Australian Government

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Numerical and Analytical Modelling of Reinforced Concrete Subjected to Large Inertial Impact

Michael Saleh

Luiz Bortolan Neto

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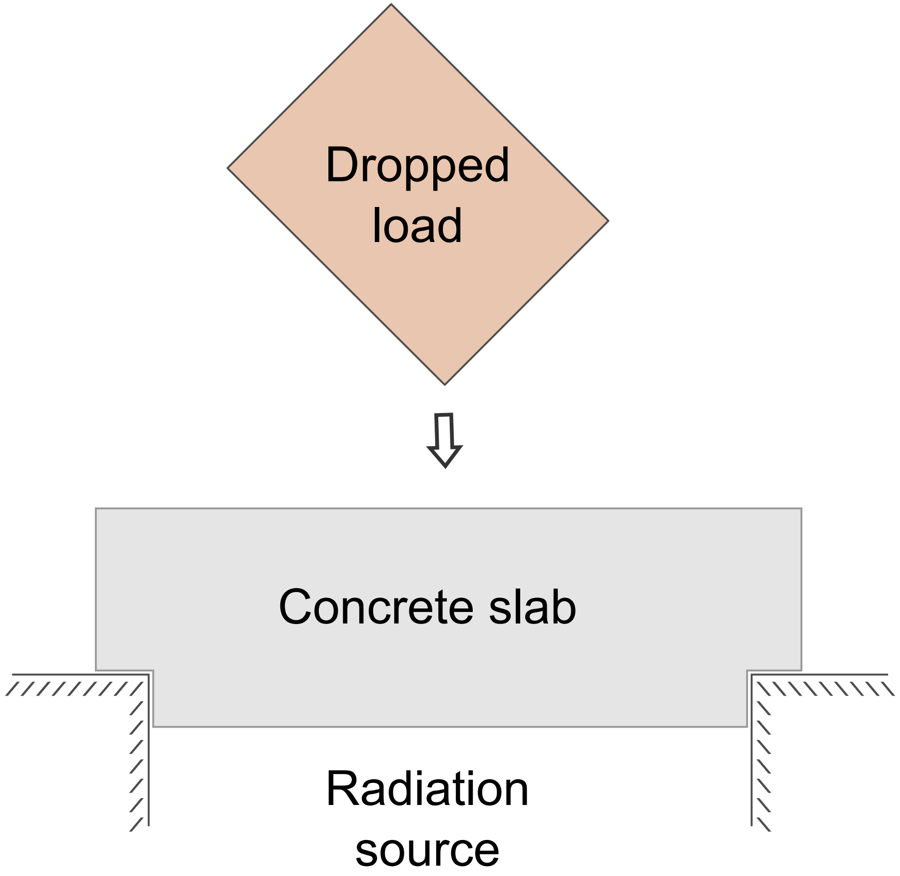
Dropped Loads in Nuclear Facilities

- Dropped loads can undermine the structural integrity of safety critical components
- Relatively high impact velocities can result in significant local damage to the target, such as yielding of materials (bending), buckling or local failure or penetration
- In nuclear facilities, a response of this sort may directly or indirectly lead to a transient or sustained radiological release



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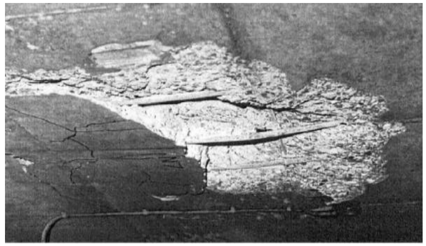
Concrete damage

- The main damage models are listed below:
  - Penetration: Tunnelling into the target by the projectile (the length of the tunnel is called the penetration depth).
  - Cone cracking and plugging: Formation of a cone-like crack under the projectile and the possible subsequent punching-shear plug.
  - Spalling: Ejection of target material from the proximal face of the target.
  - Radial cracking: Global cracks radiating from the impact point and appearing on either the proximal or distal face of the concrete slab or both, when cracks develop through the target thickness.
  - Scabbing: Ejection of fragments from the distal face of the target.
  - Perforation: Complete passage of the projectile through the target with or without a residual velocity.

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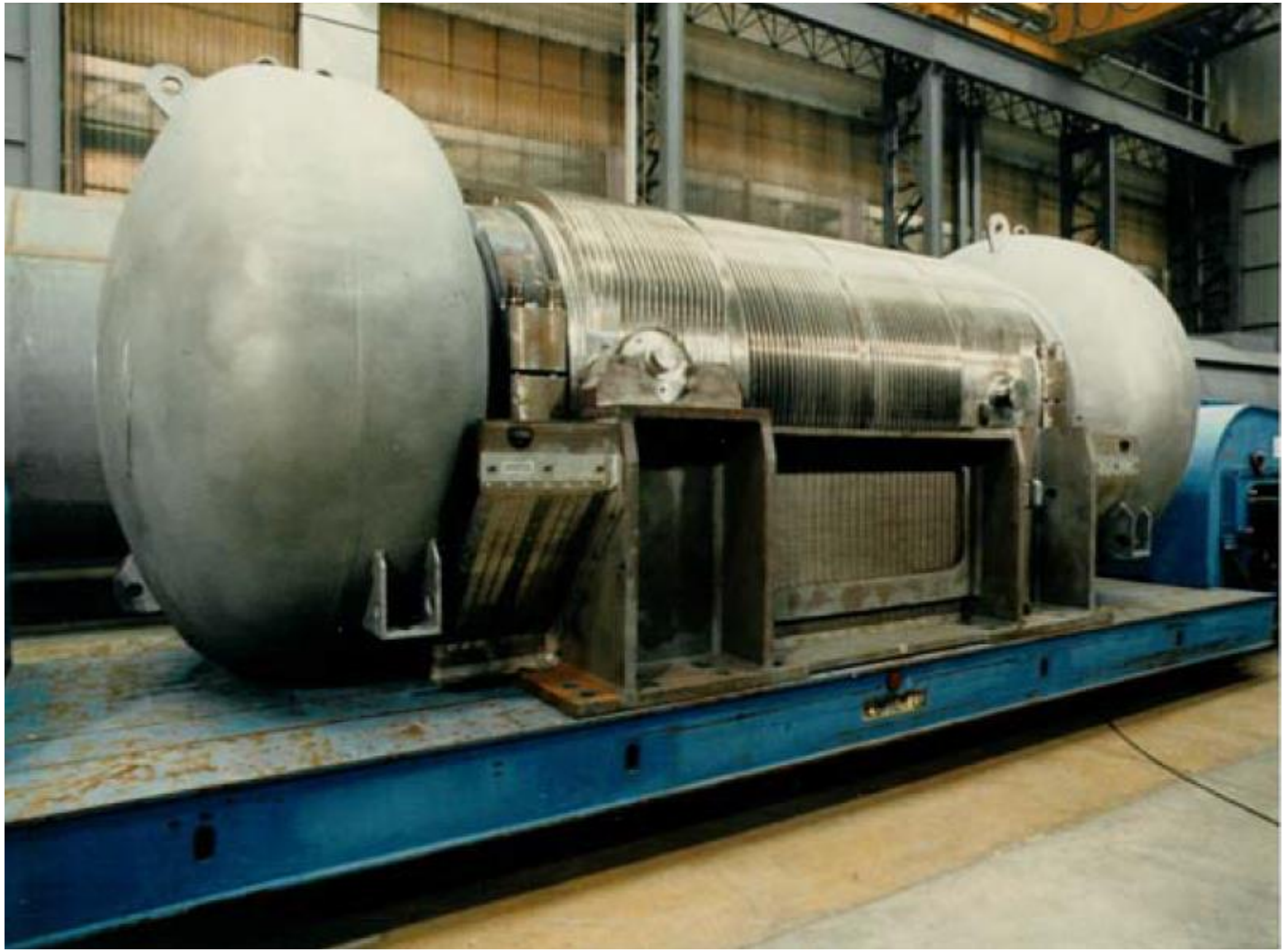
Example of nuclear spent fuel cask



- AGN-1 cask
  - Weight: 54 ton
  - Height: 4 m
  - Diameter: 1.5 m

Photo: Aquaro D, Forasassi G, Marconi M, 2003. *Ultimate resistance of a reinforced concrete foundation under impulsive loading*. In Transactions of the SMiRT 17. Paper H04-2.

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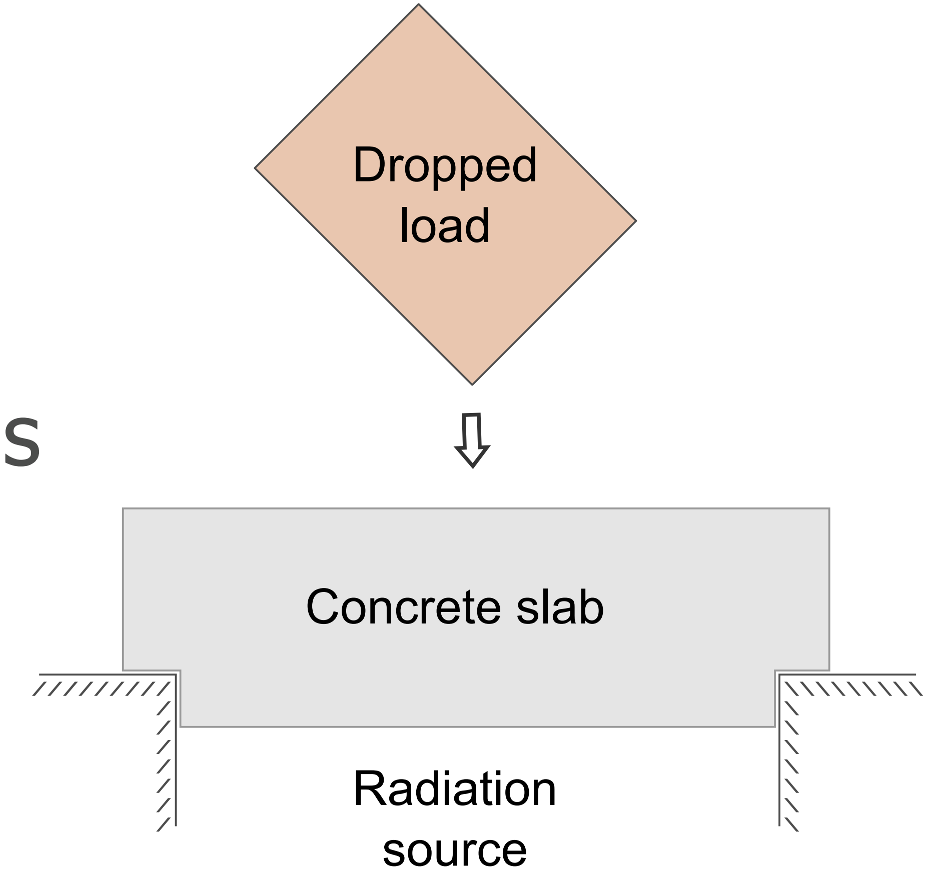
Dropped Load Case Study

