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Sandia National Laboratories/U.S. Nuclear Regulatory Commission: LS-DYNA Simulations

OECD/NEA IAGE Workshop on IRIS 2010 Benchmark on Improving Robustness Assessment Methodologies for Structures Impacted by Missiles

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Outline

- Initial and Final Computational Strategy
- Assumptions and Technical choices
- Drawbacks and Advantages of path chosen
- Improvements for future calculations

Initial Computational Strategy

- LS-DYNA Simulation Tool
  - Low level of experience with LS-DYNA
  - Extensive experience with Sandia codes (Pronto3D, Presto, EMU) and ABAQUS
- Explicit Missile Impactor for Meppen
- Explicit Concrete and Steel Reinforcing Bars
- ¼ model symmetry for Meppen II-4
- Strain Rate Dependence for Steel (Meppen II-4)
- Karazogian & Case Concrete Material Model
- Test support structure not included
- Boundary Conditions preserved motion and rotation constraints
- Issues with Missile contact modeling lead to a simplification of analysis approach

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Final Computational Strategy

- LS-DYNA Simulation Tool
- Riera Function Substituted for Missile Impactor
- Explicit Concrete and Steel Reinforcing Bars
- ¼ model symmetry (Meppen II-4) and Full model symmetry (Flexural and Punching Mode test)
- Strain Rate Dependence for Steel (Meppen II-4)
- Karazogian & Case Concrete Material Model
- Test support structure not included
- Boundary Conditions preserved motion and rotation constraints

