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LSDYNA Analysis of Test 673

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Outline

- Test summary
- Finite element model
- Analysis results and comparison to test data
- Observations
- Possible additional modeling for test 673

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Test Summary

- Impact of soft missile on slender RC slab with stirrups
- 2300mmx2000mmx150mm thick slab
- 50.3 kg missile at 127 m/sec
- Light to moderate damage
  - About 70 mm maximum deflection (back side)
  - About 30 mm residual deflection (back side)
  - Scabbed not observed (based on still images from video)
  - Vertical crack on back side
  - Local punching deformation small

Finite Element Model

- LSDYNA model built with ANSYS-LSDYNA.

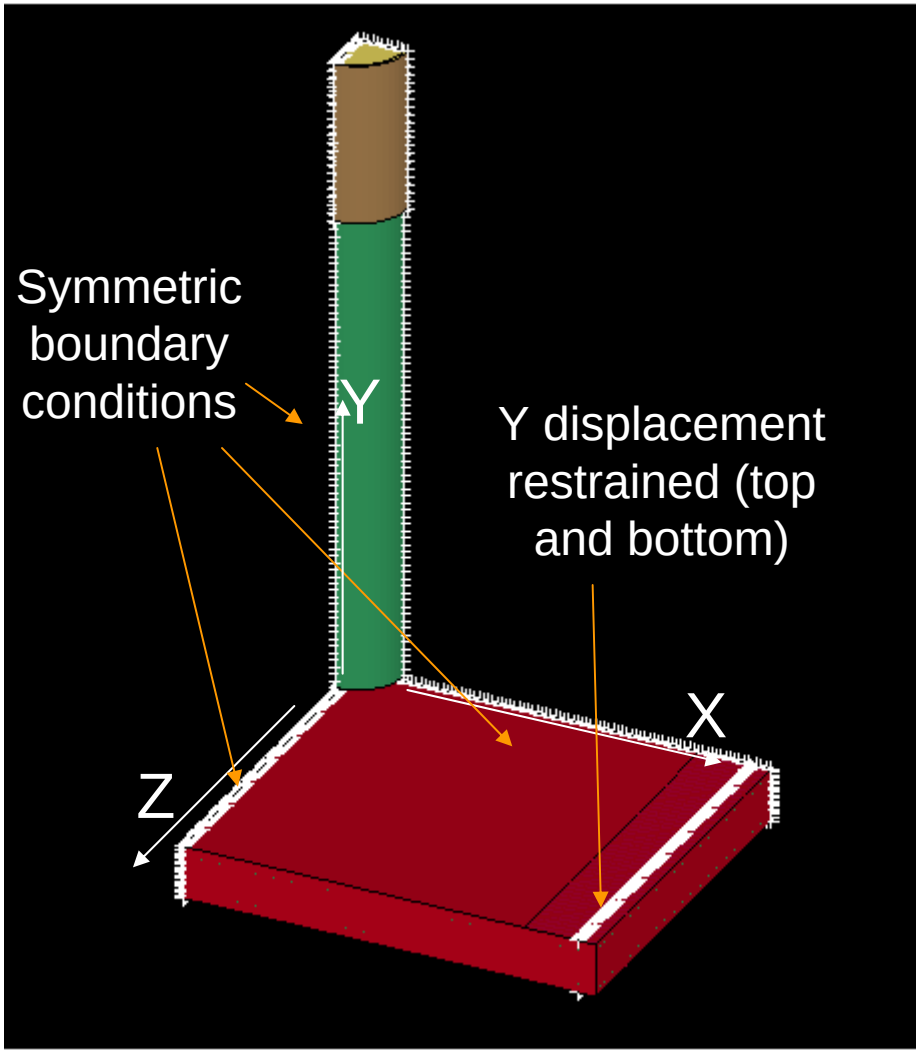
Z – Vertical test direction
X – Horizontal test direction

<u>Quarter symmetry</u>
<u>Elements:</u>

Slab
- 132480 solid elements
- 10448 rebar elements
- 2560 shell elements (plates near supports)