- Low impact velocity (< 16 m/s)
- High kinetic energy (~ 1 MJ)

- Evaluation of available empirical models
- Numerical simulation (LS-DYNA)



Empirical models considered

- R3 Concrete Assessment Procedure
  - Critical kinetic energy

- CEA-EDF Perforation Formula
  - Perforation limit
  - Scabbing limit
  - Ballistic limit

- UK Atomic Energy Authority (UKAEA)
  - Scabbing limit
  - Ballistic limit

R3 model

The R3 impact assessment procedure establishes critical kinetic energies that if exceeded could lead to cone cracking, scabbing and/or perforation of the concrete slab. The critical kinetic energy for scabbing $E_{c,s}$ is calculated from

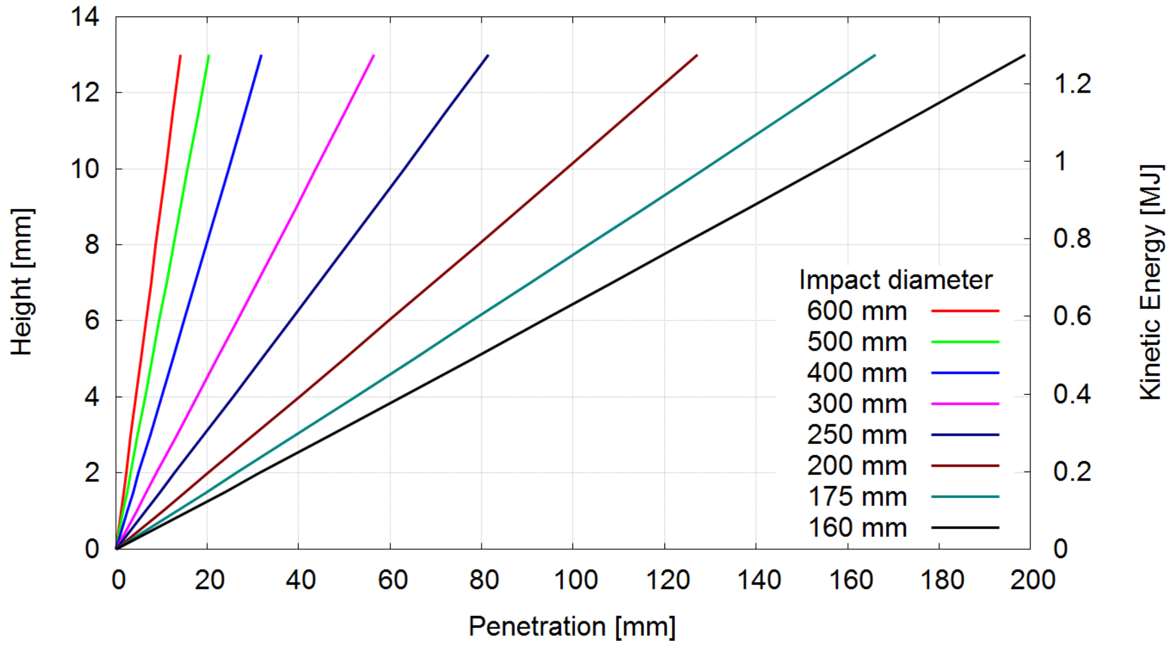
$$\frac{E_{c,s}}{\eta\sigma_t d^3}\frac{N^*}{0.72} = 0.01386\left(\frac{H_0}{d}\right)^2 - 0.005441\frac{H_0}{d}$$

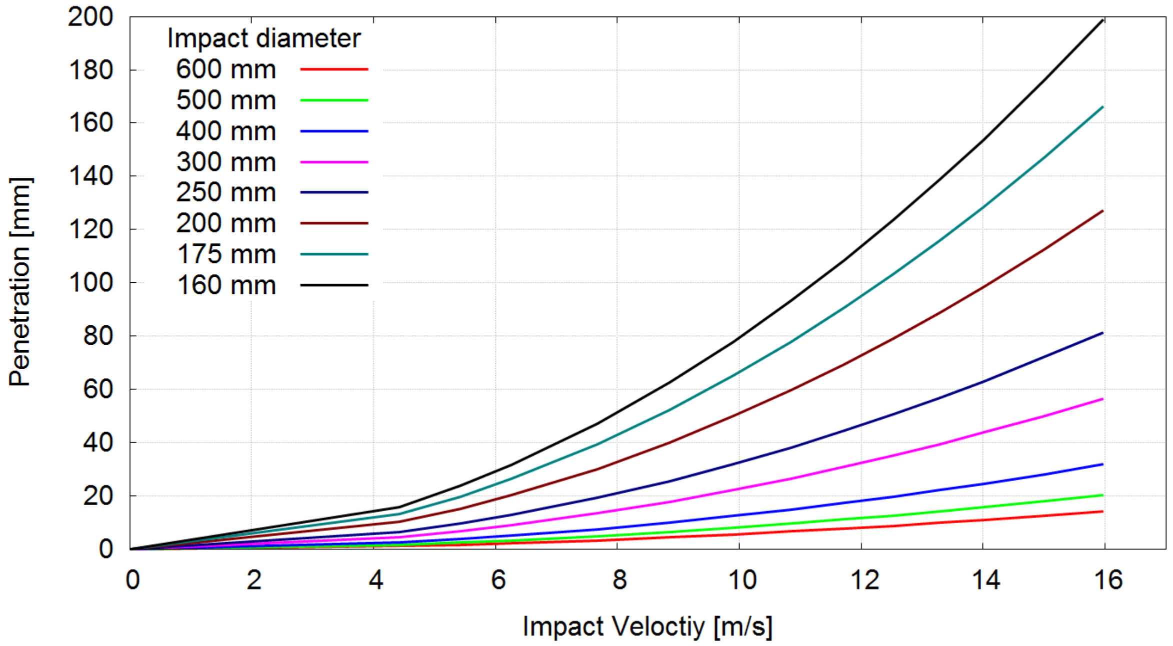
Both the critical kinetic energy for cone cracking $E_{c,c}$ and the critical kinetic energy for perforation $E_{c,p}$ can have the influence of the nose shape disregarded, being respectively obtained from

$$\frac{E_{c,c}}{\eta\sigma_t d^3} = \begin{cases} 0.00113\left(\frac{H_0}{d}\right)^2 - 0.00031\frac{H_0}{d} & \text{if } 0 < \frac{H_0}{d} \le 2 \\ 0.00130\left(\frac{H_0}{d}\right)^3 - 0.00325\frac{H_0}{d} & \text{if } 2 < \frac{H_0}{d} < 5 \end{cases}$$

$$\frac{E_{c,p}}{\eta\sigma_t d^3} = \begin{cases} 0.01506\left(\frac{H_0}{d}\right)^2 - 0.00506\frac{H_0}{d} & \text{if } 0 < \frac{H_0}{d} \le 1 \\ 0.02\left(\frac{H_0}{d}\right)^3 - 0.01\frac{H_0}{d} & \text{if } 1 < \frac{H_0}{d} < 5 \end{cases}$$

R3: Concrete penetration





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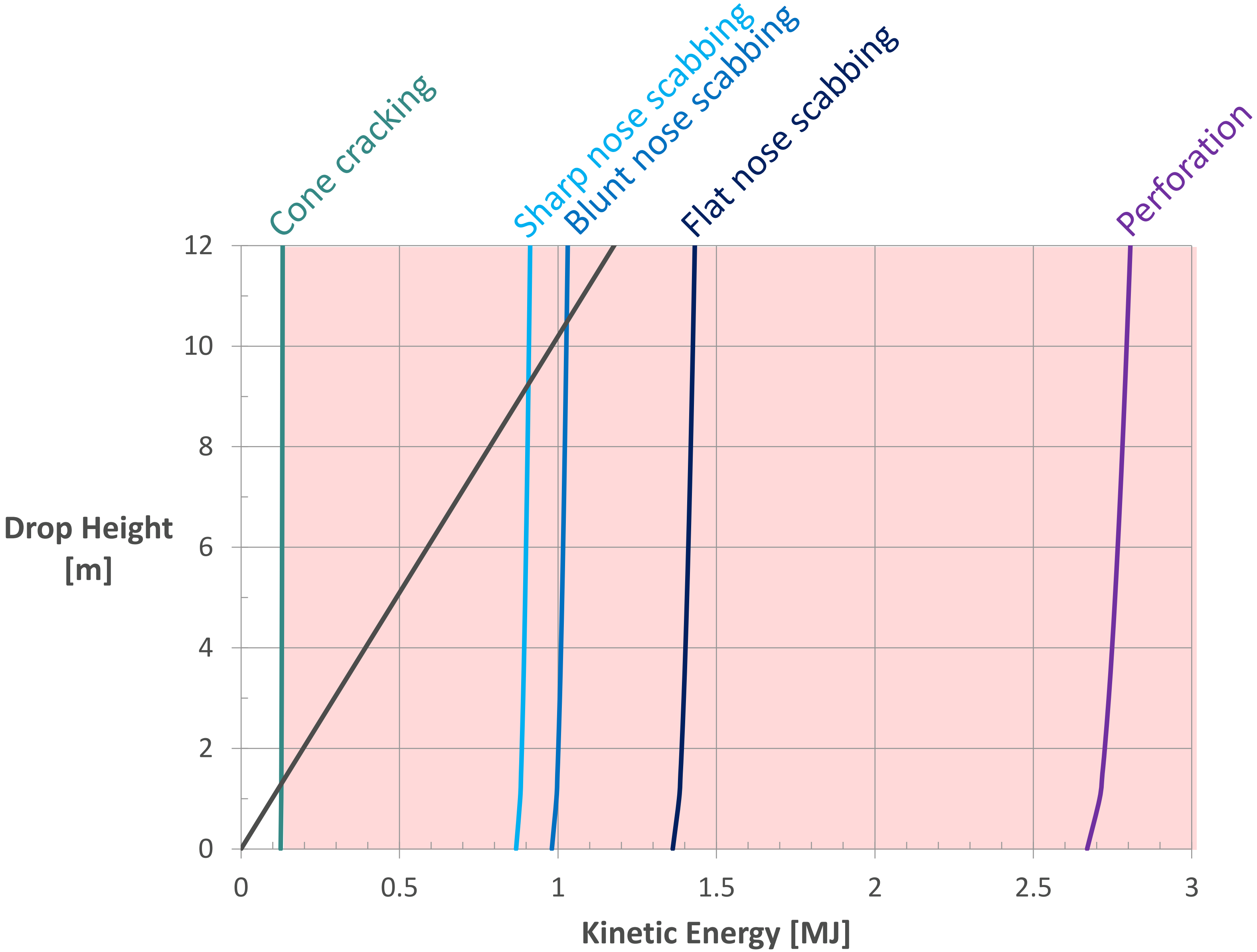
R3: Impact Energy



Kinetic energy limits for a 800mm thick concrete slab for different nose shapes.

