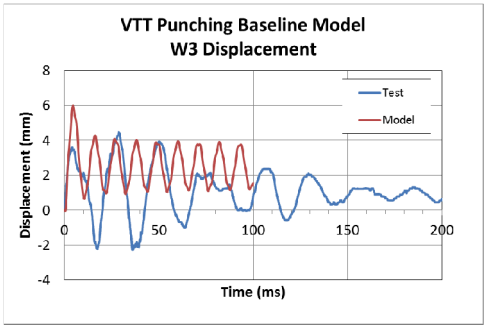


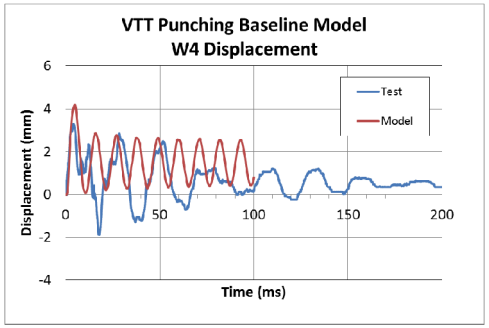
VTT Punching – Target Disp. (BL)

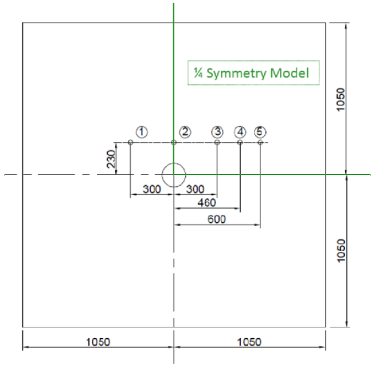
- BL simple model does a poor job of predicting overall response.
- Missile Exit Velocity Too High
- Bending Failure Predicted Instead of Punching.
- Amplitude of Target Displacements Over Predicted.
- Frequency of Target Displacement Response Too High.

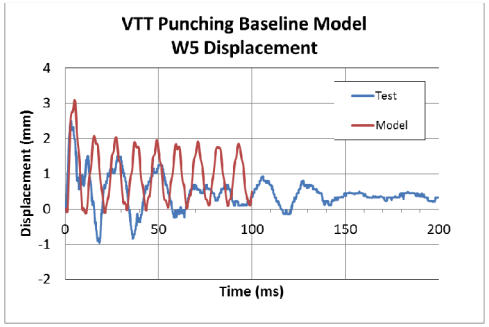




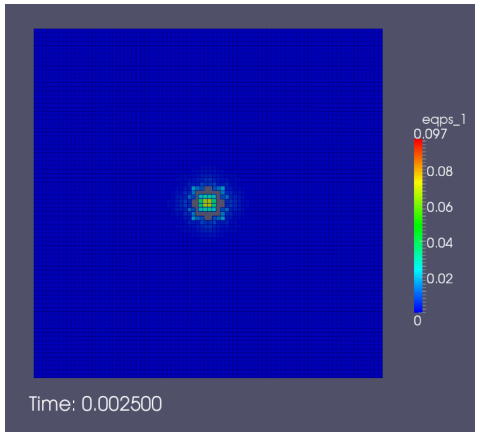


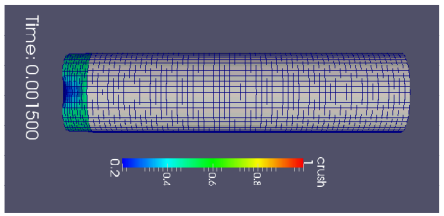


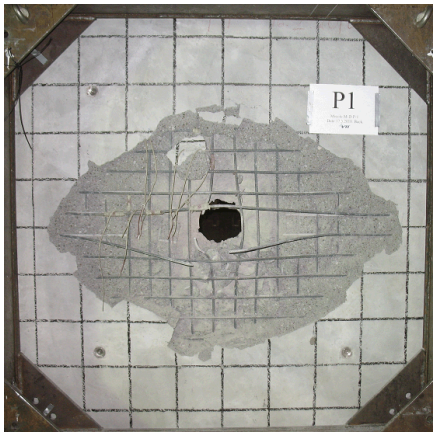


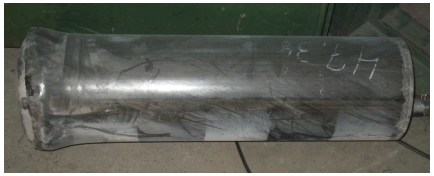


VTT Punching Results (HS&S)