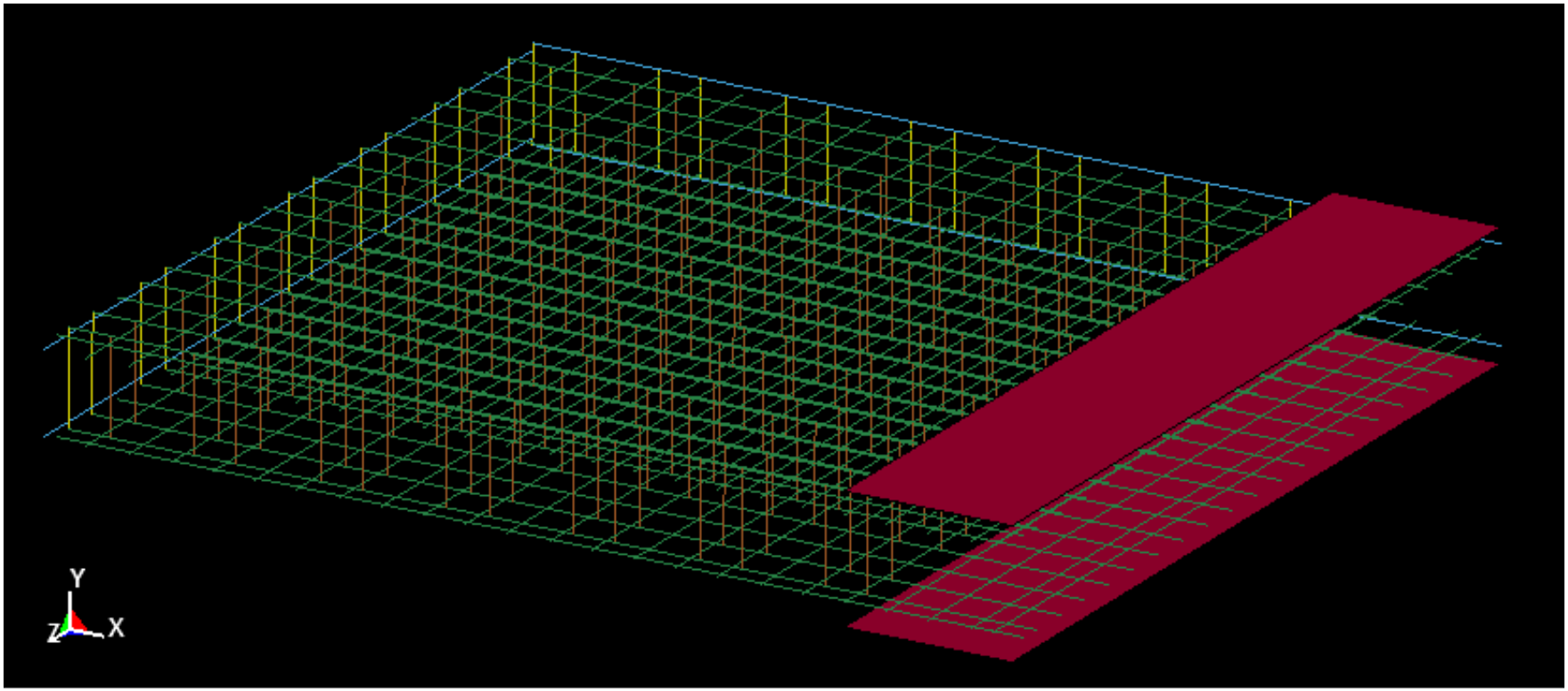
Missile
- 1488 shell elements

Arrangement of the transverse reinforcement is not symmetric (the analysis used an approximate arrangement)



Finite Element Model

Green\blue lines: flexural steel (8 mm diameter bars at 50 mm)
Orange\yellow lines: stirrups (6 mm diameter bars)



Solid element sizes (not shown above):
12.5 mm horizontal; from 8 mm to 9.5 mm vertical
Red: steel plates at the supports

Finite Element Model

Material Models

- Concrete:
  - Winfrith concrete with strain rate effects
  - Hourglass control
    - Standard LSDYNA viscous form (hourglass coefficient = 0.10)
- Steel
  - Bilinear kinematic
  - Cowper-Symonds model for strain rate effects (except for the missile steel)
  - Maximum strain failure criterion
- Aluminum (missile)
  - Bilinear kinematic