The black line indicates the impact energy.

Impact diameter: 600mm

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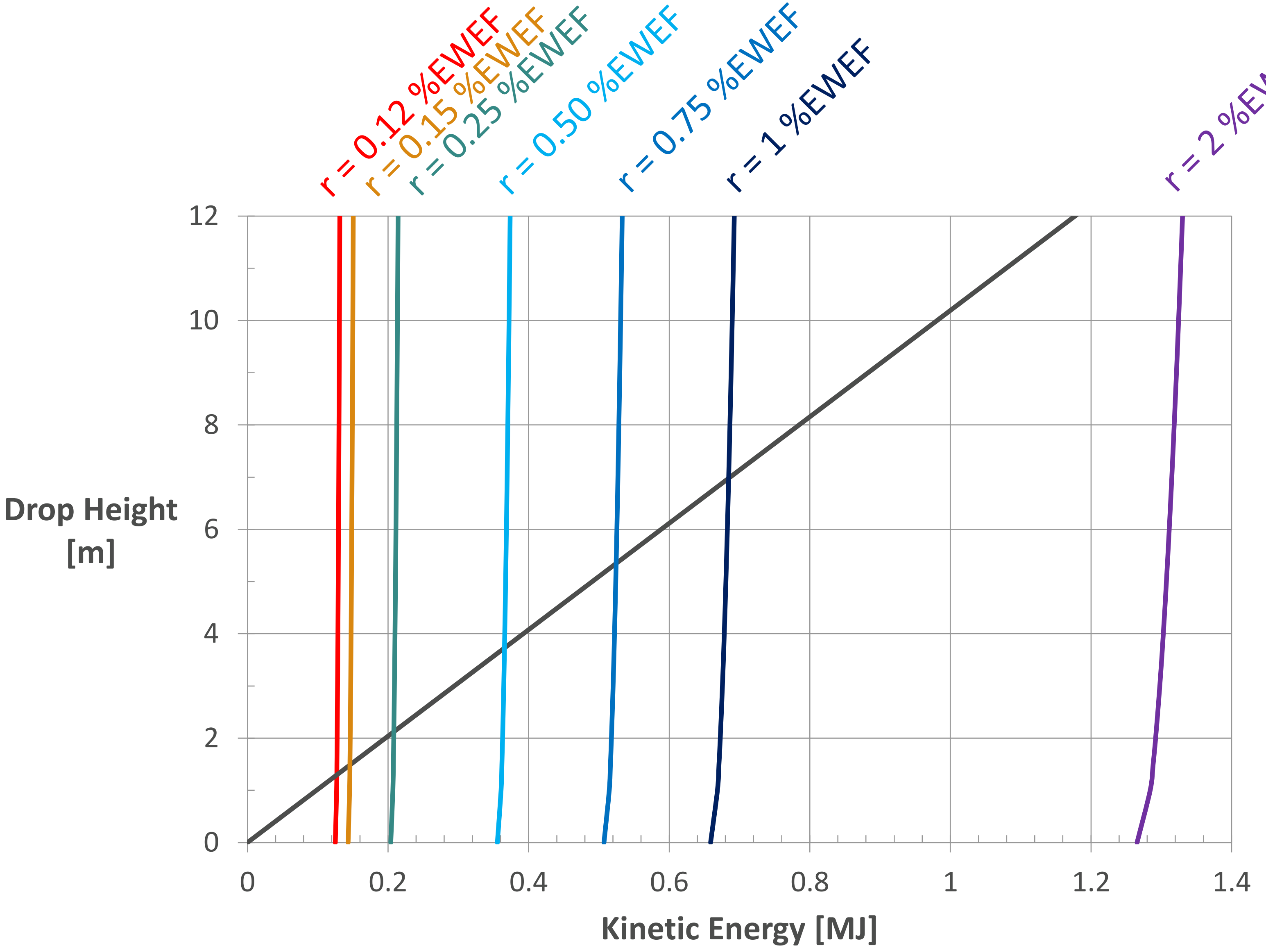
R3: Energy limits for cone cracking



Critical kinetic energy limits for cone cracking of a 800mm thick concrete slab for varying percentage of reinforcement.

The black line indicates the impact energy.

Impact diameter: 600mm

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CEA-EDF

- CEA and EDF France developed a large testing programme to reliably compute the behaviour of reinforced concrete walls under missile impacts. These tests were conducted on reinforced concrete slabs, with thicknesses that were representative of reactor containment structures.
- And the ballistic limit, the minimum initial impact velocity to perforate the target, was later formulated by Fullard et al[1] for non- circular cross sections to be:

$$V_p = 1.3\rho_c^{\frac{1}{6}} f_c^{\frac{1}{2}} \left(\frac{pH_0^2}{\pi M}\right)^{\frac{2}{3}} (r + 0.3)^{1/2}$$

- Scabbing may occur on the side opposite the contact surface even if the missile does not perforate the concrete slab; this will lead to breach of containment as outlined in the introduction. The formula for the scabbing limit was developed by Bechtel Power Corporation and is based on test data applicable to missile impacts on nuclear-plant structures where the scabbing limit, h_s, is given by:

$$\frac{h_s}{d} = 38.98 \frac{M^{0.4} V_0^{0.5}}{f_c^{0.5} d^{1.2}}$$

[1]Fullard, K., M.R. Baum, and P. Barr, *The assessment of impact on nuclear power plant structures in the United Kingdom.* Nuclear Engineering and Design, 1991. **130**(2): p. 113-120..

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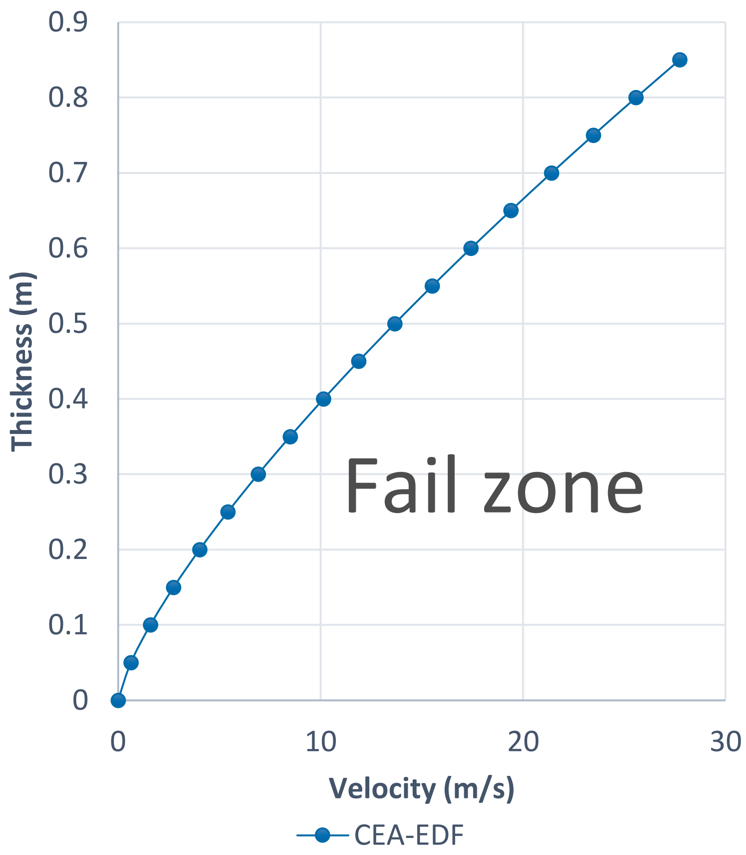
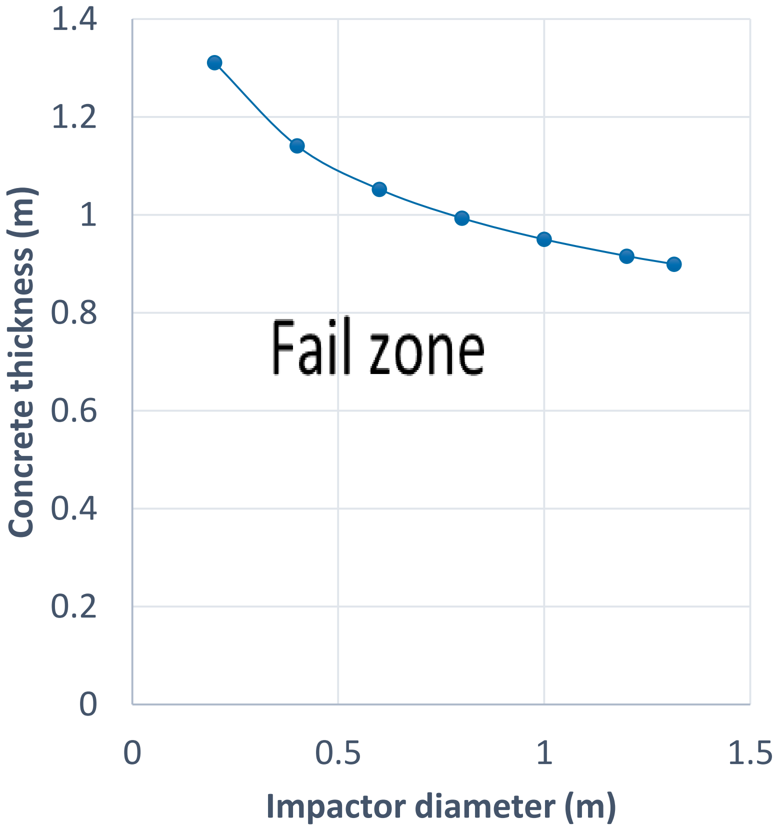
CEA Results

