IAPS 2020
Experimental and Numerical Analysis of Reinforced Concrete Subjected to Blast

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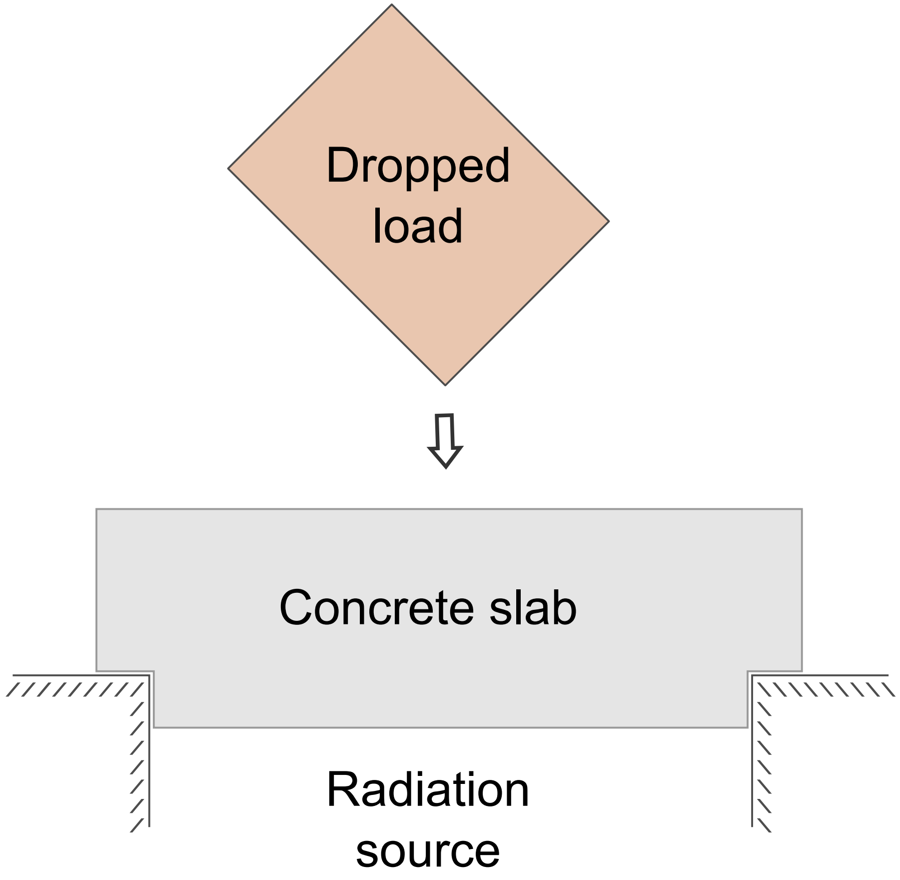
Dropped Loads and accidental blast in Nuclear Facilities

- Dropped loads (nuclear flasks) or accidental blast (combustible gases, deuterium/hydrogen release e.g. Fukushima accident) can undermine the structural integrity of containment structures and lead to a transient or sustained radiological release.
- Current regulatory guidelines and standards employ empirical formulas to calculate local responses of RC walls and slabs of nuclear facilities impacted by projectiles.
- These formulas were calibrated with data that are no longer available for reassessment and fail to predict complex scenarios.
- More accurate design equations can be developed by blast and impact analysis of RC panels using novel experimental and numerical techniques



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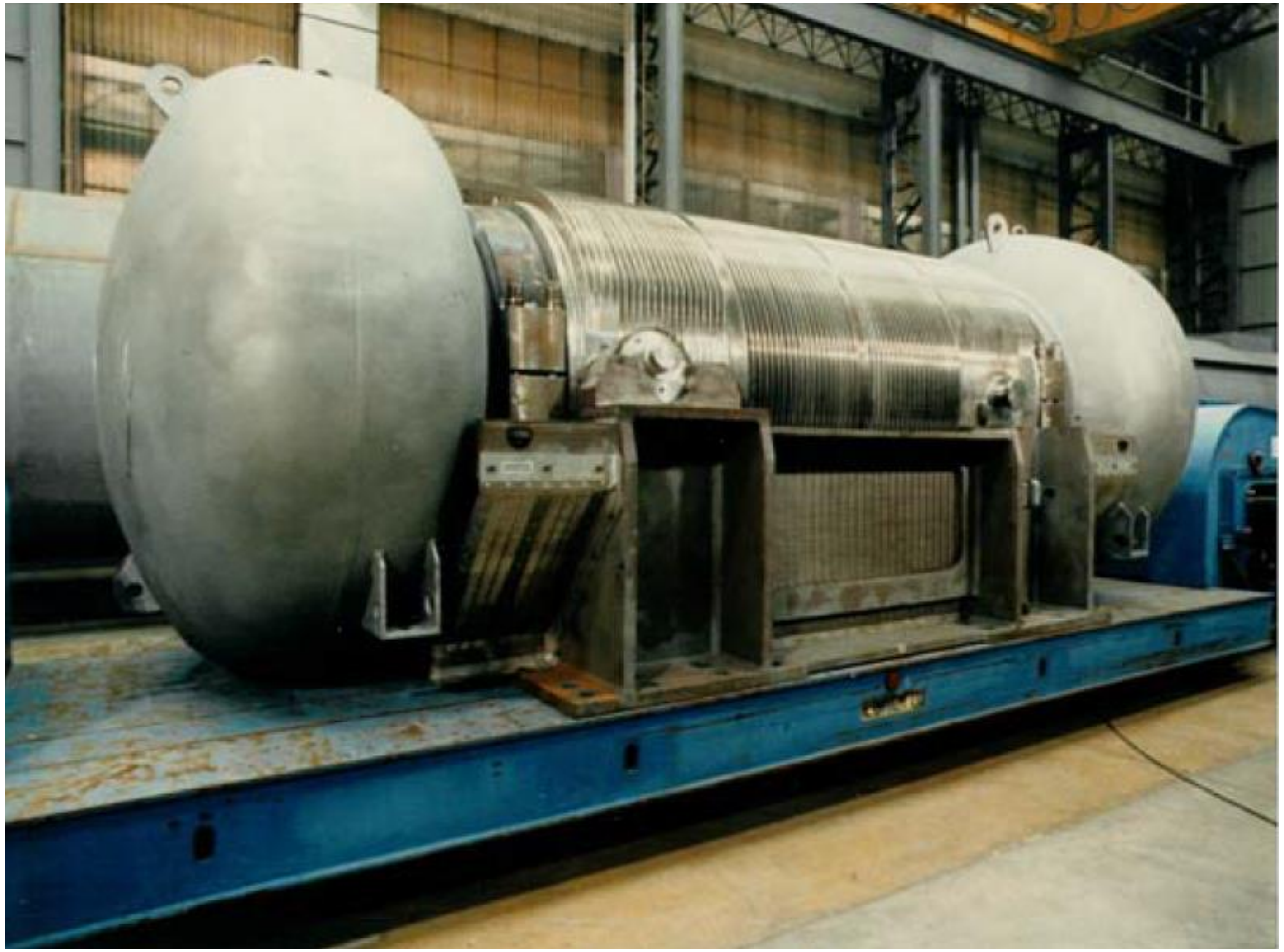
Example of nuclear spent fuel cask



- 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.

Previous Numerical study at IAPS 2018

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)