Finite Element Model

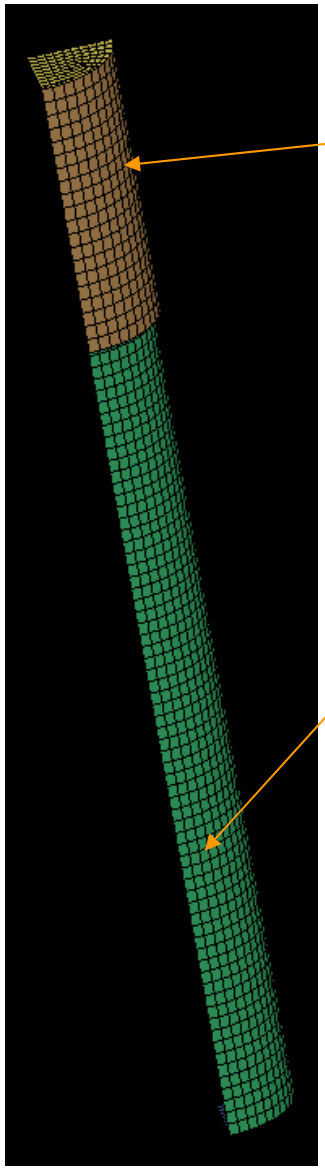
Material Properties (slab)

- Concrete
  - Uniaxial crushing strength – 59 MPa (cube strength)
  - Tensile strength – 3.6 MPA (cylinder splitting strength)
  - Tangent modulus – 27000 MPa
  - Aggregate size – 8 mm diameter
  - Fracture energy – 150 J/m^2
  - Density – 2300 kg/m^3
- Steel (reinforcement)
  - Yield strength – 535 MPa
  - Young's modulus – 210000 MPa
  - Post-yield modulus – 550 Mpa
  - Failure strain – 0.20.
  - Density – 7900 Kg/m^3
  - Cowper-Symonds strain rate effects model
    - $F_{yd} = F_{ys}(1+E_R/C)^{1/q}$ with C = 40/sec and q = 5
    - F_{yd} = dynamic yield stress; F_{ys}= static yield stress; E_R = strain rate

Finite Element Model

Material Properties (missile)

- Aluminum
  - Yield strength – 217 MPa
  - Young's modulus – 70000 MPa
  - Post-yield modulus – 290 Mpa
  - Failure strain – not used.
  - Density – 2700 Kg/m^3
  - Strain rate effects not included
- Steel
  - Yield strength – 355 MPa
  - Young's modulus – 200000 MPa
  - Post-yield modulus – 500 Mpa
  - Failure strain – not used.
  - Density – 7900 Kg/m^3
    - Adjusted to 9100 for a total missile mass of 50.3 kg
  - Strain rate effects are not included.
  - Steel just impacts the back of the aluminum tube but is not otherwise deformed.