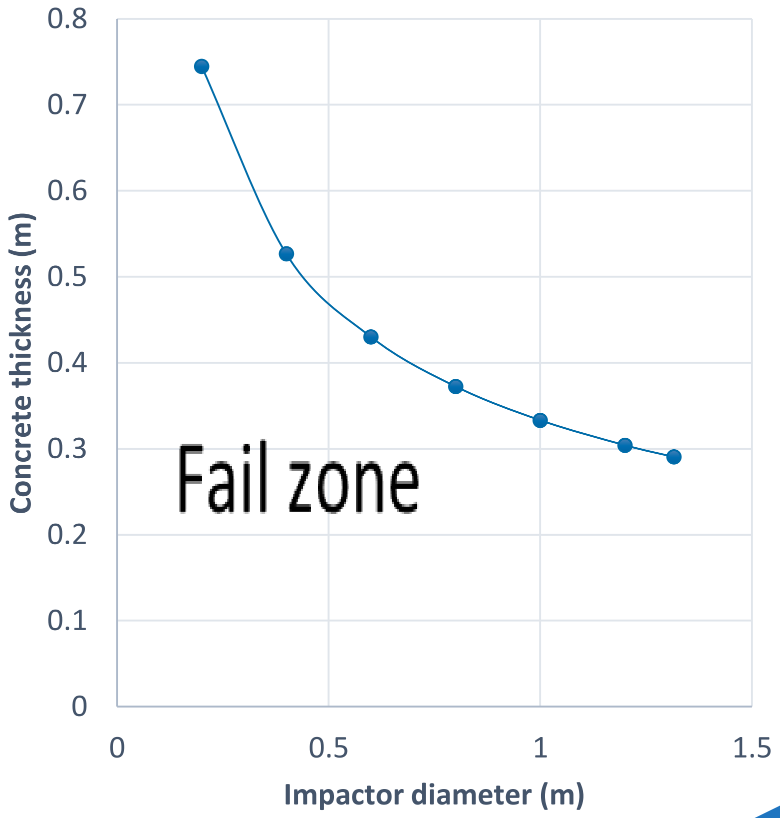
Ballistic limit



Scabbing limit



Perforation thickness



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UKAEA

Based on extensive studies of the protection of nuclear power plant structures in the UK, Barr[2] proposed some new variations of previous formulations with their efforts directed mainly towards the lower impact velocities more relevant to the nuclear industry. The formulation utilises the non-dimensional G-function:

$$G = 3.8 \times 10^{-5} \frac{N^* M}{d\sqrt{f_c}} \left(\frac{V_0}{d}\right)^{1.8}$$

- For the scabbing limit, h_s, Barr proposed:

$$\frac{h_s}{d} = 5.3 G^{0.33}$$

- where G is calculated from the equation above simple rearrangement of this formula yields the critical velocity to generate scabbing from the target. The accuracy of this formula in the ranges of parameters of $29 < V_0 < 238$(m/s), $26 < f_c < 44$(MPa), $3000 < M/d^3 < 222{,}200$(kg/m3) has been assessed as ±40% for $2.0 < h_s/d < 5.56$.
- The ballistic limit, the minimum initial impact velocity to perforate the target, formula was modified as per the CEA-EDF formula with the inclusion of the rebar spacing:
- $$V_p = 1.3 \rho_c^{\frac{1}{6}} k_c^{\frac{1}{2}} \left(\frac{p H_0^2}{\pi M}\right)^{\frac{2}{3}} (r + 0.3)^{1/2} \left[1.2 - 0.6 \left(\frac{c_r}{H_0}\right)\right]$$

[2]Barr, P., Guidelines for the design and assessment of concrete structures subjected to impact. 1990, Warrington, Cheshire: Great Britain Safety Reliability Directorate.

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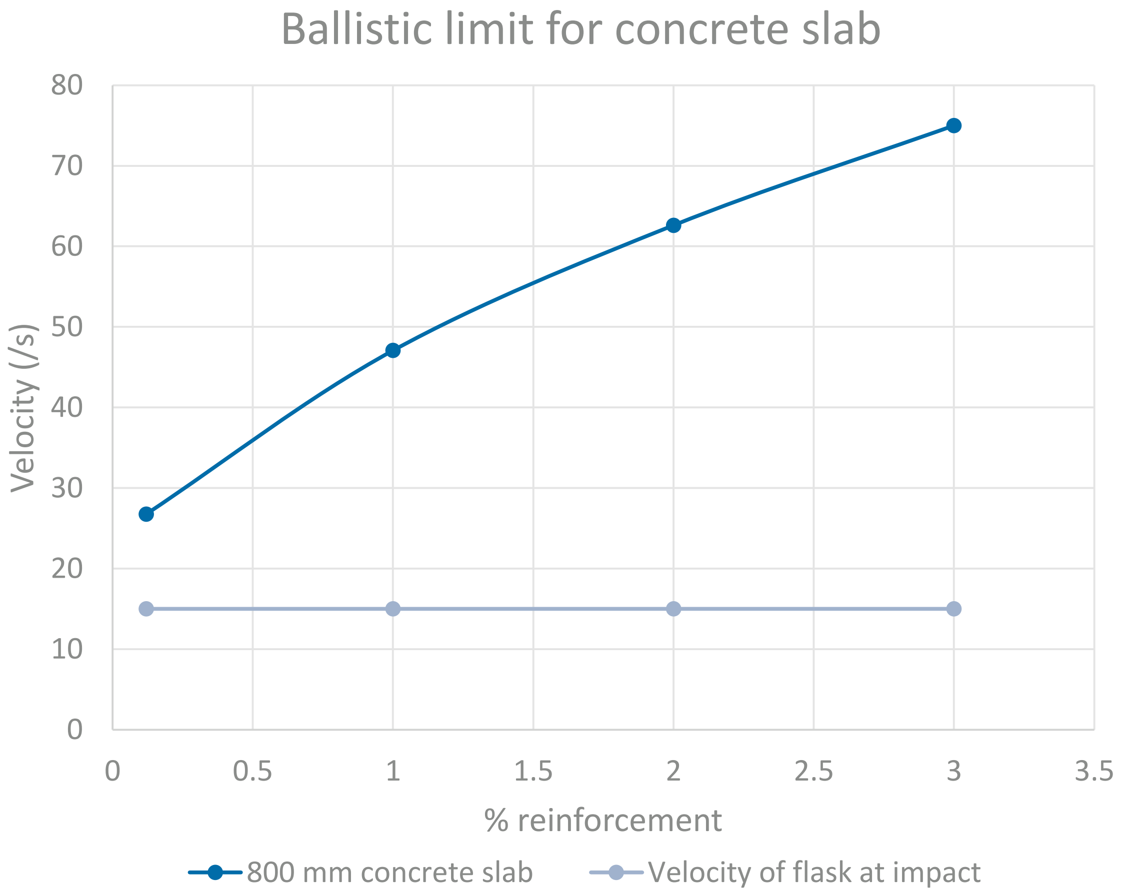
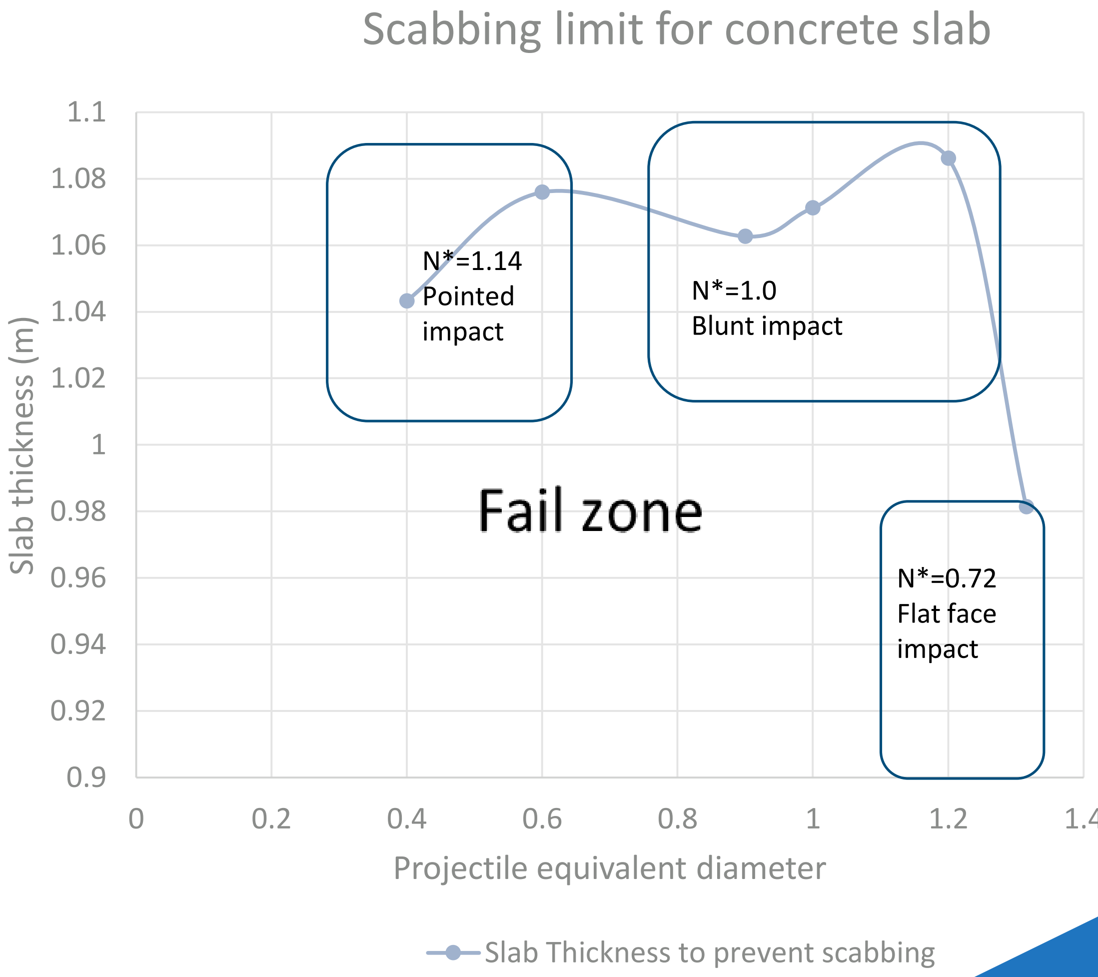
UKAEA results





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Numerical study

The concrete is modelled using the Winfrith concrete model that was developed specifically to address impact and blast problems within the nuclear industry. The Winfrith model is a smeared crack model where three orthogonal cracks planes are allowed per element, hence crack propagation can be modelled. Other features of the model are:

- Elastic-plastic model formulation.
- Ability to treat both compressive and tensile triaxial stress states using a third stress invariant.
- Includes strain softening behaviour in tension.
- Regularisation of the model is done through crack width criteria, fracture energy and aggregate size.
- The model also contains a smeared rebar formulation where the rebar need not to be modelled explicitly.