LS-DYNA Simulation Tool

- **LS-DYNA: A Program for Nonlinear Dynamic Analysis of Structures in Three Dimensions, Version: mpp971d R5.0, Revision: 59419. *Livermore Software Technology Corporation (LSTC)* . Livermore, California, USA.**
- **LS-DYNA simulations executed using 8 central processor units on Linux Red Hat operating system (RHEL 5) with 16 GByte Random Access Memory cores.**
- **Typical LS-DYNA simulations used:**

```
Meppen II-4: 6.9295E+04 CPU seconds (8864 sec. = 02:27:44; for 27824 cycles)
   Flexural: 2.7583E+04 CPU seconds (3587 sec. = 00:59:47; for 43405 cycles)
   Punching: 1.6295E+04 CPU seconds (2175 sec. = 00:36:15; for 21033 cycles)
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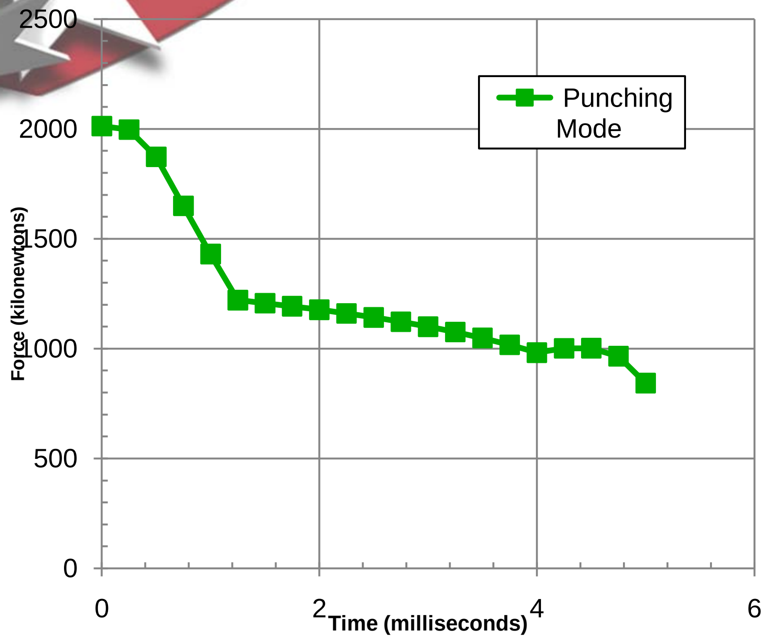
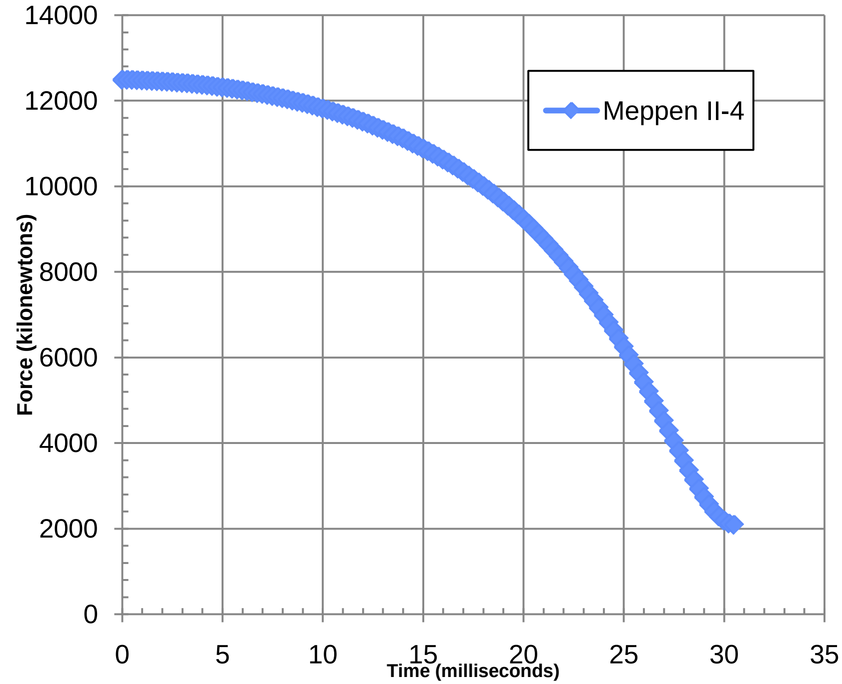
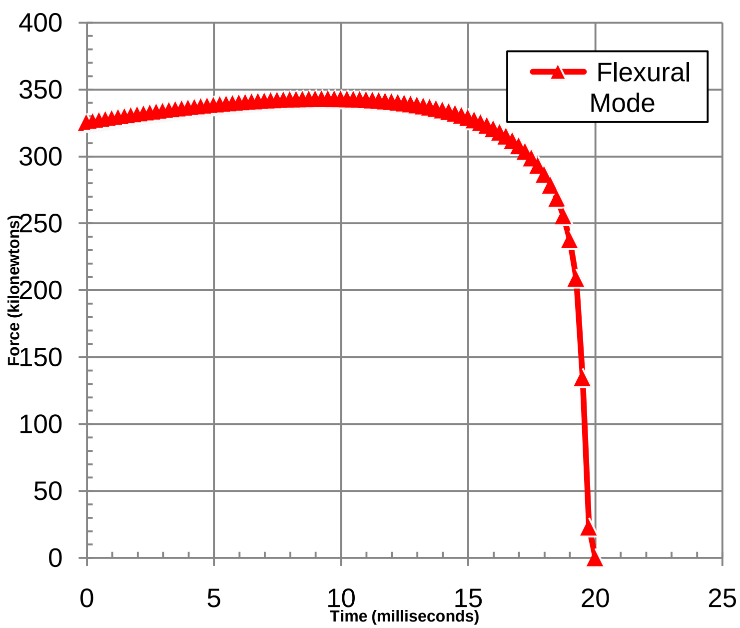
Riera Function Instead of Missile Impacting Target

- Riera loading function used to replicate missile impact response on concrete target reinforced with steel bar.
- Reduce computational complexity arising from contact and penetration of steel missile interacting with both implicit steel reinforcing bars and concrete material
- Unique Riera loading function for each test (Meppen, Flexural, Punching) due to unique missile geometry and mass distribution.
- Construction of sufficiently robust Riera function is the critical link to produce the reinforced concrete target's response.
- Both Flexural and Punching mode Riera functions were designed based on techniques learned from the Meppen II-4 benchmark simulations.