Analysis Results Summary

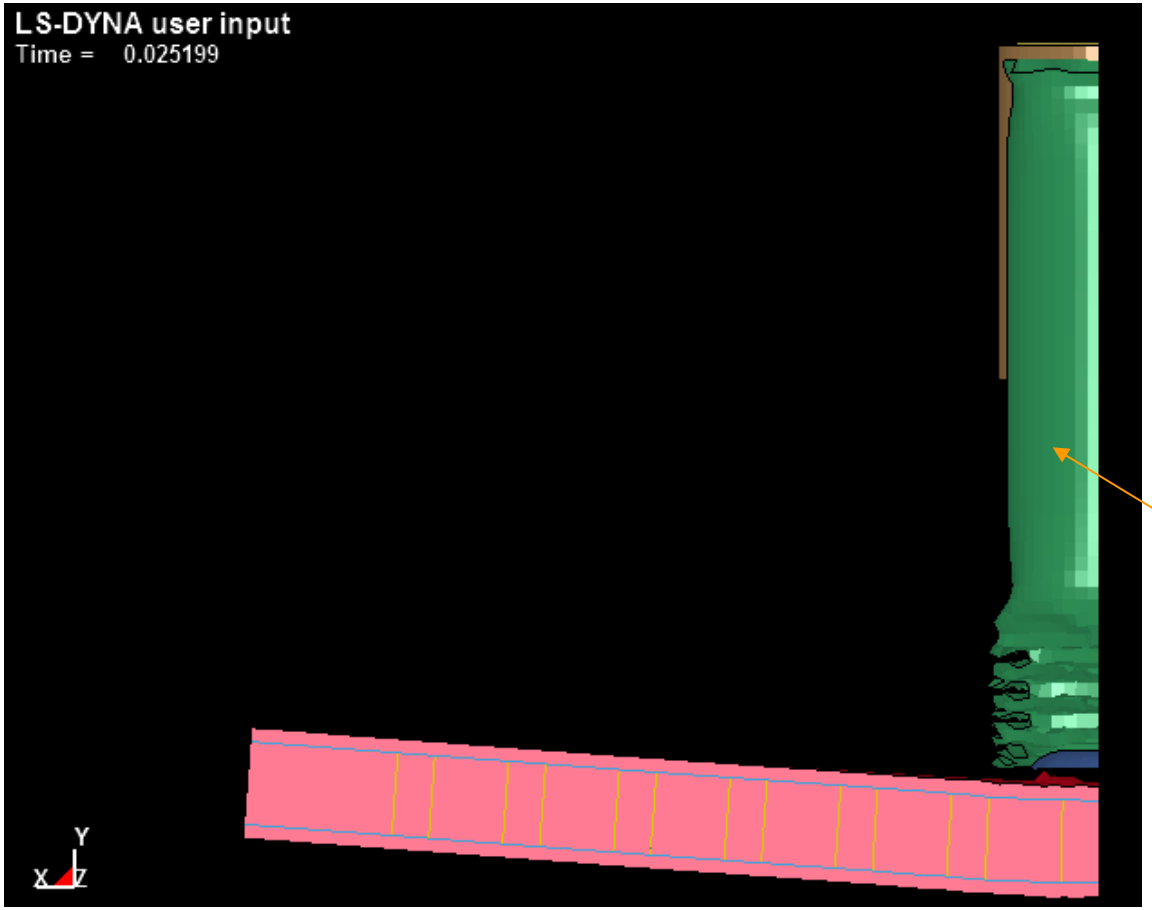
Consistent with test data	Test	Analysis
• Maximum back deflection	~70 mm	75 mm
• Residual back displacement	35 mm	22 mm
• Scabbing	No	No
• Punching cone	Small local effect	Small local effect
• Maximum displacements		
– Gage 2	57 mm	53 mm
– Gage 3	46 mm	41 mm
– Gage 4	54 mm	48 mm

Observed inconsistency with test data

- Test data shows oscillatory free-vibrations while the analysis damps the slab motion after the first one and half cycles (also observed for the analysis of test 699).