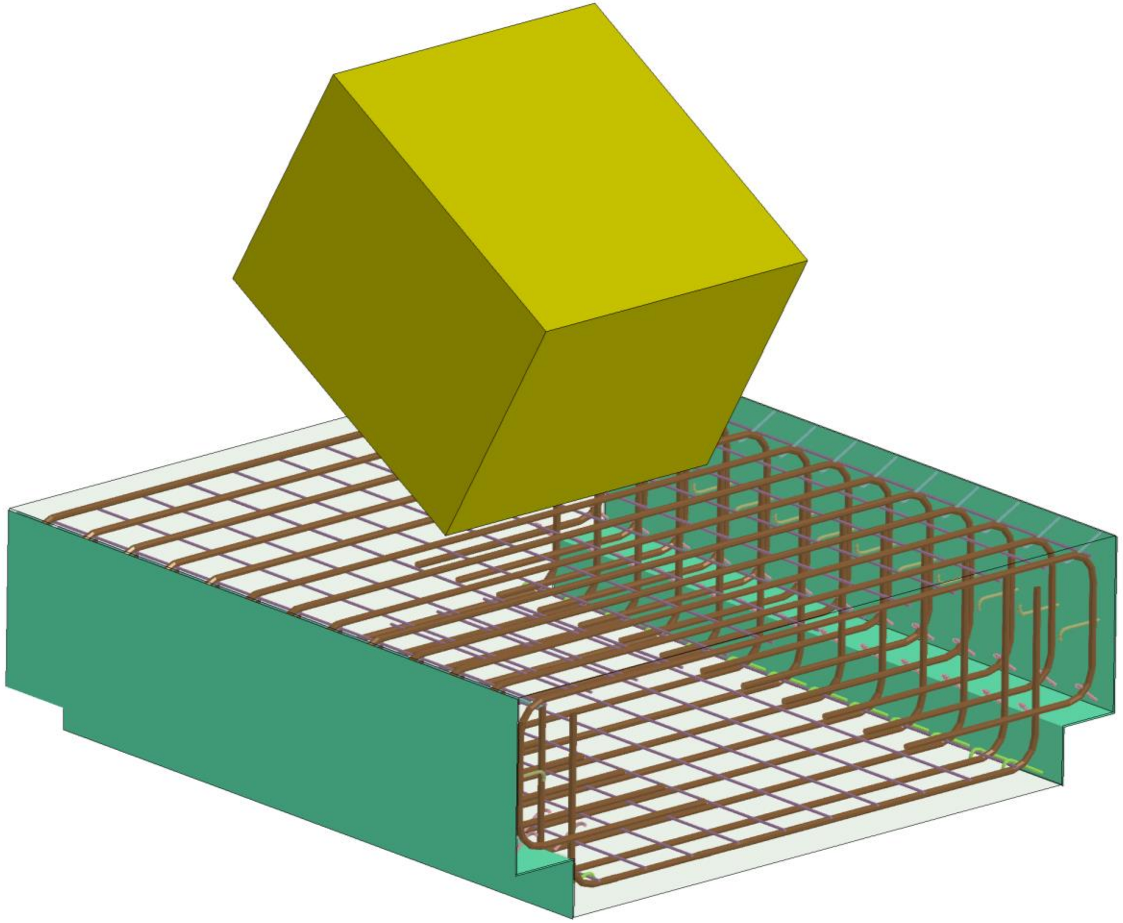
Model setup

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



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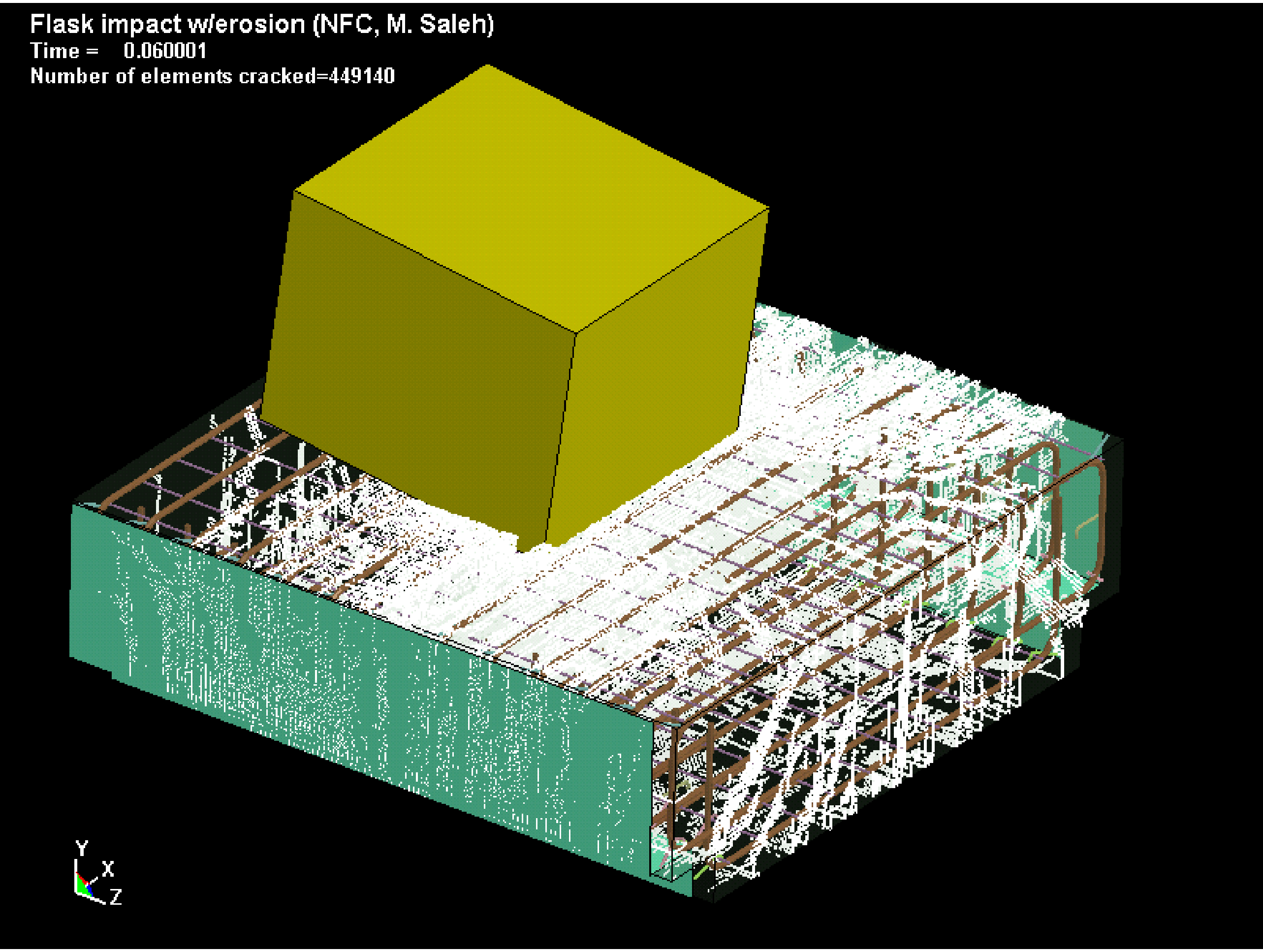
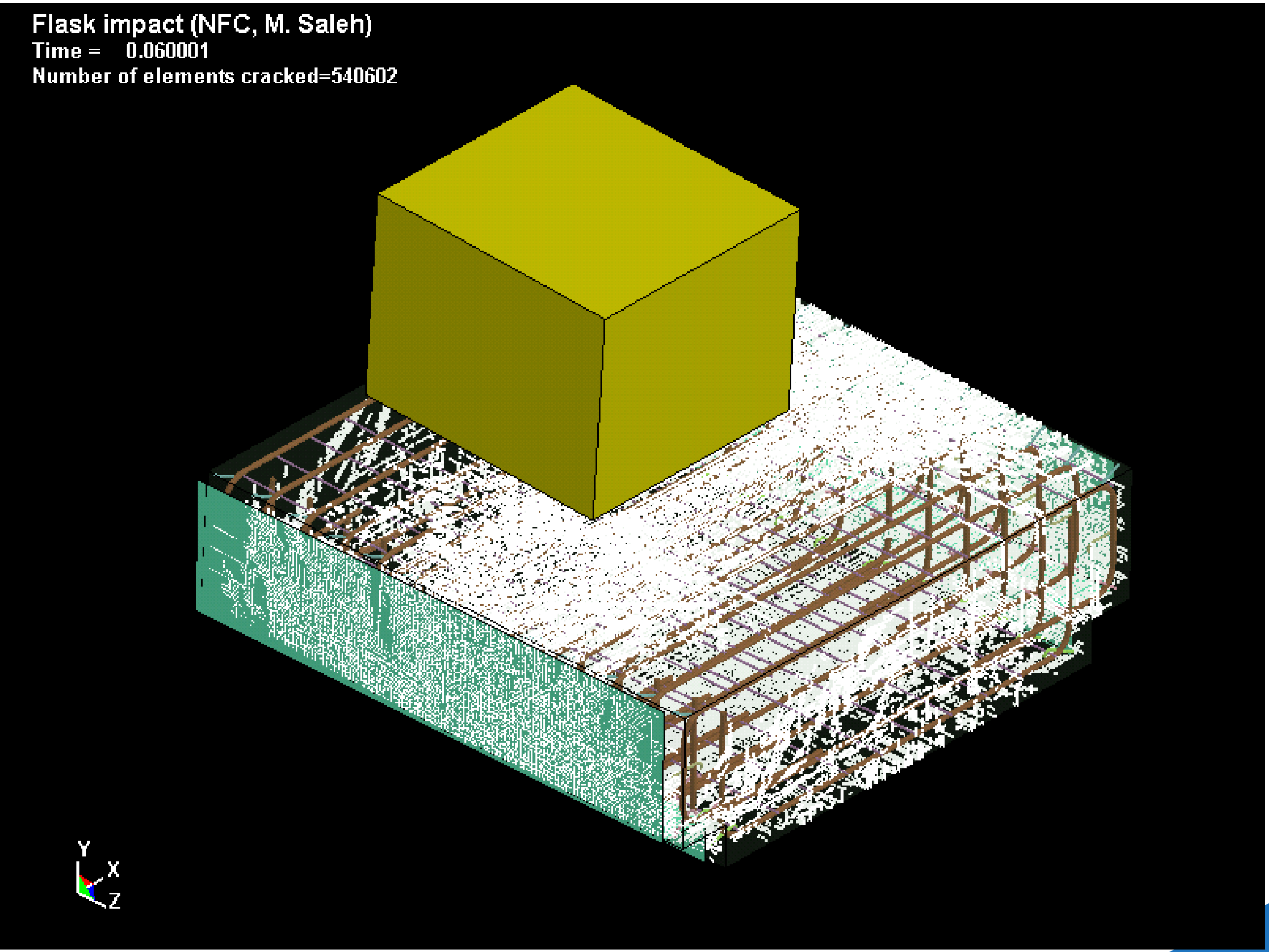
Crack evolution with and w/o erosion