The hydrostatic stress is modelled using a default non-dimensionalised volume compaction curve . The deviatoric stresses are incremented elastically with a shear yield surface described by Ottosen[3]. The shear failure envelope is shown below:

$$F\left(I_1, J_2, \cos 3\theta\right) = a\frac{J_2}{\left(f_c'\right)^2} + \lambda\frac{\sqrt{J_2}}{f_c'} + b\frac{I_1}{f_c'} - 1$$

The model is a function of the first stress invariant, I_1, along with the second invariant of the deviatoric stress, J_2. The terms a, b and λ are material constants that govern the shape of the shear failure surface based on the ratio between the unconfined tensile and compressive strength.

[3]Ottosen, N.S., “A Failure Criterion for Concrete,” Journal of the Engineering Mechanics Division, Vol. 103(4), pp. 527-535. (1977)

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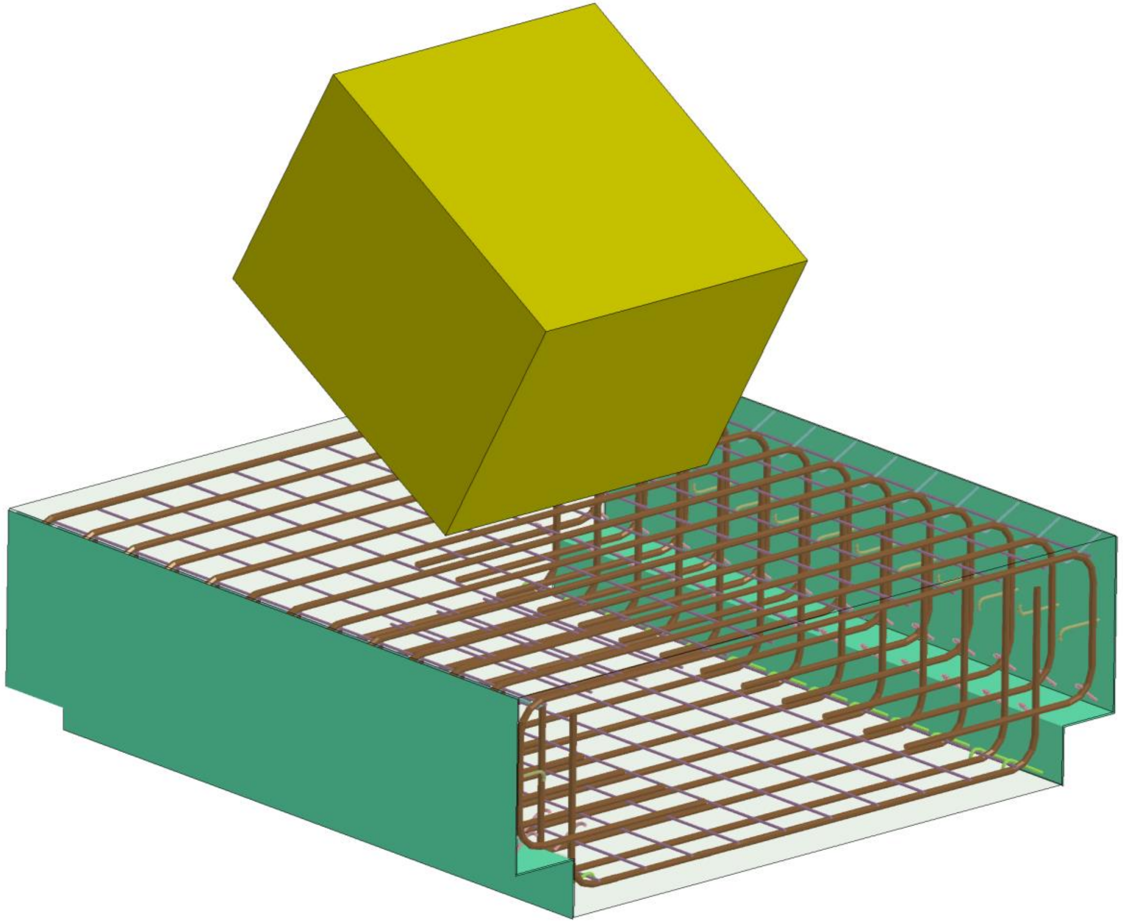
Model setup

A numerical model for reinforced concrete that is capable of simulating the entire process from impact loading through to the final global deformation phase. To accurately simulate the response of the reinforcement , steel beam elements are embedded within the concrete and are constrained to the concrete to ensure adequate coupling.

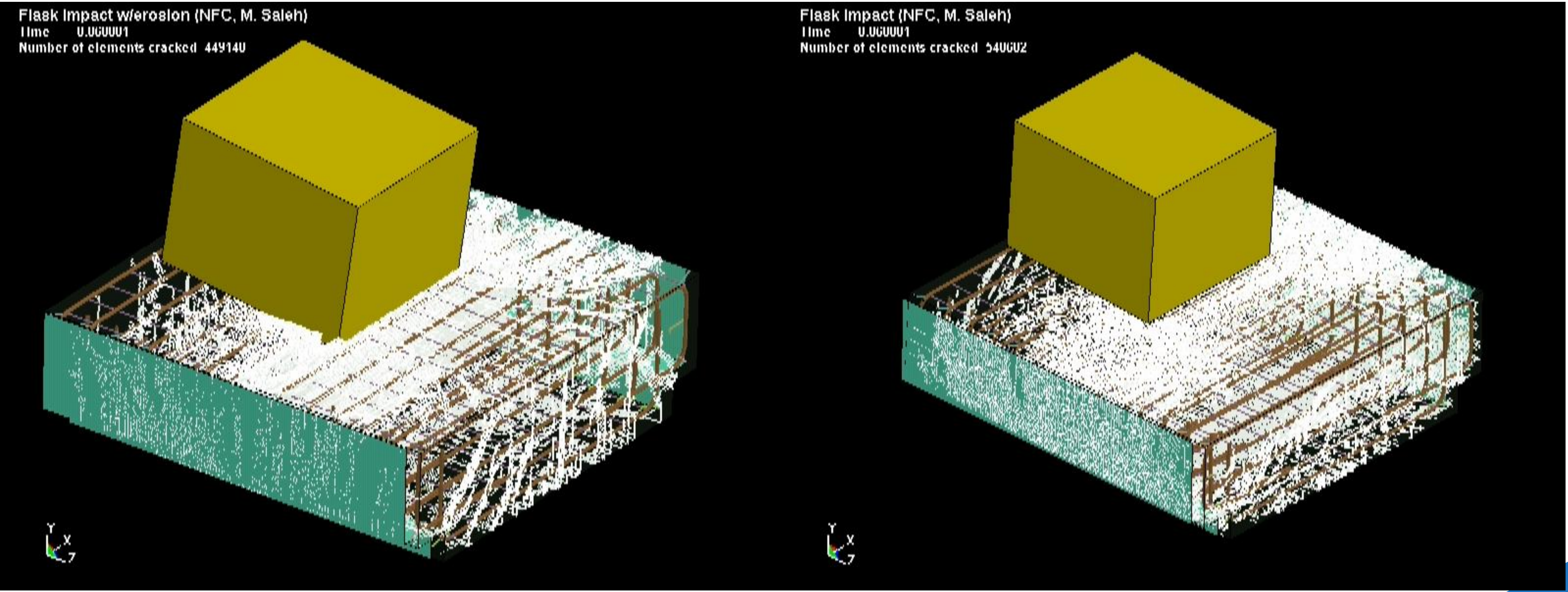
Contact for edge-to-edge beam elements is implemented to ensure non-physical penetrations are avoided. The side wall and the impactor are treated as rigid. The steel is modelled at elastic-plastic with kinematic hardening, $\sigma_y = 500MPa, \varepsilon_f = 0.1$.