Analysis Results

Near time of maximum displacement

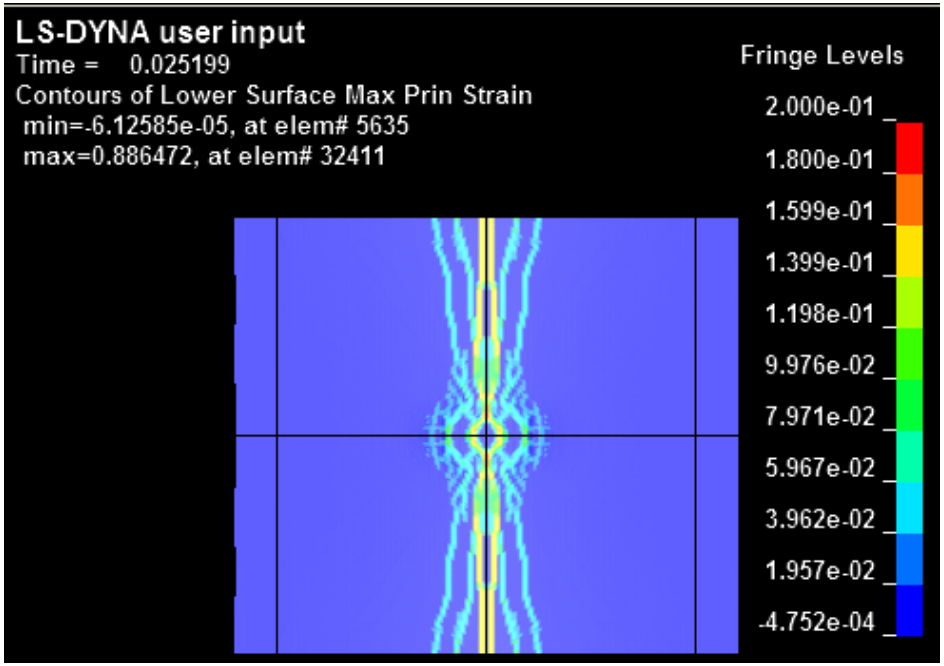


Inside of aluminum tube

Erosion of missile (aluminum) elements disabled

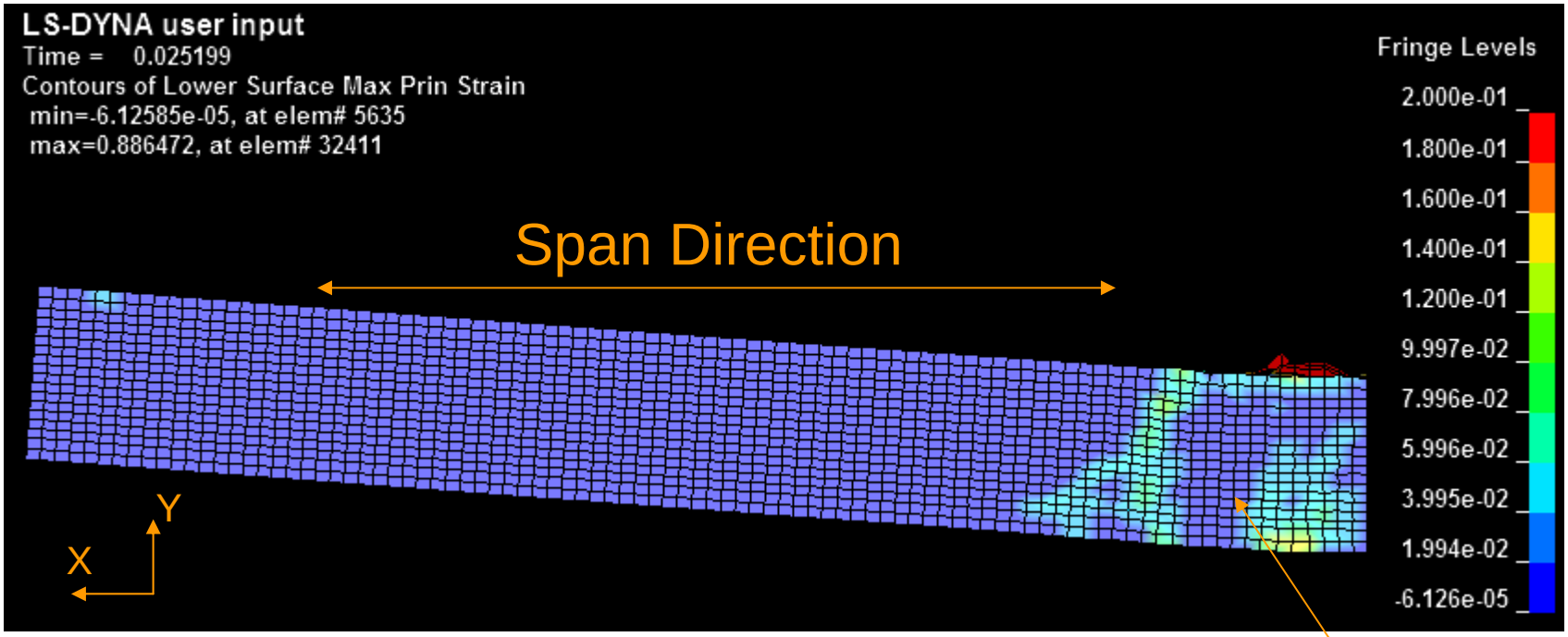
Analysis Results

Strains (near time of maximum displacement)