- All Riera loading functions assumed a missile to be a long thin-walled cylinder, whereby the crushing strength and mass distribution were linear piecewise functions.
- The Riera loading function was applied to an area of the target equal to the cross-sectional area of the missile.

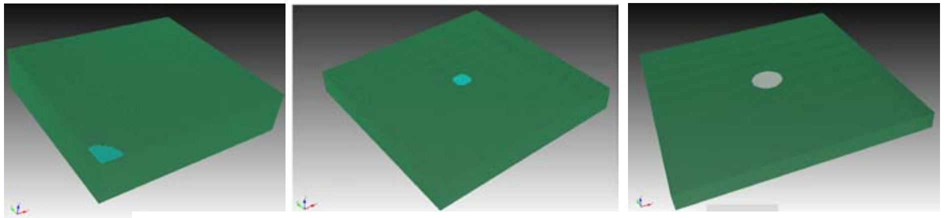






Meppen II-4 Riera Load Function Strategy

- Criteria for designing load curve was based on the final load value (ideally near zero), and matching the specified peak load for the Meppen II-4 impact scenario (13,100 kN).
- Several iterations of mass distribution and crushing strength configurations were completed to construct a multitude of Riera loading functions.
- Riera Load functions were applied to an area of the target based on the cross-sectional area of the missile (shown below).

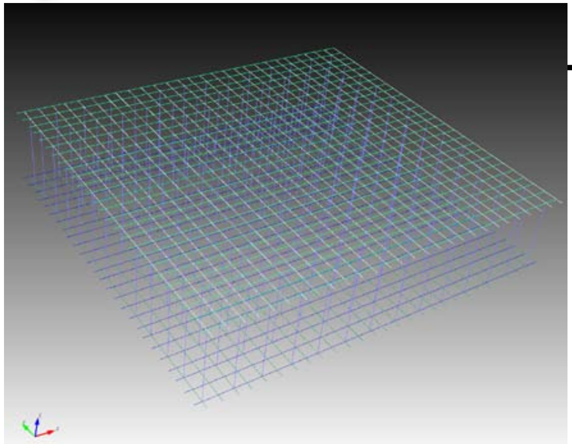


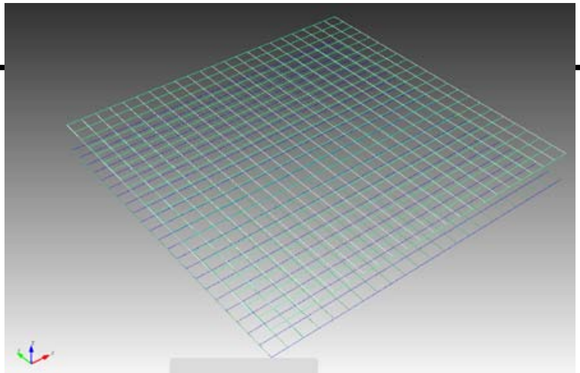
Meppen Punching Flexural

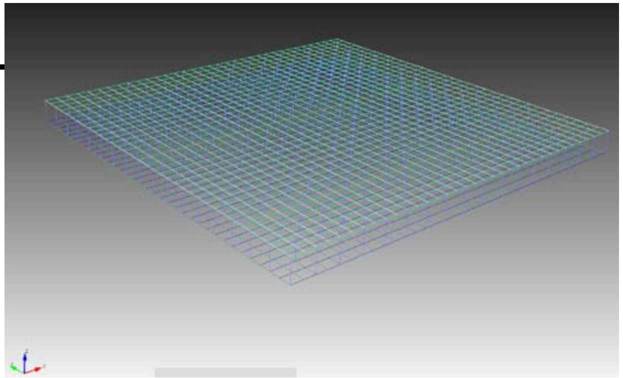
Explicit Concrete and Steel Reinforcing Bars

- The concrete material of the slab was modeled using hexagonal brick 8-noded element with one integration point.