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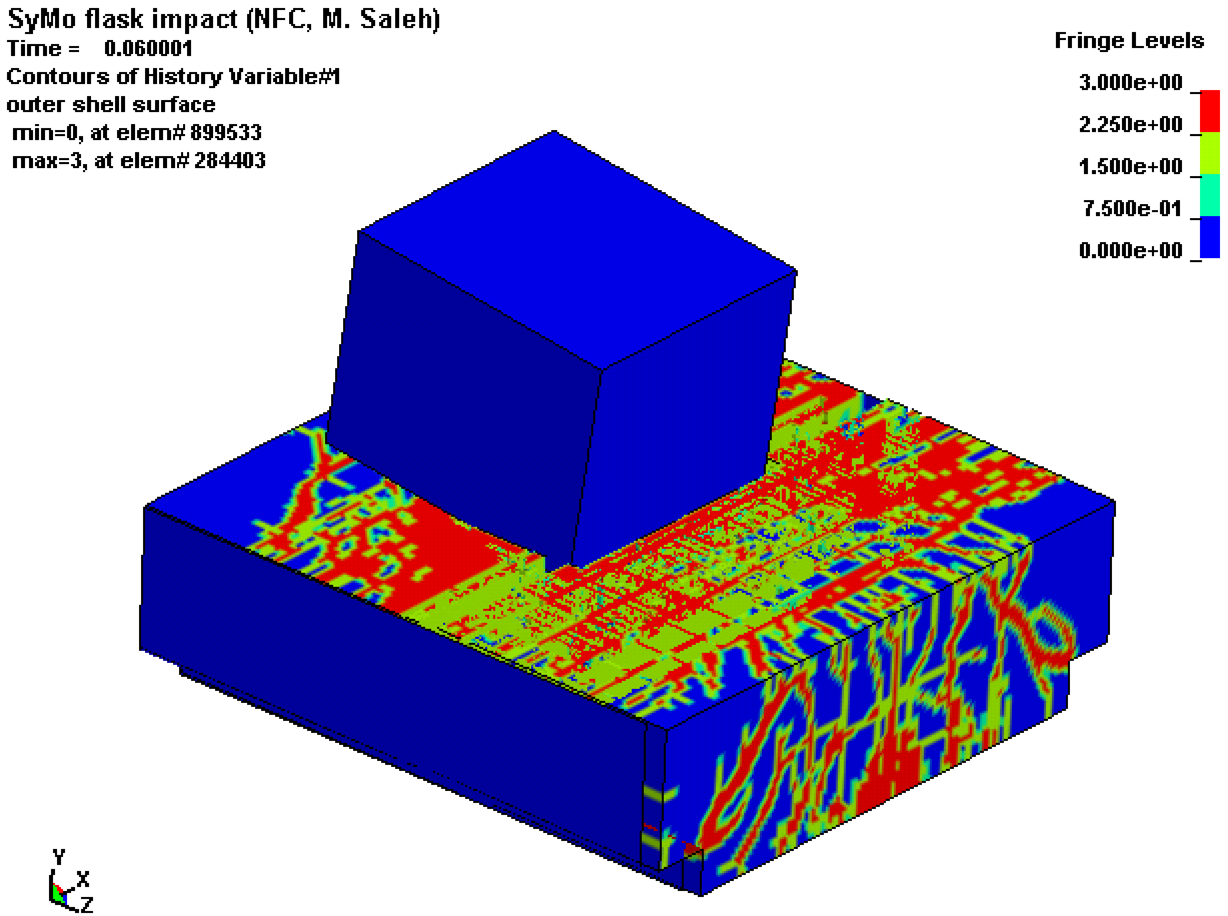
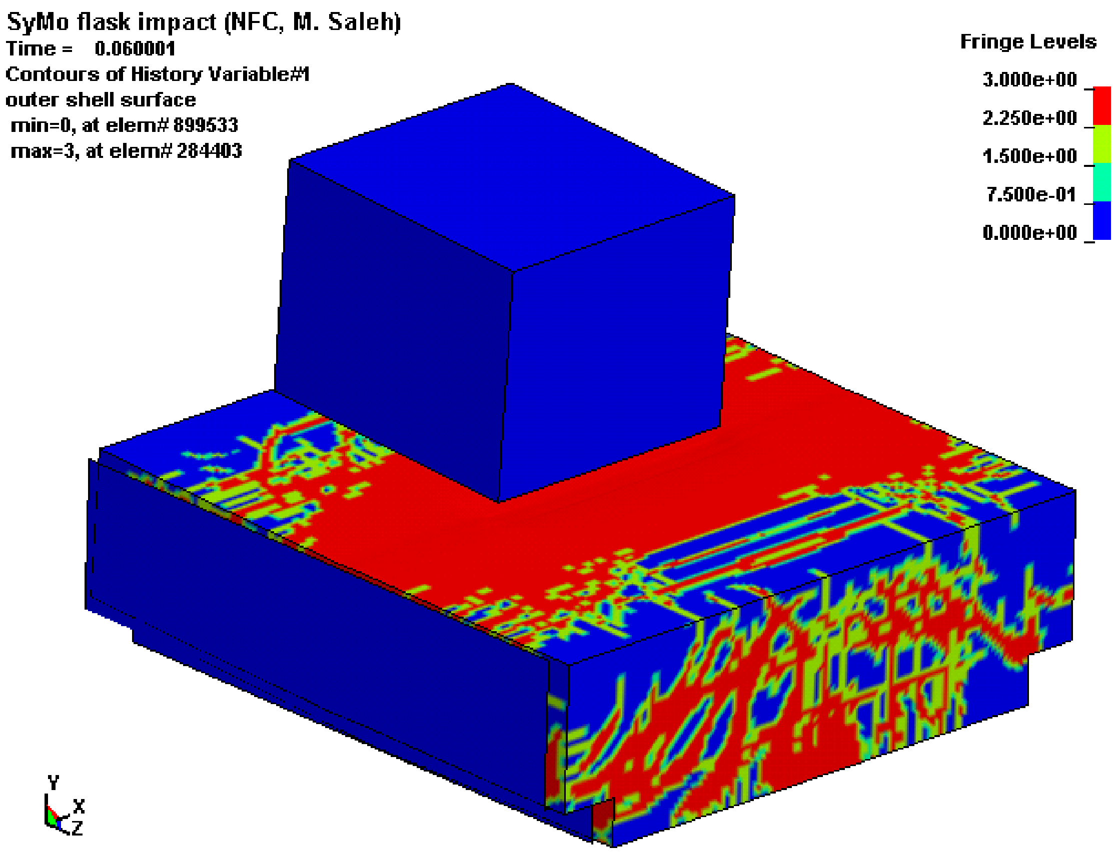
Damage evolution





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).