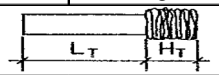








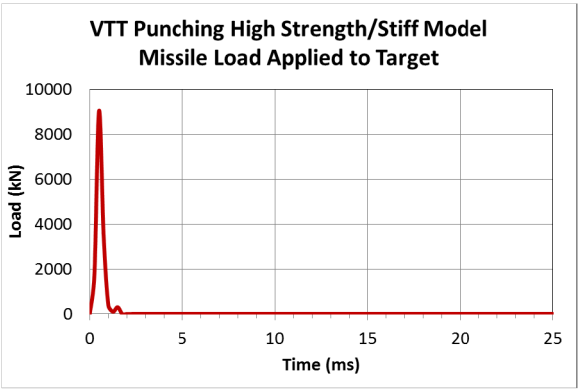
Missile Results	Baseline Model	Test Measured Value
Shock Duration	1.5 ms	Not Reported
Peak Load	9,058 kN	Not Reported
Total Impulse	3.75 kN-s	Not Reported
Missile Residual Velocity	33.3 m/s	33.8m/s
LT at Shock Termination	N/A – Rigid Missile	Not Reported
HT at Shock Termination	N/A – Rigid Missile	Not Reported

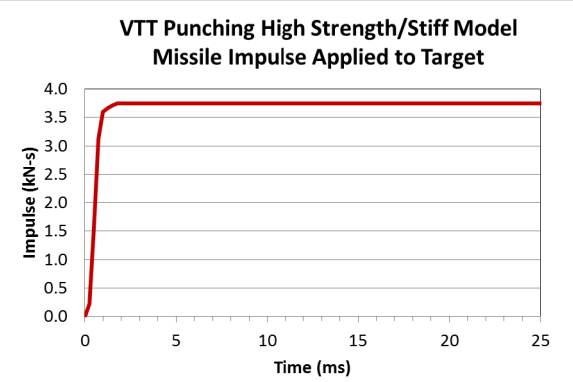


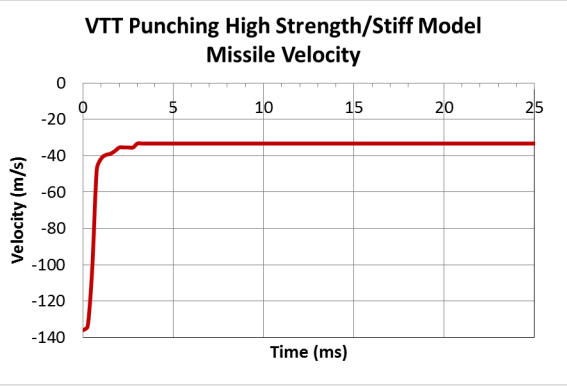
Target Results	Baseline Model	Test Measured Value
Initial Max W1 and W3 Displacement	6.58 mm at 2.5 ms	3.60 mm at 3.6 ms
Initial Max W2 Displacement	8.34 mm at 2.5 ms	3.96 mm at 5.5 ms
Initial Max W4 Displacement	5.03 mm at 2.0 ms	3.31 mm at 4.1 ms
Initial Max W5 Displacement	4.05 mm at 2.0 ms	2.50 mm at 3.3 ms
Total Max Support Force	19,577[a] kN at 1.5 ms	1,095 kN at 8.5 ms
Total Max Support Impulse	~3.50[b] kN-s	~4.0 kN-s
Target Failure (Yes/No)?	Yes	Yes
Target Failure Mode	Bending	Punching

[a] Peak value in first 10 ms.

[b] Approximate value average over first 10 ms.