- Steel reinforcing bars inside the concrete slab were implicitly defined using Hughes-Liu Beam elements with a rectangular cross-section type.
- All rebar cross-sections were assumed to be square-box shaped, with the side length of the cross-section equal to the particular reinforcing steel bar outer diameter.
- All beam elements used the default LS-DYNA integration scheme, 2 x 2, or four integration points. The reinforcing steel bars, were modeled using 3-noded beam elements, where a reference node (node #3) is used only to reference the orientation of the two primary beam element nodes.
- The contact between rebar elements (beams) and concrete elements (hexagonal 8-noded bricks) was assumed to be rigid, thus not permitting any rebar slippage or pull-out behavior around the concrete material.
- All simulations utilized a finite element model comprised of a coincident node, reinforcing bar (*i.e.,* a bar element) meshing scheme that connected 2-noded bar elements to nodes of 8-noded hexagonal brick elements that represent the concrete material.
- Combining the reinforcing steel density with the overall slab dimensions, a nominal hexagonal 8-noded brick element had a characteristic length of 20.0, 15.6, and 15.2 millimeters for the Meppen, Punching, and Flexural mode simulations, respectively.

Rectilinear Steel Reinforcing Grids (coincident nodes)







Meppen II-4:
¼ Symmetry Model
Stirrups (z-direction)

Punching:
Full Symmetry Model
No Stirrups

Flexural:
Full Symmetry Model
Stirrups

The spacing of the steel reinforcing bars was limited by the concrete hexagonal 8-noded element sizes. Shown below are the computed model reinforcing steel bar grid dimensions (*i.e.*, number of bars) for each of the three reinforced concrete targets:

Simulation Model	Width or X-direction (m)	Length or Y-direction (m)	Number of bars along X direction	Number of bars along Y direction	Number of bars along Z direction
Meppen II-4*	6.0	6.5	52	56	728
Punching	2.1	2.1	23	23	N/A
Flexural	2.1	2.1	37	37	324

* Note that Meppen II-4 used ¼-model symmetry; these values correspond to a full model

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Steel Reinforcement Grid Density

Meppen II-4 Target Rebar Geometry

Geometry		
Longitudinal rebars (each direction)	Front face	Rear face
Diameter (mm):	20	28
Density (cm²/m):	27.3	53.6
Concrete cover (mm):	30	30
Transverse rebars		
Diameter (mm):	20	
Density (cm²/m):	50.2	16∅20/m²

The table below shows the final reinforcing bar diameters that satisfy the longitudinal and transverse reinforcing steel bar densities.

Punching Target Rebar Geometry

Rebars
Longitudinal rebars:
8.7cm²/m each direction, each face
by 10mm diameter bar @90mm

No transverse rebars

Flexural Target Rebar Geometry

Rebars
Longitudinal rebars:
5cm²/m each direction, each face
by 6mm diameter bar @55mm

Transverse rebars: about 50cm²/m²

Description	Specified Longitudinal Steel Reinforcing Bar Density (cm²/m)	Specified Transverse Steel Reinforcing Bar Density (cm²/m²)	Computed Reinforcing Steel Longitudinal Bar Diameter (mm)	Computed Reinforcing Steel Transverse Bar Diameter (mm
Meppen II-4 (Front Face, X-direction)	27.30	N/A	20.03	N/A
Meppen II-4 (Front Face, Y-direction)	27.30	N/A	20.01	N/A
Meppen II-4 (Rear Face, X-direction)	53.60	N/A	28.06	N/A
Meppen II-4 (Rear Face, Y-direction)	53.60	N/A	28.14	N/A
Meppen II-4 (Transverse, Z-direction)	N/A	50.2	N/A	18.65
Punching (Front or Rear Face, X- or Y-direction)	8.70	N/A	10.06	N/A
Flexural (Front or Rear Face; X- or Y-direction)	5.00	N/A	6.011	N/A
Flexural (Transverse, Z-direction)	N/A	50.00	N/A	9.309