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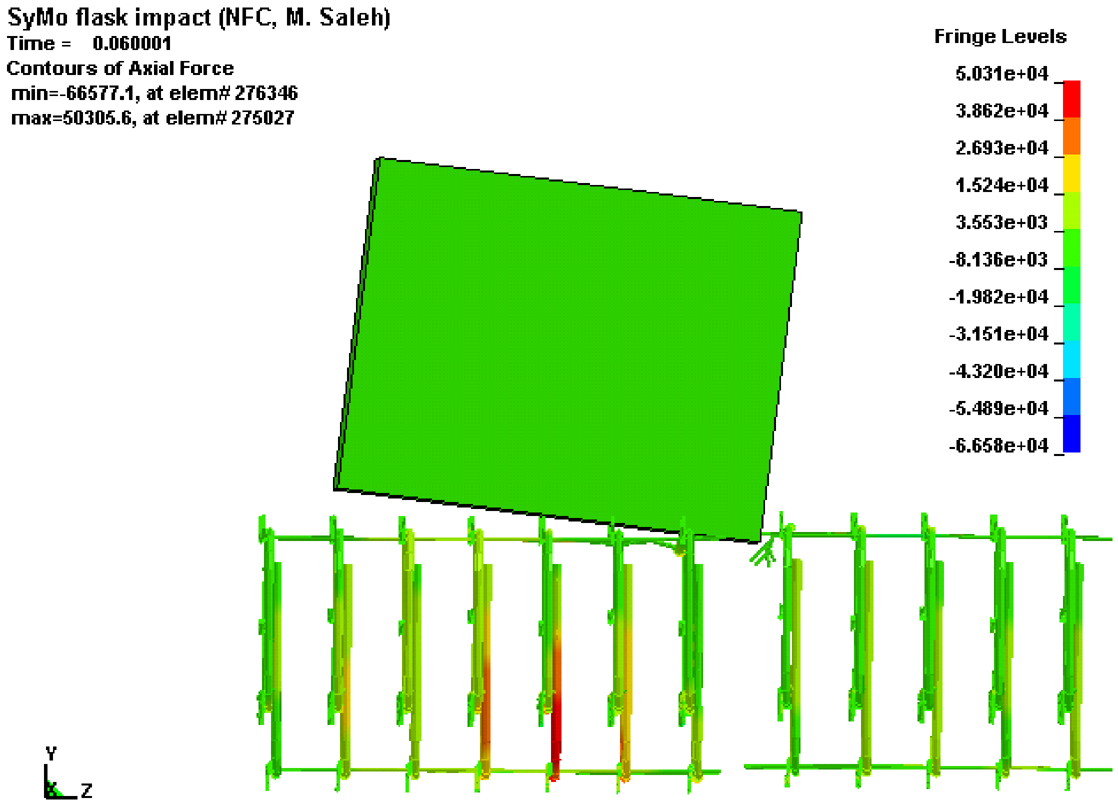
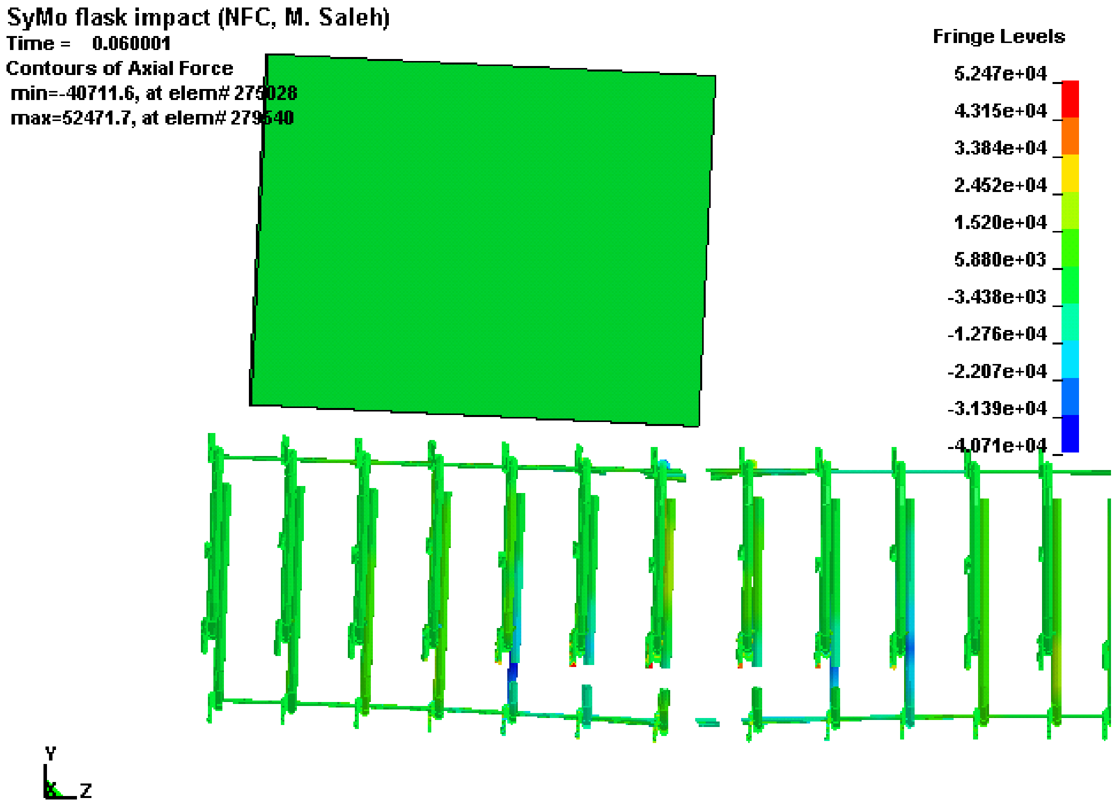
Steel Reinforcement response





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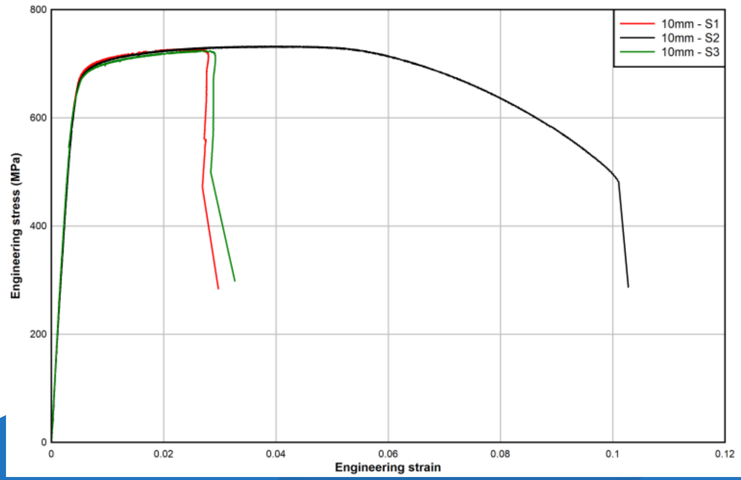
New Experimental Program

- Panels were designed and tested using CAD and FE simulations to ascertain likely deformations based on ANSTO input. These were then manufactured with a single layer of reinforcement.
- The purpose built blast simulator at the National Facility for Physical Blast Simulation (NFPBS) at UOW generates shockwave down its chamber, mimicking the behaviour of real blasts.
- A series of experiments were conducted using the NFPBS to develop better understanding of the mechanical response of reinforced concrete (RC) nuclear containment structures to shock loadings. Laboratory qualification of concrete properties were also carried out.
- These experiments included specimens representing several typical designs of RC walls of varying strengths and steel/fibre reinforcement.