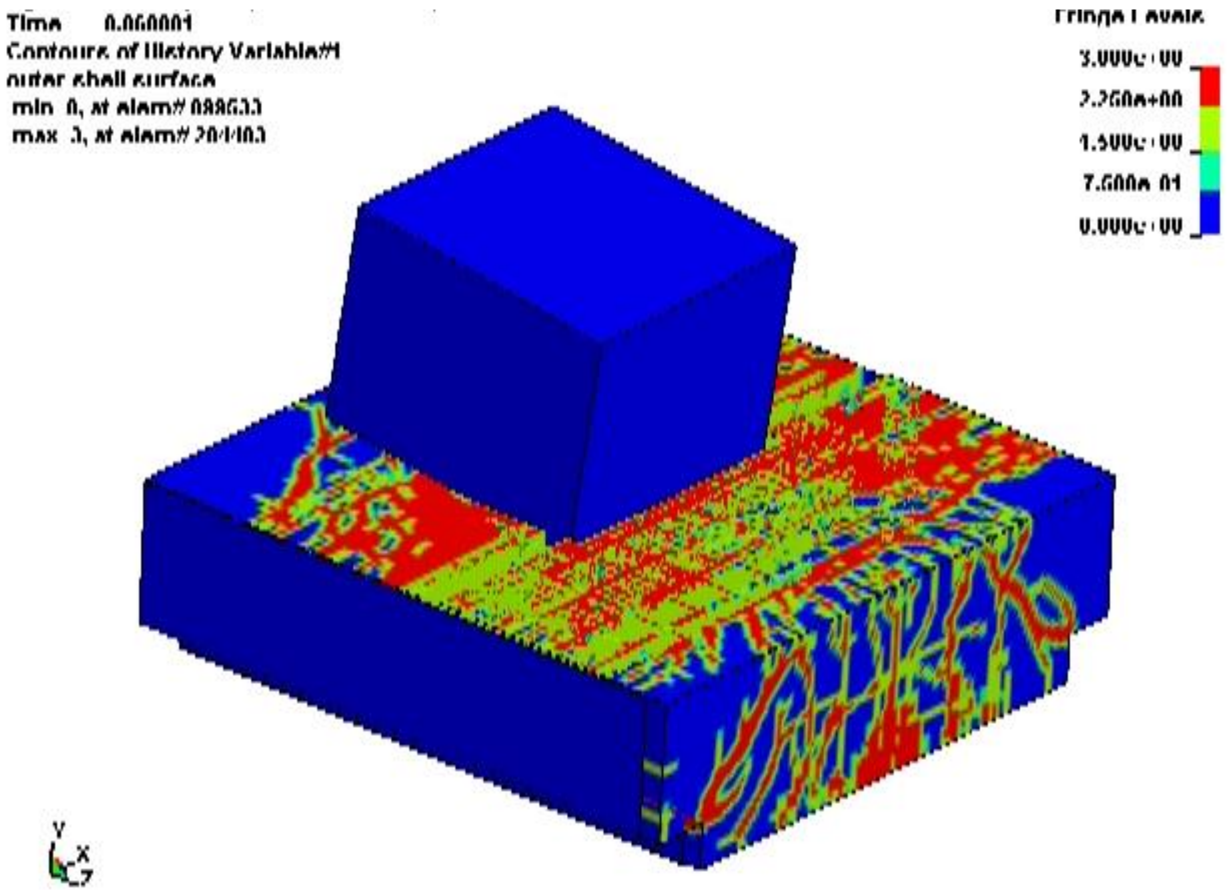
Concrete data:

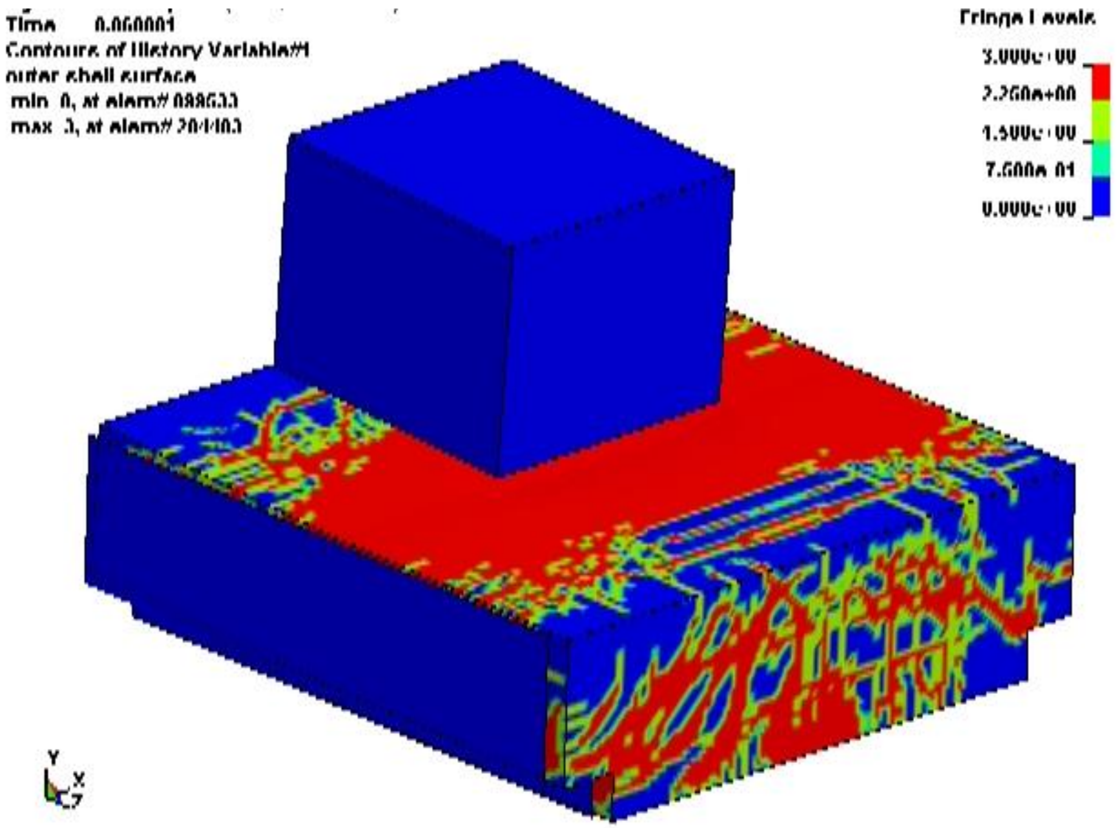
P (density)	2400Kg/m³
Et (Tangent Modulus)	35000Mpa
V (Poisson's Ratio)	0.15 (Uncracked Concrete)
Fc (Compressive Strength)	40Mpa
Ft (Tensile Strength)	3.5Mpa
Aggregate Size (diameter)	20mm

Crack evolution with and w/o erosion



Damage evolution





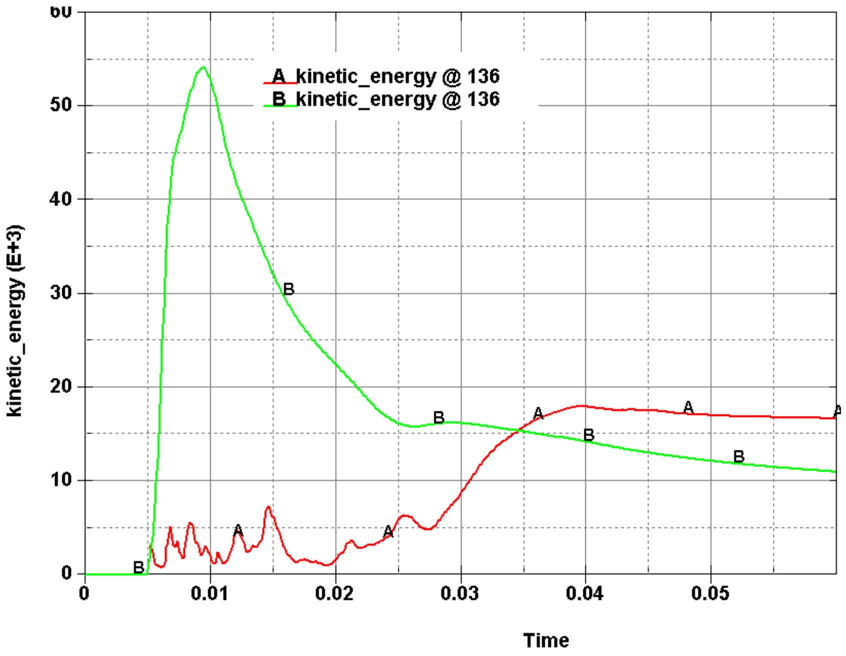
0 = Uncracked.

1 = Cracked, but still on strain softening curve (still taking some tensile stress).

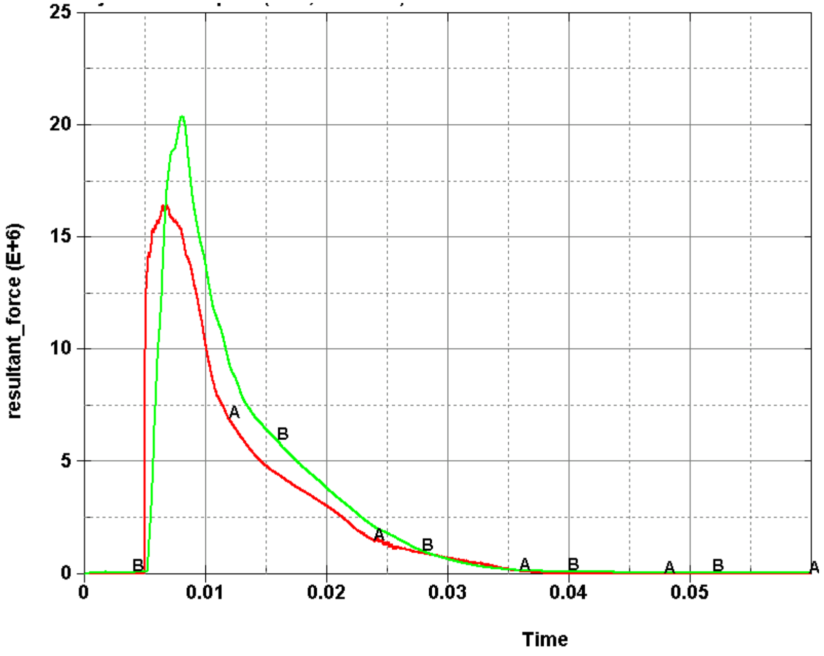
2 = Cracked, but crack is closed (i.e. can take compressive stress).

3 = Cracked fully (i.e. crack open and zero tensile stress).