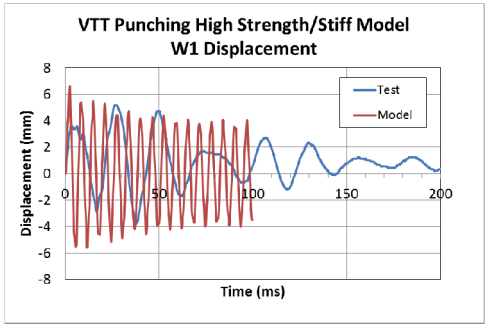


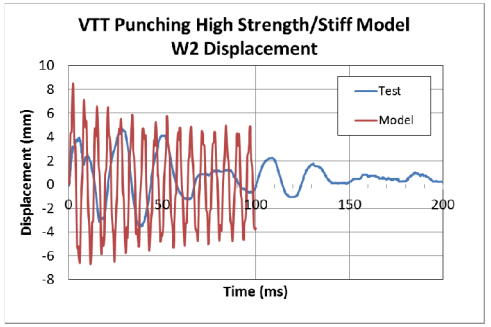


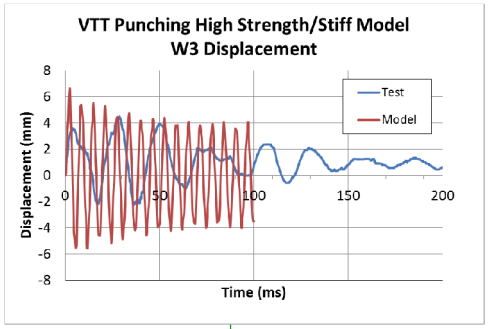


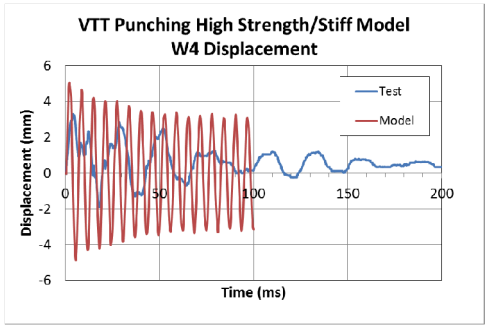
VTT Punching – Target Disp. (HS&S)

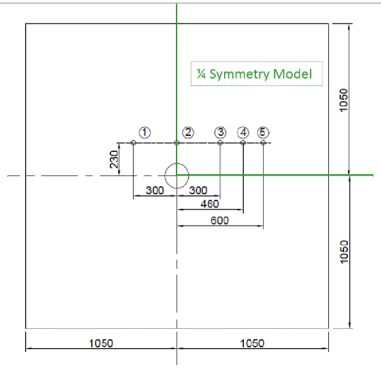
- HS&S simple model does a poor job of predicting overall response.
- Missile Exit Velocity Is Correct!
- Punching Failure is Predicted!
- Amplitude of Target Displacements Over Predicted.
- Frequency of Target Displacement Response Way Too High.

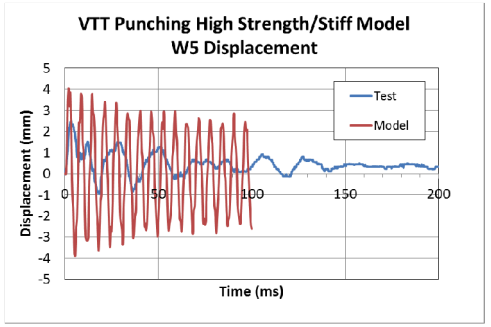












Simple Model Conclusions

Sandia National Laboratories

- Simplified methodology relatively accurate for soft missile impacts into targets in which the target response is dominated by bending and bending type failures, with the target suffering only modest damage.
- For rigid missile impacts in which punching failures in the target are expected, the simplified methodology appears to be poorly suited.
- Range of applicability difficult to predict.
  - Soft missile impacts involving significant damage and/or failure?
- Punching failure mode strength determination makes use of some test response data likely not available to analyst.
  - Conical crater depth to missile diameter ratio.
  - Shear cone failure angle.
- Results indicate that there may be a way to make simplified models work, but more effort is required.