NFPBS



Tensile testing of steel reinforcement

Compression tests

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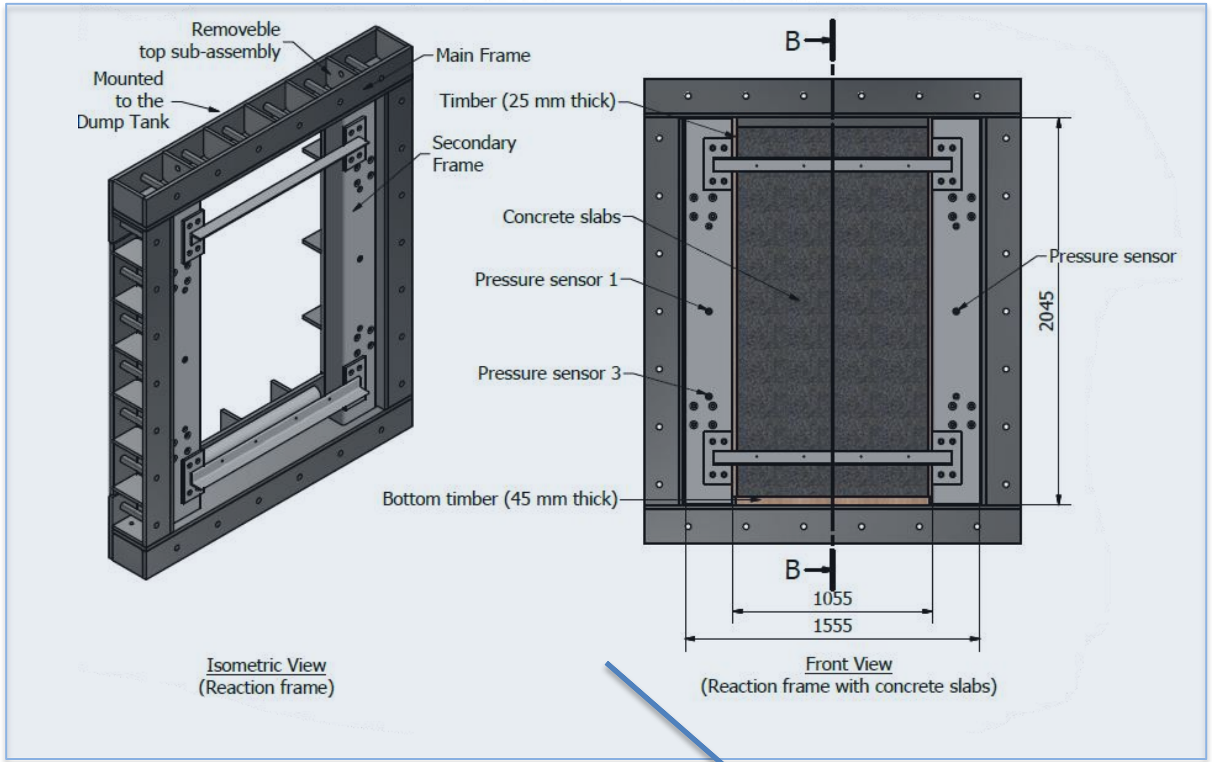
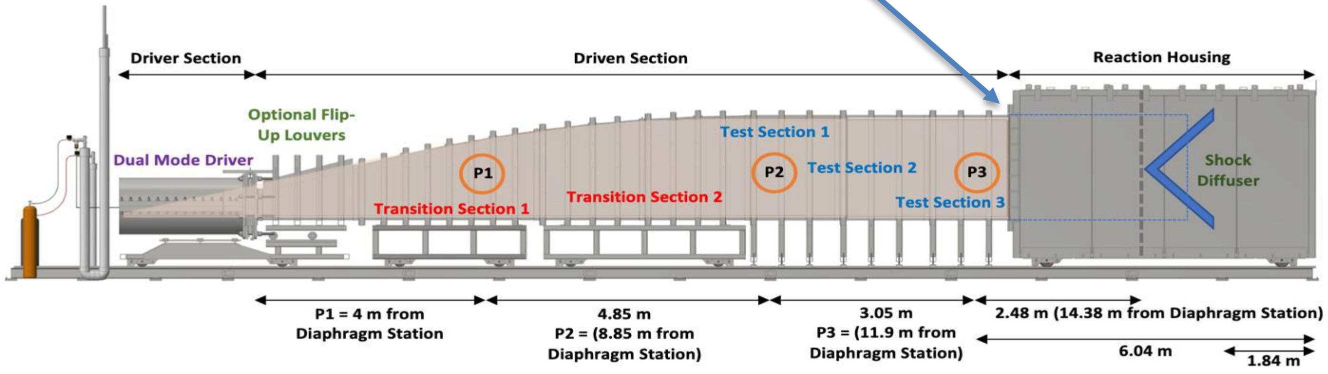
The NFPBS facility was operated in the GD (gaseous detonation) mode where combustible gases, e.g. acetylene (C2 H2) and ethylene (C2 H4), are detonated in the presence of air and/or oxygen.

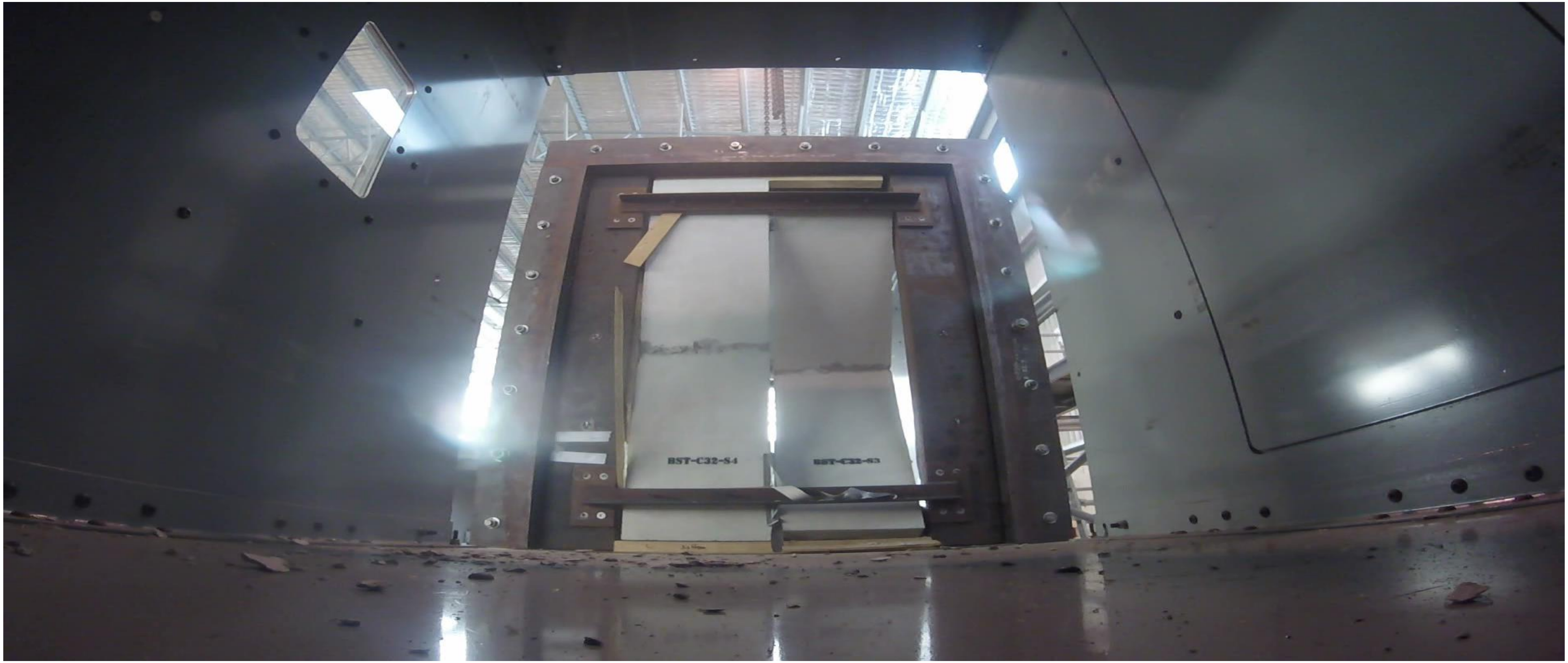
The resultant shock wave propagates downstream in the simulator containment volume. GD mode is capable of generating much higher shock levels than CG (compressed gas) mode and has the operational advantage of not requiring the setup of a frangible diaphragm





National Facility for Physical Blast Simulation (NFPBS)

Blast Testing of Concrete Panels using Advanced Blast Simulator at UOW



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Blast testing of RC panels in support of concrete model calibration – NSC vs HSC