Strain Rate Dependence (Meppen II-4)

- **Meppen II-4 Test, strain-rate data for the Type RK BSt 420/500 steel was supplied.**
- **Both Punching and Flexural Mode Simulations, used a different type of reinforcing steel, known in the European community as A500 HW. There was no strain-rate data provided for the A500 HW steel reinforcing bar material.**
- **The A500 HW steel is similar to ASTM A706 grade 60 steel, based on initial yield and ultimate strength.**
- **The reinforcing steel properties used in all simulations are listed in the table below:**

Simulation Model	Density (kg/mm^3)	Poisson Ratio	Yield Strength (MPa)	Ultimate Strength (MPa)	Ultimate or Failure Strain (%)	Strain-rate data provided ?	LS-DYNA Material Model
Meppen II-4	7.84×10^{-6}	0.30	500	620	5-18	Yes	MAT_STRAIN_RATE_PLASTICITY
Punching Mode	7.84×10^{-6}	0.30	595	669	5-10	No	MAT_PLASTIC_KINEMATIC
Flexural Mode	7.84×10^{-6}	0.30	595	669	5-10	No	MAT_PLASTIC_KINEMATIC

Karazogian & Case Concrete Material Model

- The Karazogian and Case (K&C) concrete model decouples the shear and volumetric deviatoric responses, and is based on a three-invariant model which uses three shear failure surfaces, and includes both damage and strain-rate effects.
- Due to the inherent three-invariant formulation to construct the yield surface, the model is capable of distinguishing triaxial extension and triaxial compression load paths in stress space.
- The K&C model use stress differences to describe the yield surface, the limit surface, and the residual surface. The model monitors the current state of the stress difference relative to these three failure surfaces. During the initial loading or reloading, the stresses are elastic until an initial yield surface is reached. The initial yield surface hardens to the limit surface or softens to the residual surface, depending on the loading or the material state.
- The K&C concrete model employs an equation of state (EOS) to control the volumetric response, *i.e.*, the pressure, *P*, versus volumetric strain, ε_v.
- The K&C concrete model's EOS prescribes a tabulated set of pressure and unloading bulk modulus as a function of volumetric strain.
- All simulations used the LS-DYNA K&C automatic material model generation method by supplying the unconfined compressive strength of the concrete.

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Karazogian & Case Concrete Material Model

Concrete Strength Properties used in LS-DYNA simulations with the K&C material model are listed below in the table:

Simulation Model	Density (kg/mm^3)	Compressive Strength (MPa)	Tensile Strength (MPa)	Poisson Ratio	Elastic Modulus (GPa)
Meppen II-4	2.25×10^{-6}	46.00	4.70	0.25	39.80
Punching Mode	2.30×10^{-6}	74.60	4.04	0.25	29.43
Flexural Mode	2.30×10^{-6}	76.0	3.71	0.25	26.92

Boundary Conditions

- Boundary conditions were applied to the finite element models using nodal point constraints to prescribe a zero displacement condition normal to the impact surface at the rear surface of the reinforced concrete target. This direction is the *z*-component, and is consistent for all three LS-DYNA simulations, where the target resides in the x-y direction, with the impact surface being equal to (positive) half of the target thickness (*i.e.,* at coordinate *z* = ½ target thickness).
- All of the LS-DYNA simulations employed a single point constraint method to invoke no z-displacement boundary conditions. Since the Meppen II-4 Test used ¼-model symmetry, a no *x*-displacement and no *y*-displacement boundary condition was imposed on the symmetry faces (left *yz*-plane, and bottom *xz*-plane, respectively.