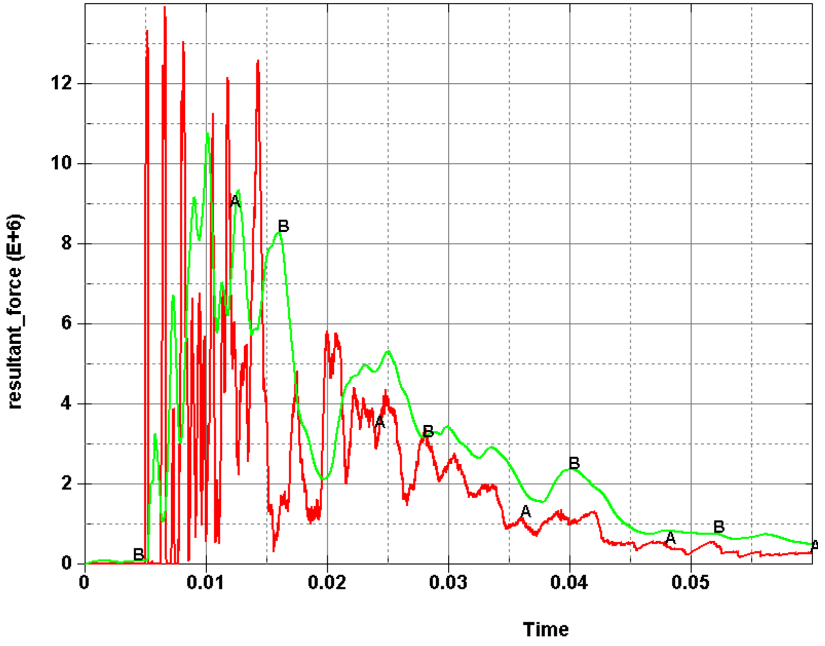
Concrete response and interaction with supporting walls



Kinetic energy of Concrete



Reaction forces at side walls, w/o erosion criteria



Reaction forces at side walls, with erosion criteria

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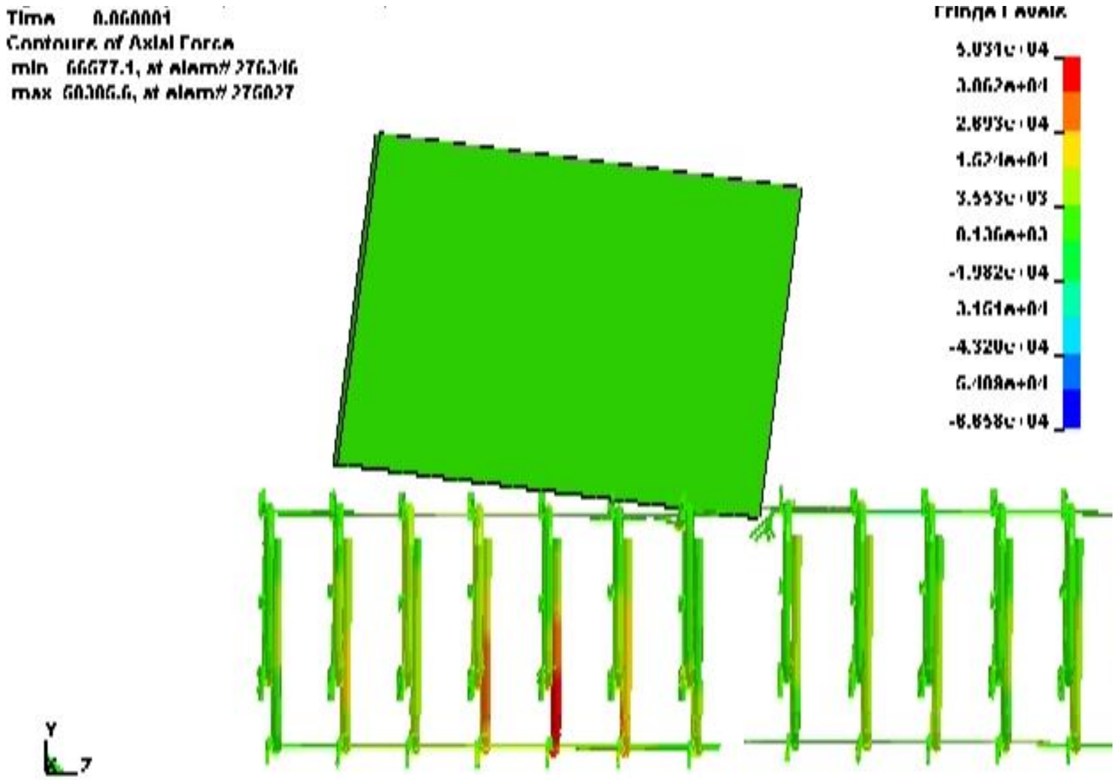
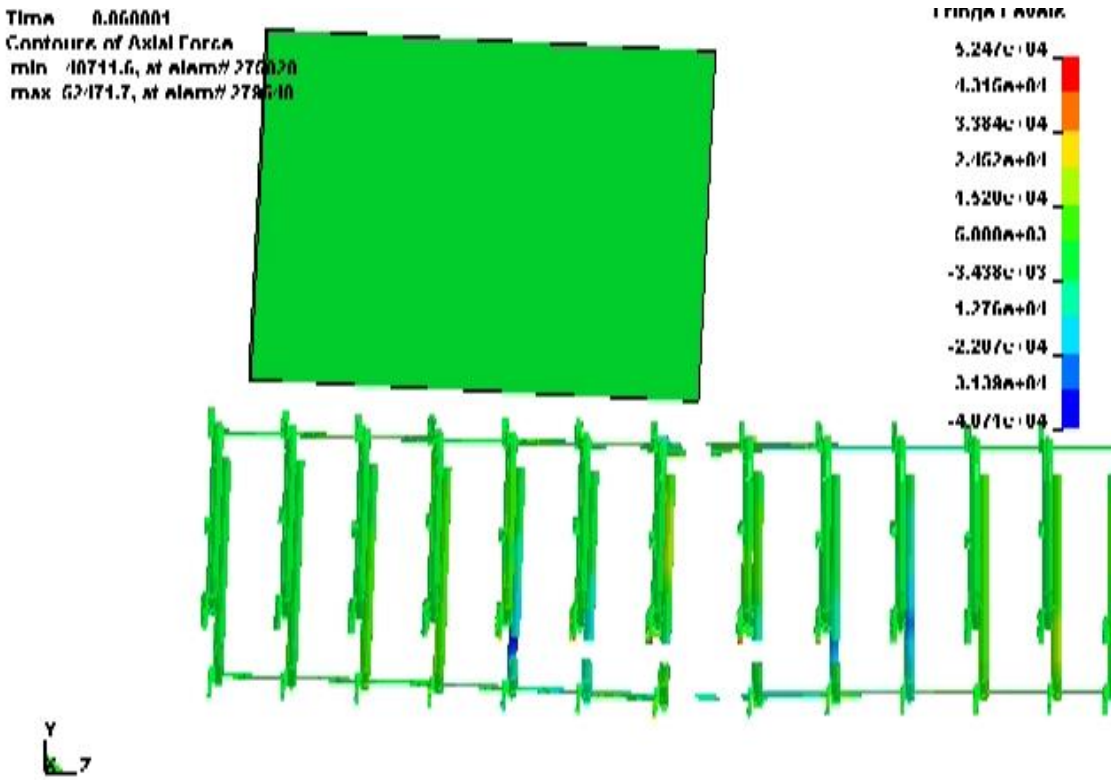
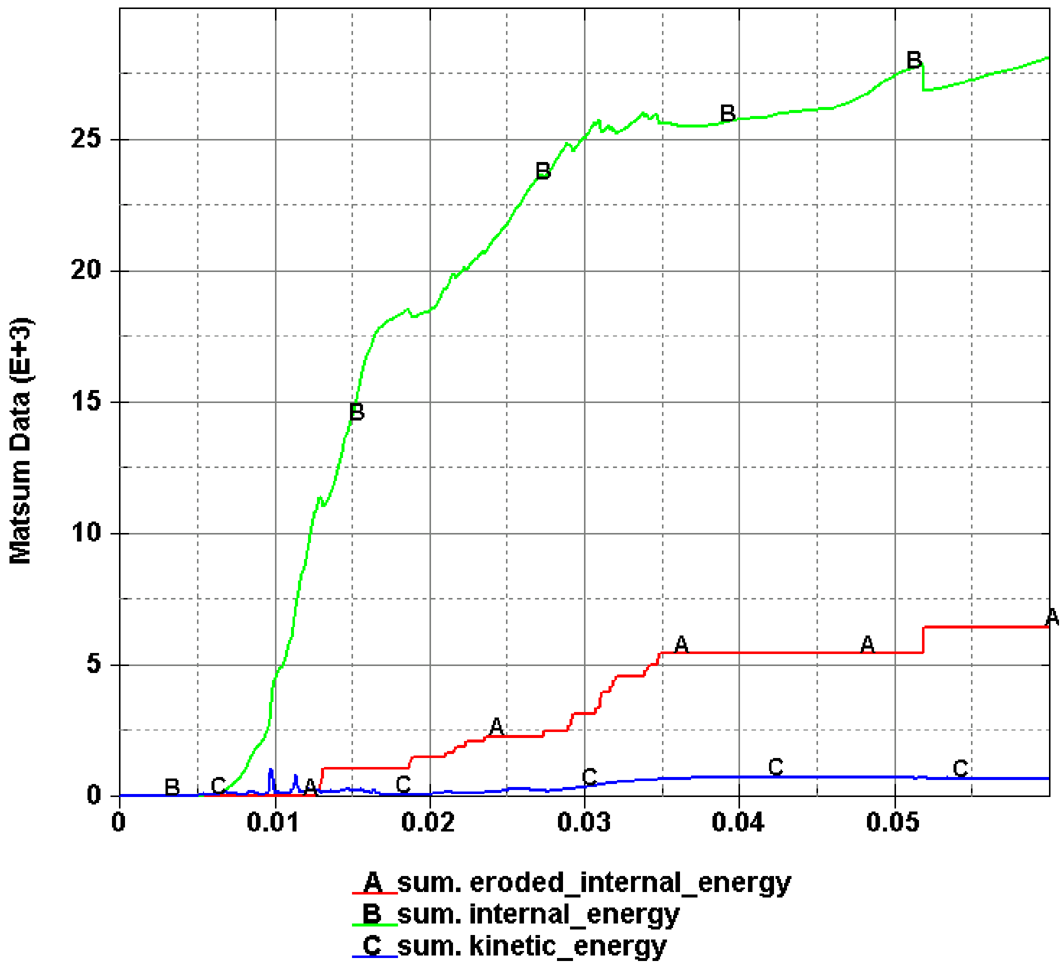
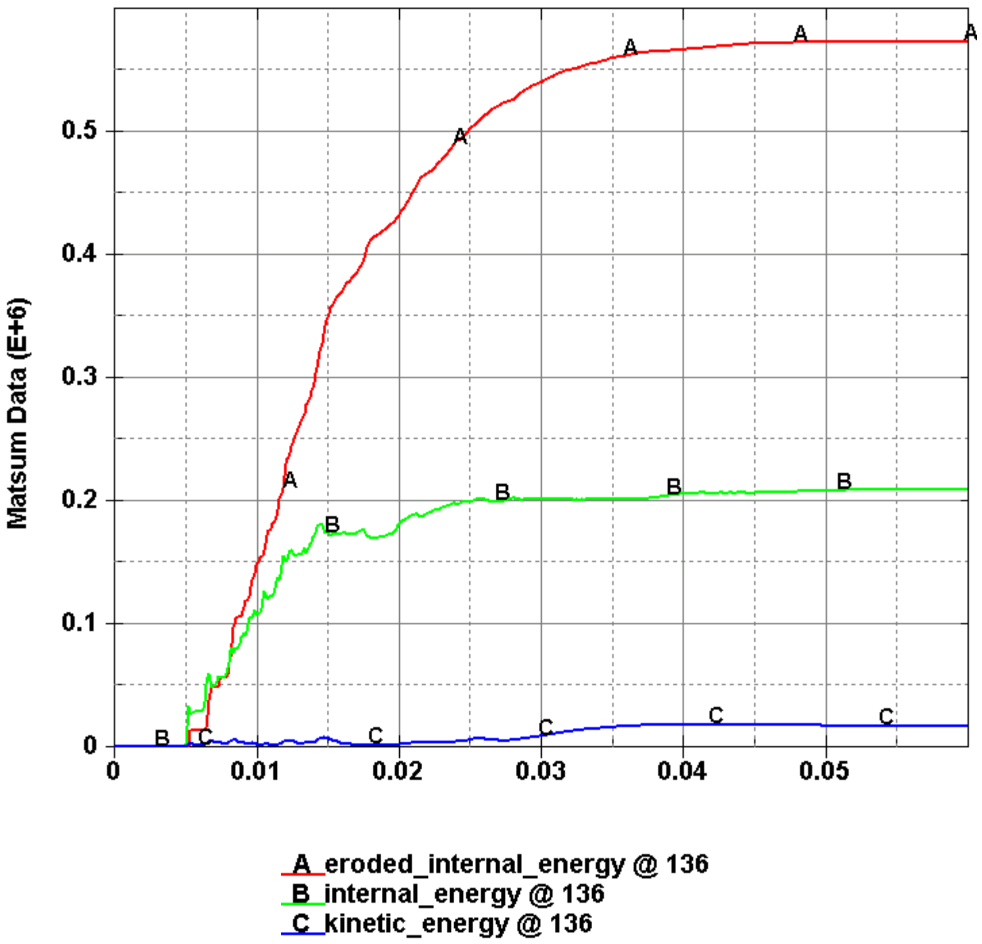
Steel Reinforcement response