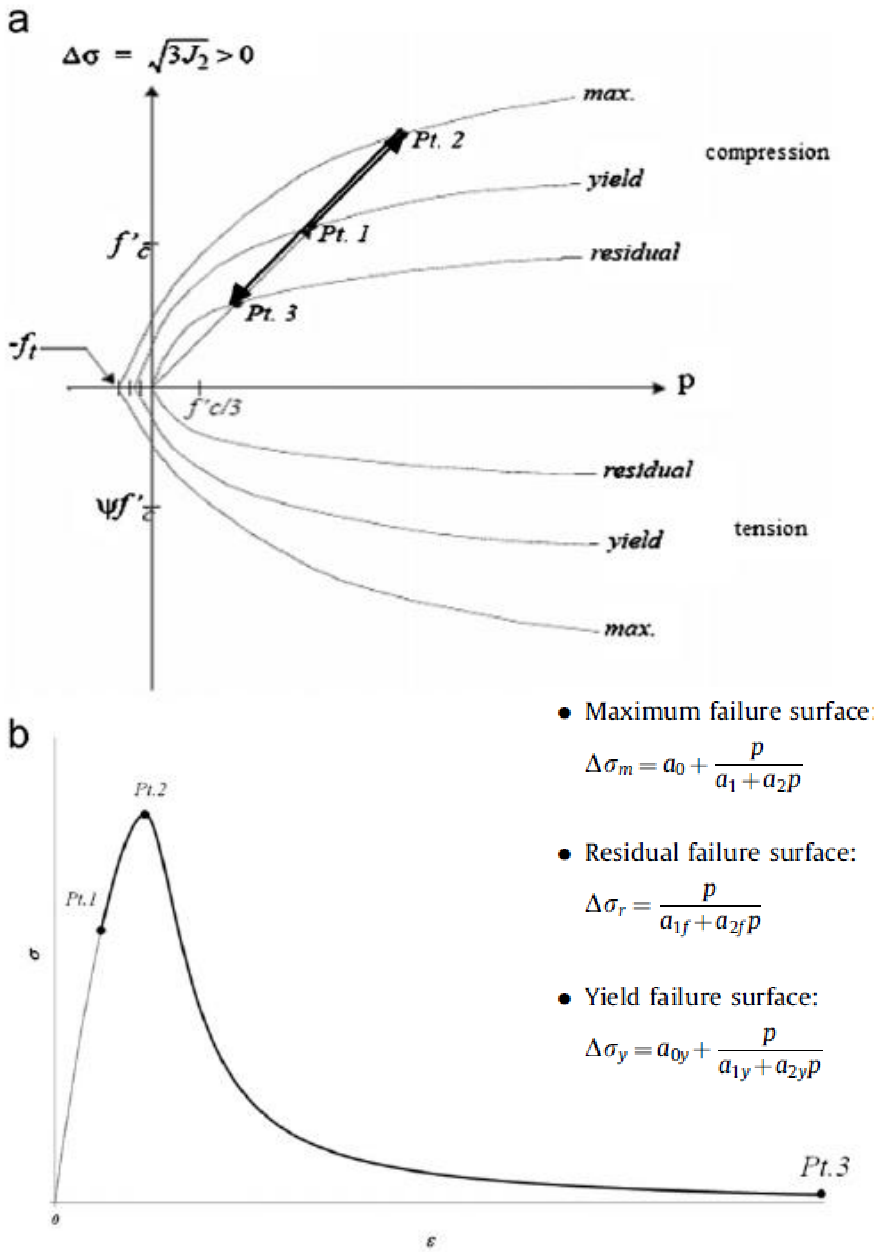
45 MPa 100 MPa

Blast side Protected side

K&C model

The three-invariant model consider the plasticity, strain-rate effects, and damage based on the three independent strength surfaces.
The model incorporates:

- Damage evolution and accumulation (b1, b2 and b3 parameters and $\eta - \lambda$ pairs)
- Confinement effects
- Strain rate effects (DIF)
- Elastic and plastic behaviour



- Maximum failure surface:

$$\Delta\sigma_m = a_0 + \frac{p}{a_1 + a_2 p}$$

- Residual failure surface:

$$\Delta\sigma_r = \frac{p}{a_{1f} + a_{2f} p}$$

- Yield failure surface:

$$\Delta\sigma_y = a_{0y} + \frac{p}{a_{1y} + a_{2y} p}$$

N. Markovich et al. / Finite Elements in Analysis and Design 47 (2011) 1280–1290

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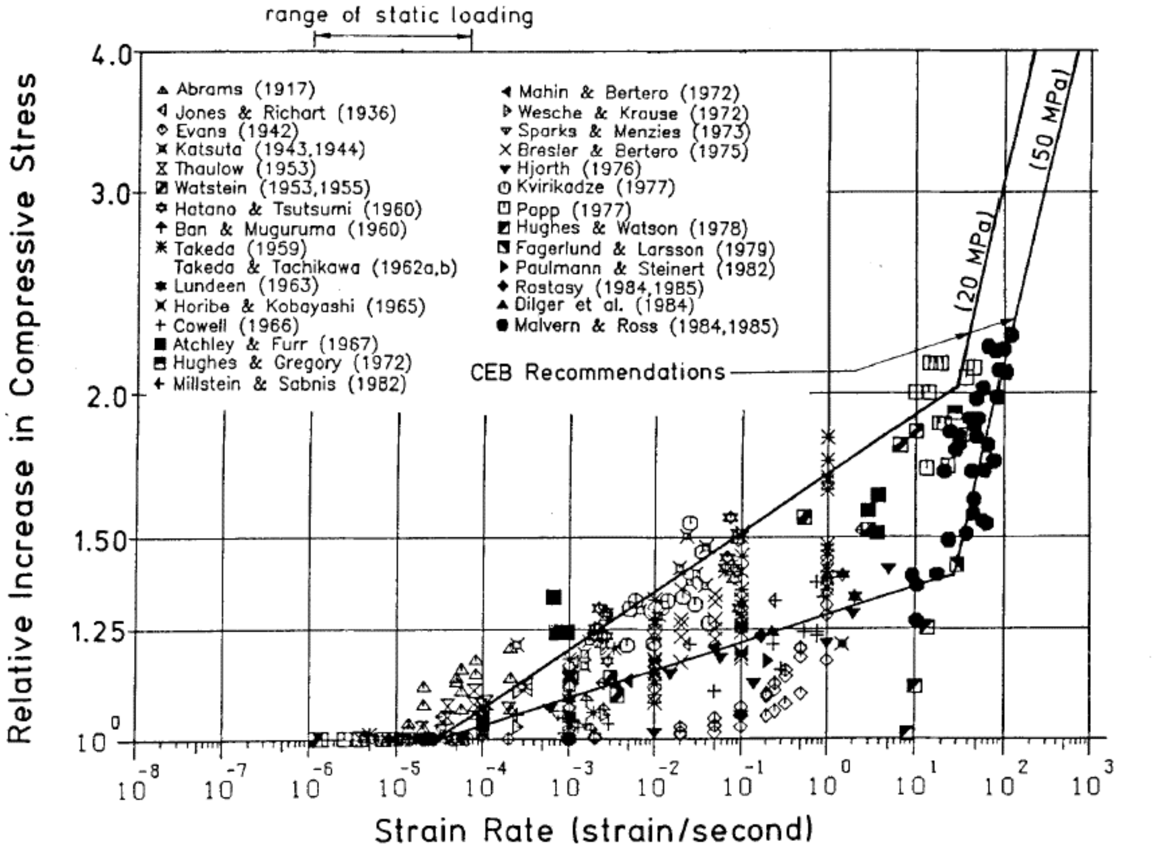
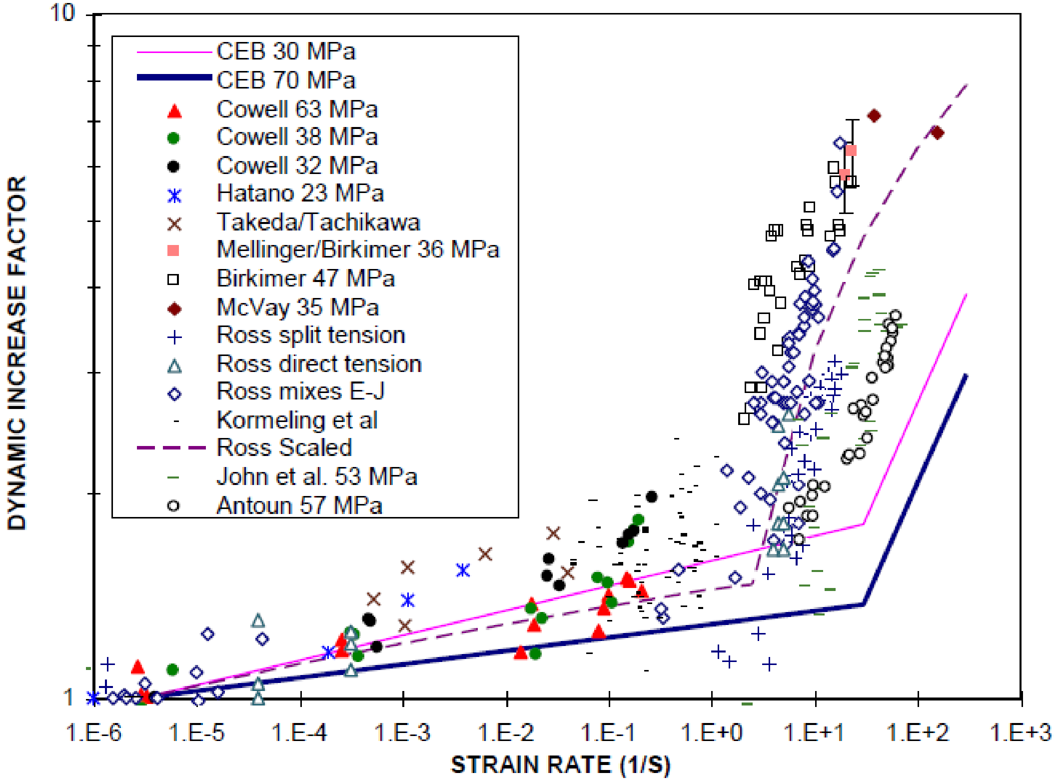
DIF and strain rate sensitivity