Analysis Results

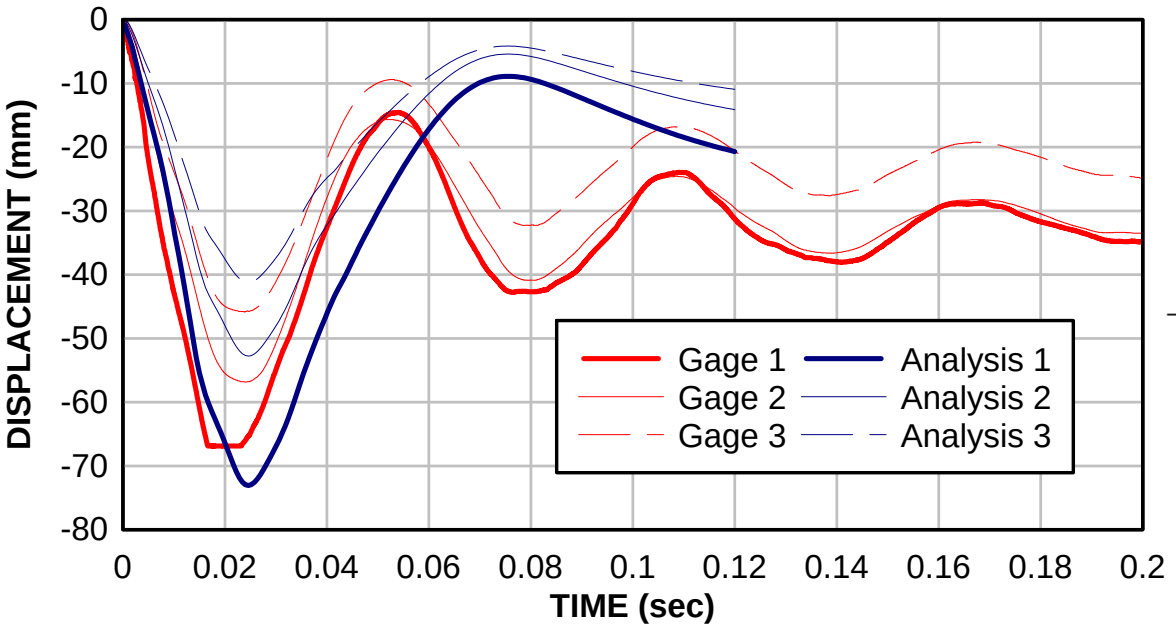
Deformation at Maximum Displacement

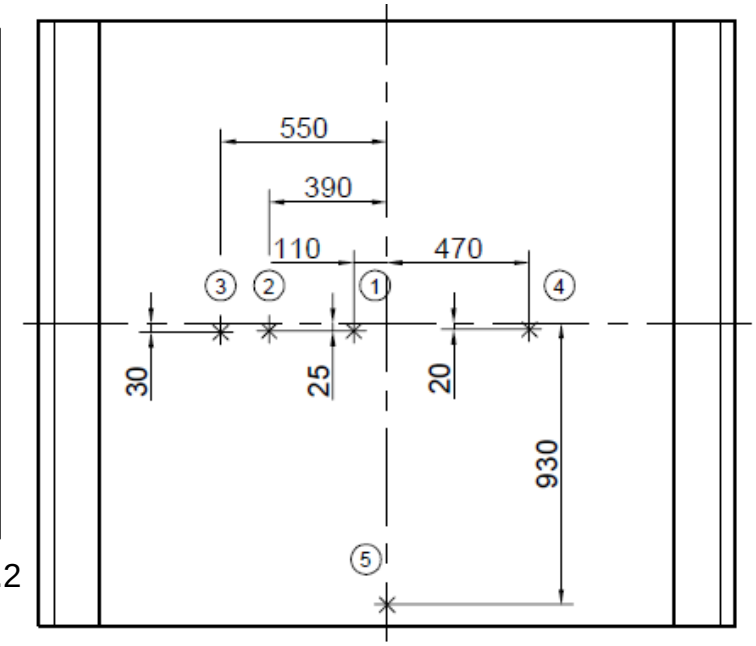


Horizontal grid size = 12.5 mm
Vertical grid size ~ 8 mm (center of model)

Analysis Results

Displacements (back side)