Energy evaluation with erosion





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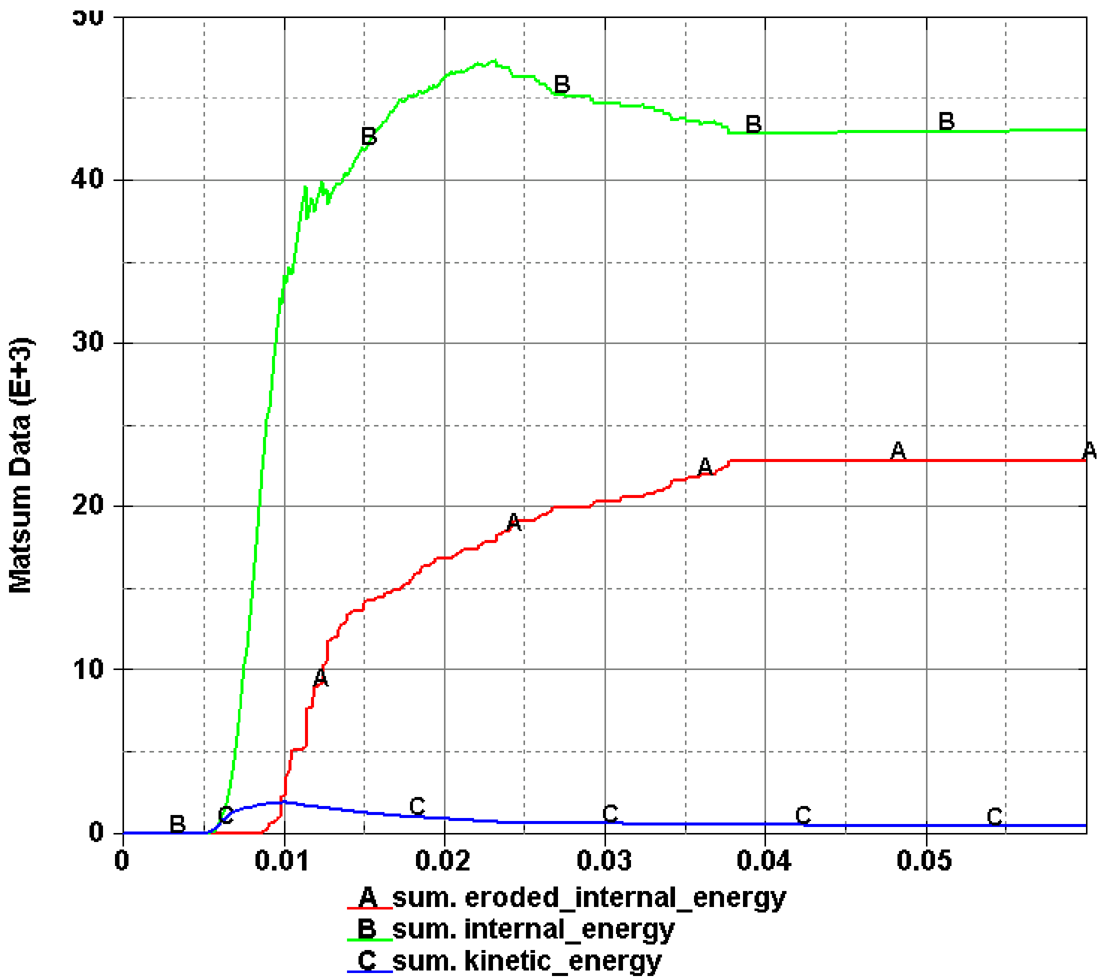
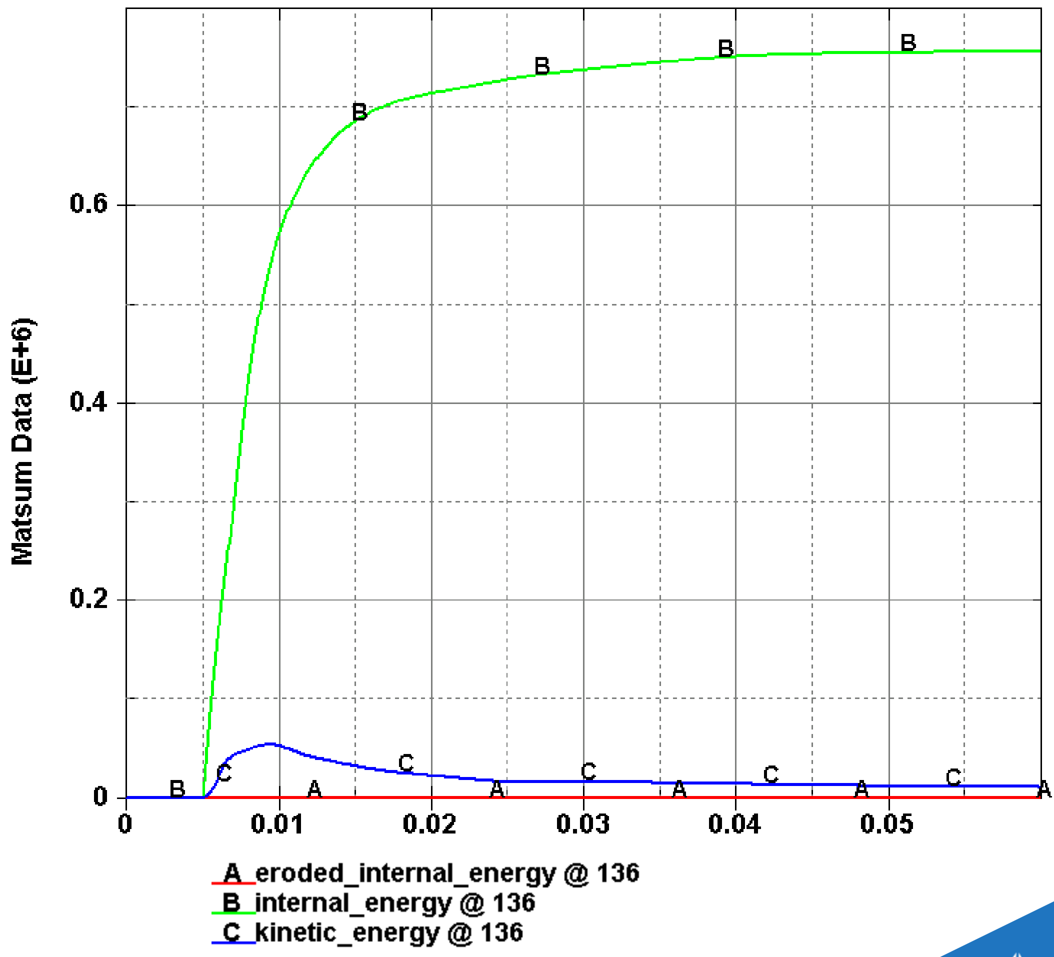
Energy evaluation w/o erosion





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Conclusions

- Analytical models indicated the susceptibility of the concrete panel to scabbing failure. This can lead to open cracks and release of radioactive materials or lead to secondary impacts with underlying structures.

- The CEA and UKAEA yield similar results but detailed reinforcement configuration cannot be readily evaluated.

- The use of numerical models does not show perforation of the concrete slab but profuse cracking is apparent.

- The use of the erosion criteria for the concrete significantly affects the global response and affects the energy of the system.

- The model with erosion did not pass the safety metrics with breach of containment likely owing to the through thickness cracks formed and the complete separation of the reinforcing steelwork.

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