Compressive DIF



Tensile DIF

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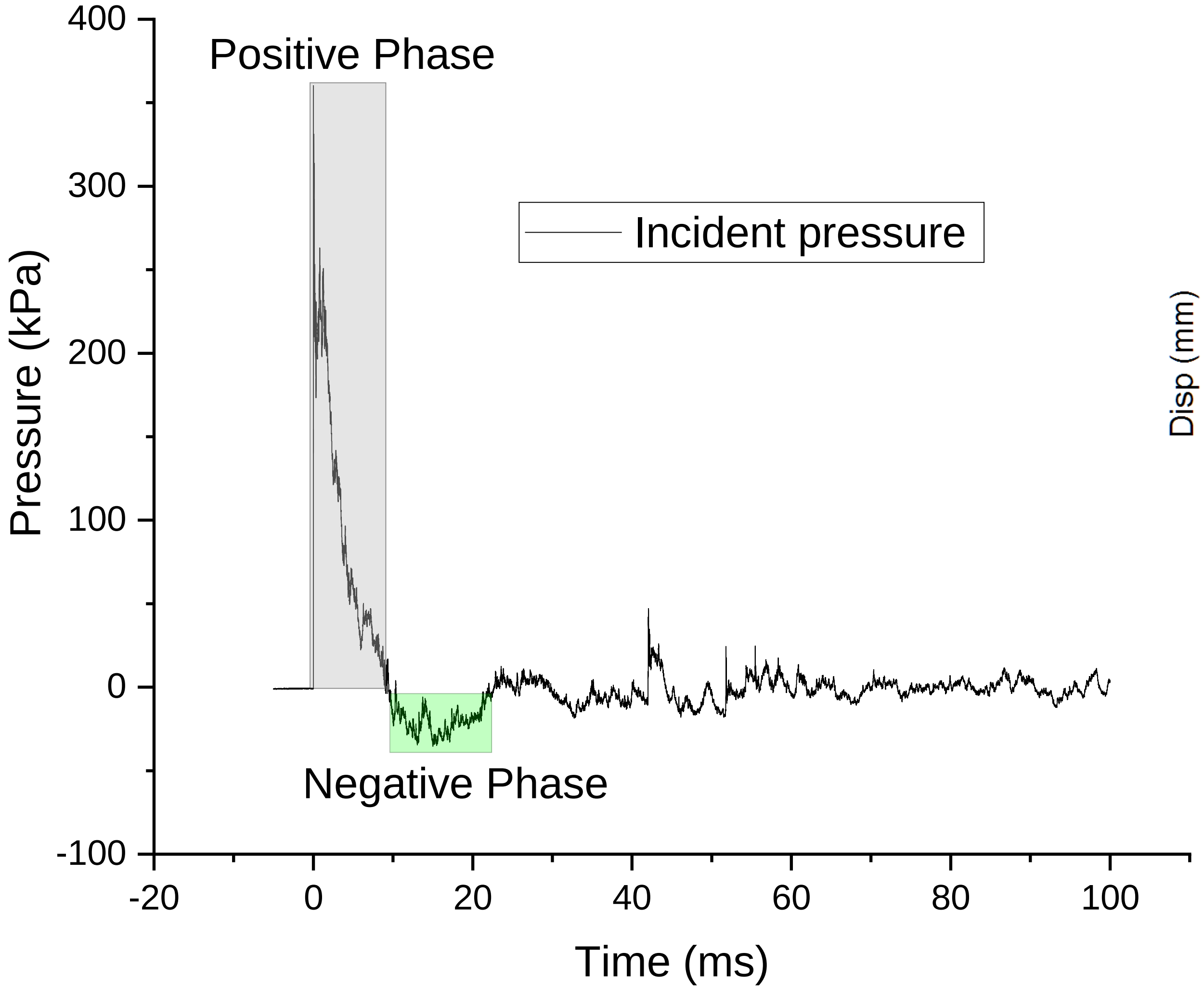
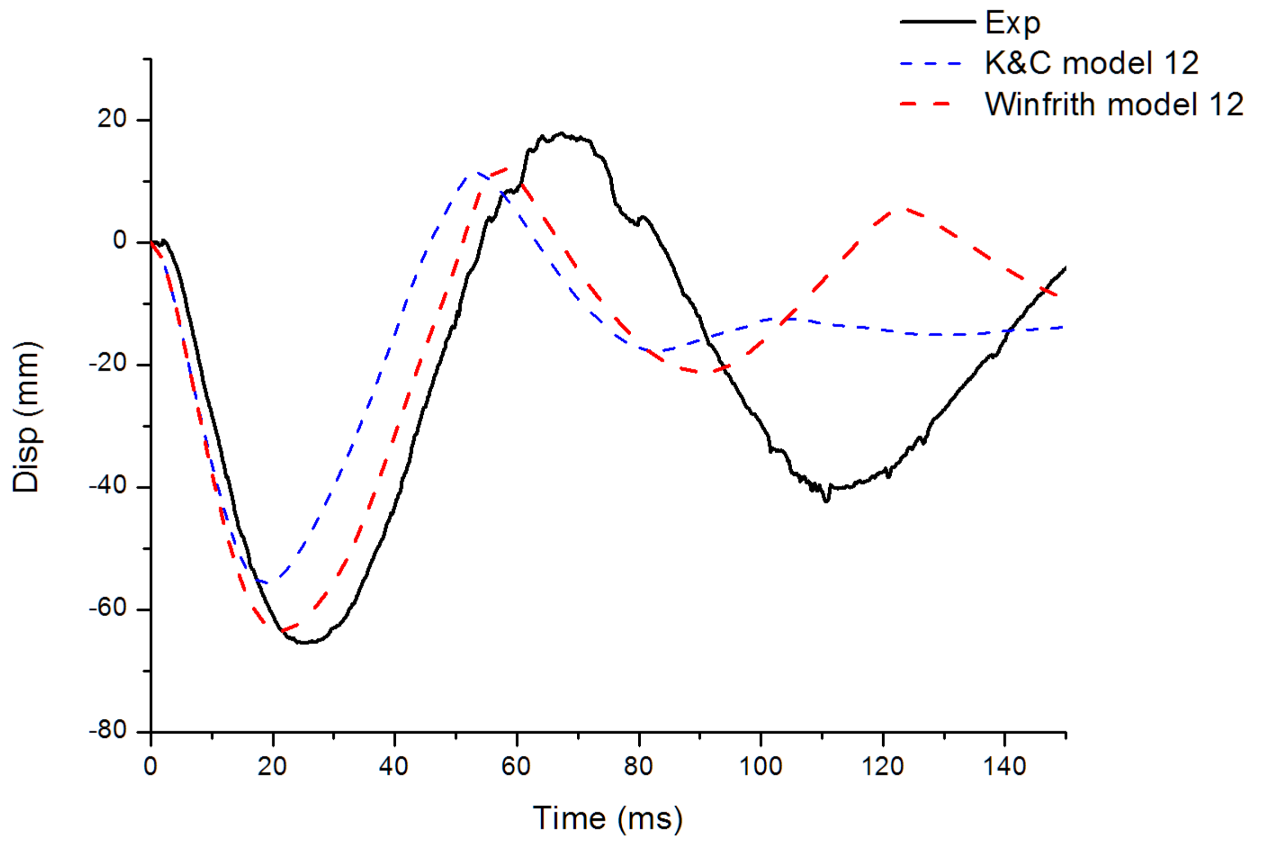
Blast testing of RC panels in support of concrete model calibration – HSC