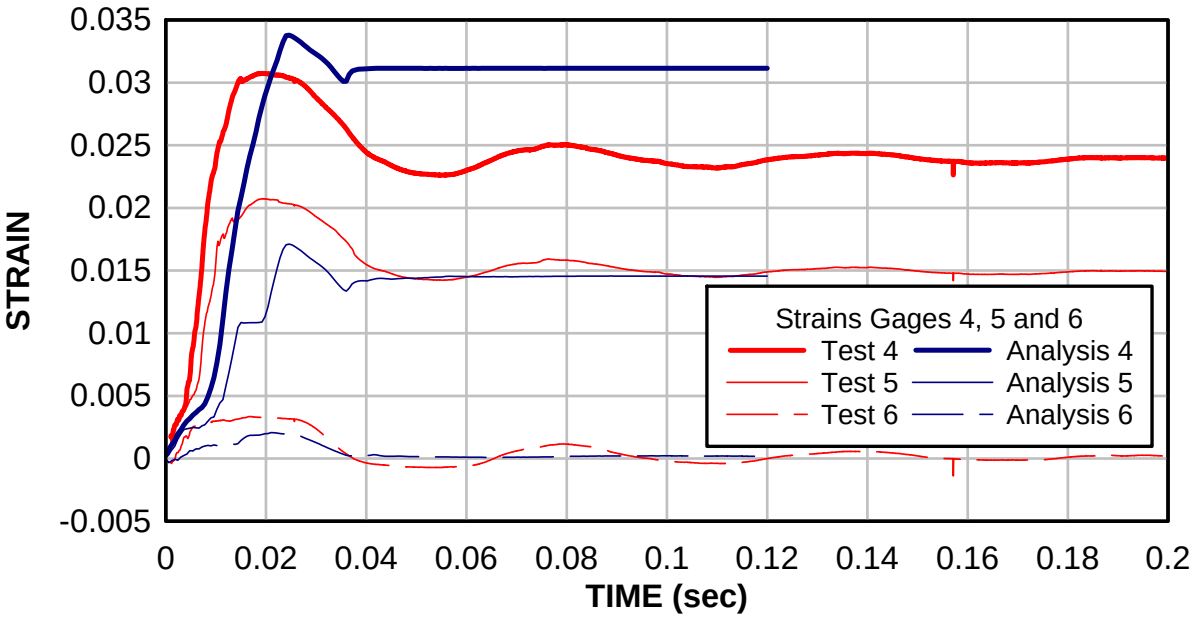


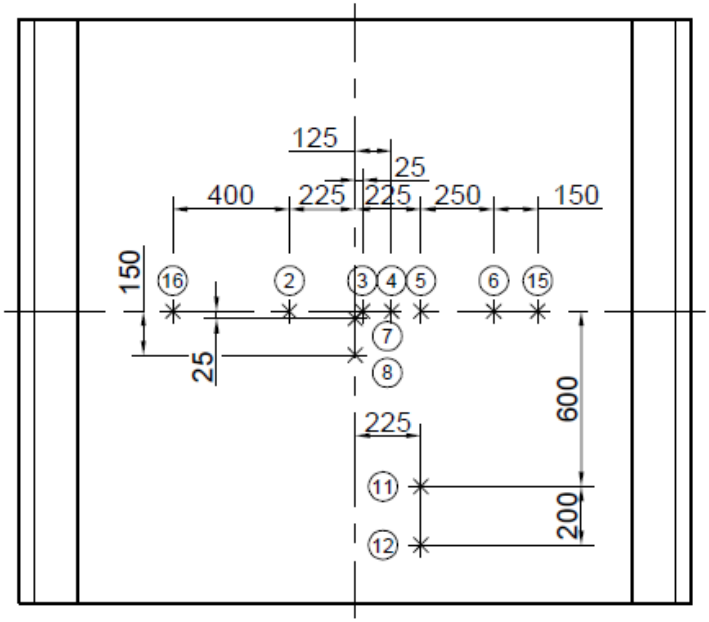
From drawing W-R-673-23 (back side)

- First cycle, maximum and residual displacements agree reasonably well measured data 3, 4 and 5.
- Softer analytical model (Low concrete tangent modulus)
- Lower permanent deformation
- Free vibrations not captured

Analysis Results

Strains (flexural reinforcement)





From drawing
W-R-673-21
(back side)

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Observations

- LSDYNA analysis predicts reasonably well the maximum deformation and damage.
  - Model is softer than the test.
  - Analysis underestimates the residual deformation.
- LSDYNA analysis damps the free vibration motion.
  - Causes for the damping of the free vibration to be investigated (may be related to the behavior of the concrete model in cyclic loading after severe damage).

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Possible Additional Modeling for Test 673

- Model full slab (without recourse to symmetry)
- Investigate other concrete material models
- Investigate causes for damping of free vibration
- Impact missile on rigid wall to calculate missile load.
  - Compare with plate test (if available).
  - Analyze the response of the slab with the calculated forces.