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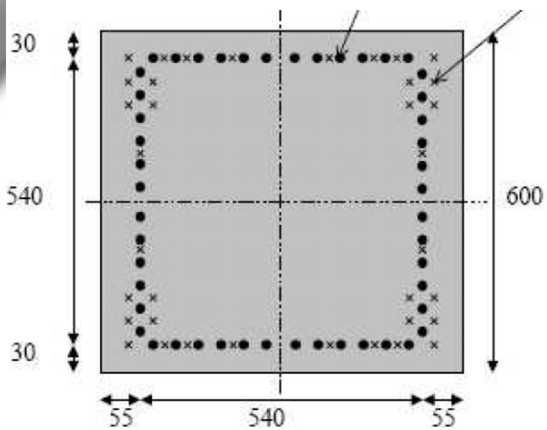
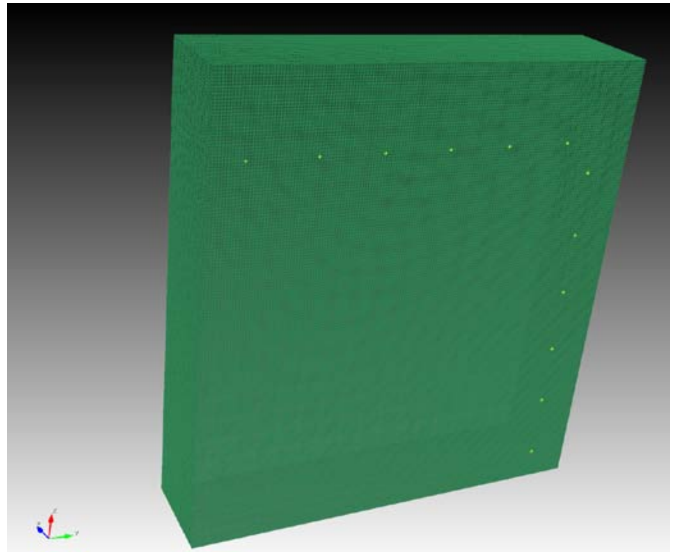
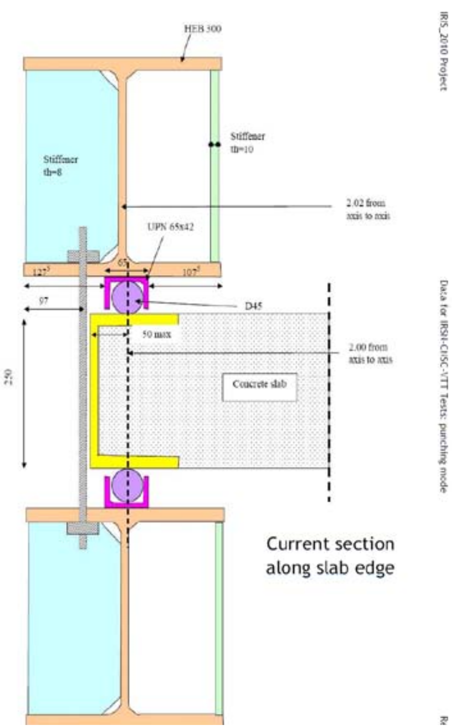
Boundary Conditions (continued)



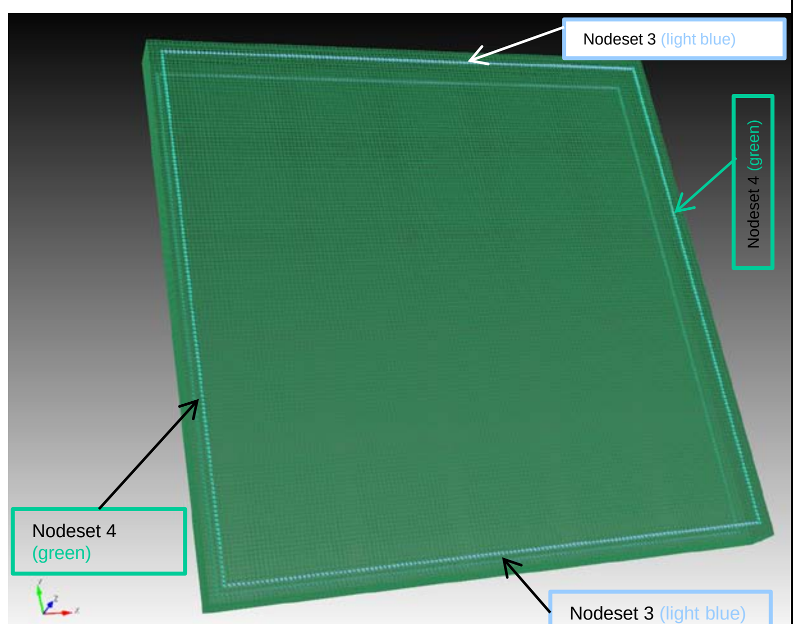
Meppen II-4 Test: Support Points (black dots) on rear of target, z = -0.35 m



Meppen II-4 Model: no Z-displacement boundary condition constraint applied at light green dots. (Note: ¼ model symmetry)



Punching Test Frame (Flexural Test Frame was similar)



Punching Model and Flexural Model Target BC nodes

Both Punching mode and Flexural mode targets were modeled using LS-DYNA boundary single point constraint (SPC) conditions at defined node sets as shown.

Nodeset 3 is the boundary condition to clamp the front and back faces of the target along the x-direction; whereby a no z-displacement constraint is applied and rotations about the x-direction are allowed (displacements in both the x-direction and y-direction are allowed, and no rotation about the either the y-direction or the z-direction is allowed).

Likewise, nodeset 4 is the boundary condition used to enforce clamping on the front and back faces of the target along the y-direction; whereby a no z-displacement constraint is applied is and rotations about the y-direction are allowed (displacements in both the x-direction and y-direction are allowed, and no rotation about either the x-direction or the z-direction is allowed).

Assumptions and Technical Choices

- Riera Load function approach simple (but has consequences)
- Karazogian & Case concrete model provides a robust description of concrete response based on two input parameters.
- No attempt to incorporate Steel Reinforcing Bar slippage/pullout behavior
- Steel Reinforcing bar strain rate effects not included in Punching and/or Flexural model LS-DYNA simulations.
- ¼ model symmetry chosen for Meppen II-4 test
- Full model symmetry chosen for Punching and Flexural tests.

Advantages and Drawbacks of Analysis Path Chosen

Advantages	Consequences and Drawbacks
Riera Load Function approach simple: avoids contact models and alleviates constructing an additional finite element model of missile.	Crushing Strength and Mass Distribution of missile is challenging for simplified Riera Loading approach. Visual penetration of target from a missile not possible (*e.g.*, plugging type target response presents extra challenges)
Karazogian and Case (K&C) concrete material model input requires only two parameters	K&C concrete material model does not provide a crack pattern visualization
Reinforcing Steel Bar material model based on yield strength (Flexural and Punching tests) without strain rate dependence.	Dynamic Increase Factors are well known attributes of steel reinforcing bar used in concrete structure response; they are strain rate dependent.
Coincident nodes for concrete material (hexagonal 8-noded brick elements) and reinforcing steel (pseudo 3-noded beam elements) permit orthogonal steel grid and concrete material geometric distribution.	(1) Steel Reinforcing Bar is not allowed to slip or exhibit pullout behavior – more sophisticated contact model required between concrete and steel reinforcing bar. Finite Element Models may not have capability to include both coincident nodes and slippage/pullout response type behavior. (2) Steel Reinforcing Bar density (length steel/area concrete) may not always be preserved. (Caveat was to change diameter of steel bar to enforce density specifications.)
Meppen II-4 Simulations using ¼ Model Symmetry reduces computational resources	Unable to adequately include angle of attack and/or angle of impact; Forced symmetry may not replicate response of test target behavior (*e.g.*, radial crack pattern, measured load response at force transducers, etc.)

Improvements for Future Calculations

- **Use greater computational resources to include full finite element model of missile.**
- **Include steel penetrator (missile) and concrete material contact model + steel penetrator and steel reinforcing contact model.**
- **Include erosion effects (LS-DYNA terminology) to replicate scabbing and spall behavior of concrete material**
- **Explore different concrete material model (*e.g.*, LS-DYNA Winfrith Concrete model) to exploit fracture/crack patterns for visualization.**

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