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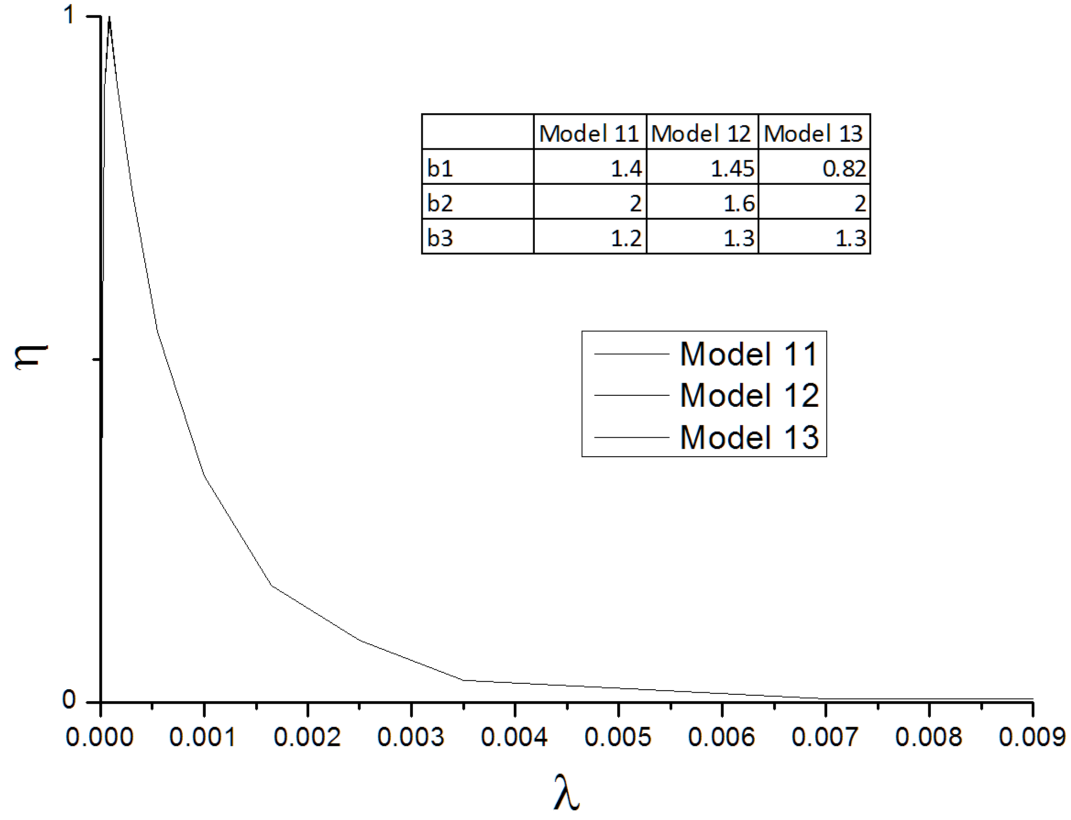
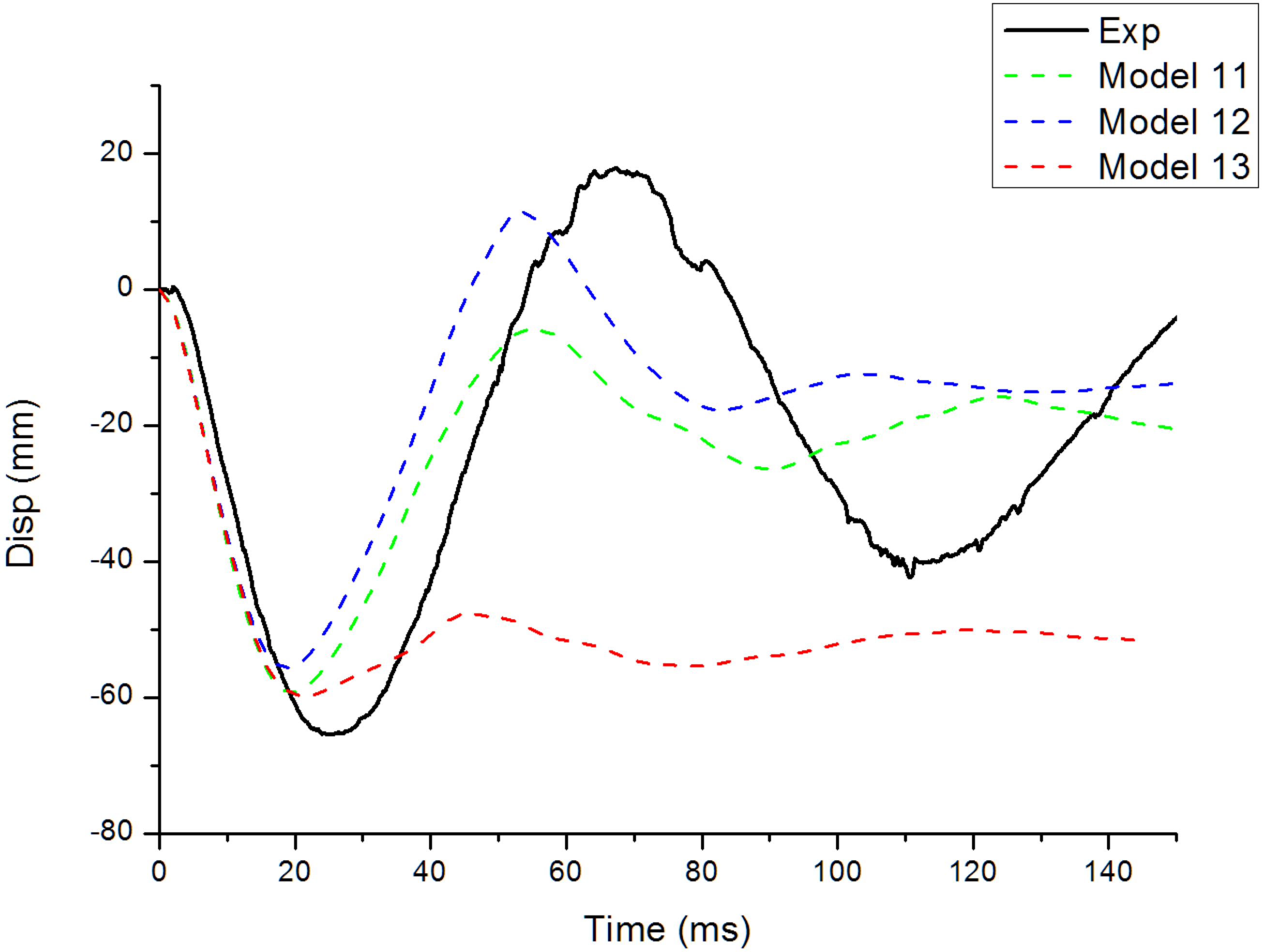
K&C model sensitivity

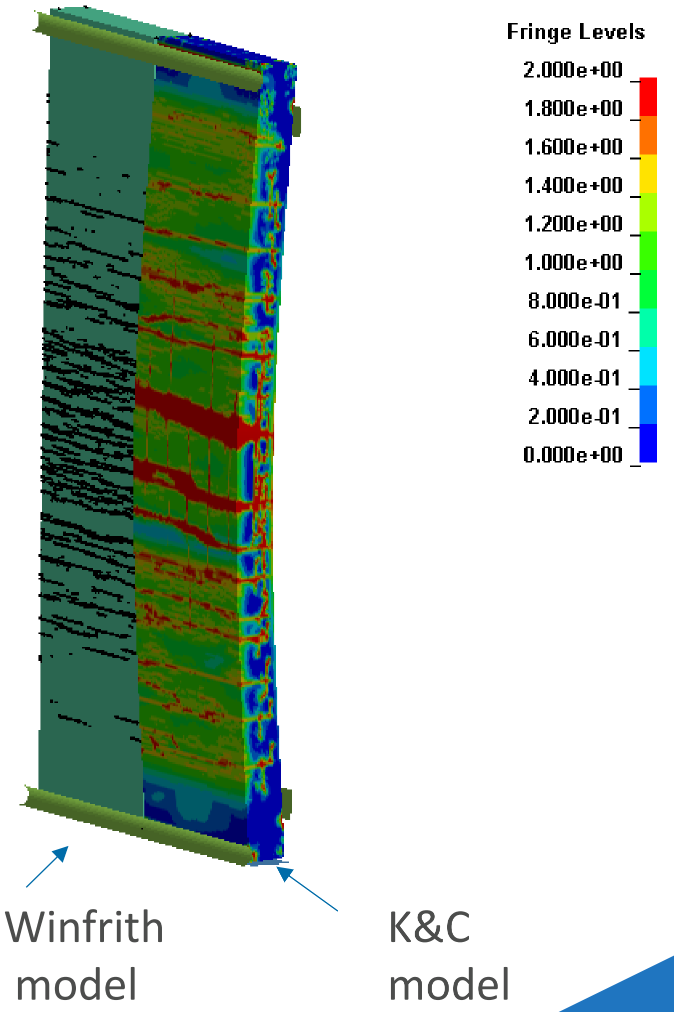


	Model 11	Model 12	Model 13
b1	1.4	1.45	0.82
b2	2	1.6	2
b3	1.2	1.3	1.3



Concrete models (Winfrith and K&C)

- Initial calibration of the K&C model show the resultant displacement are more aligned to the experiment for the initial peak displacement. The rapid softening and damage evolution leads to premature cracks and deviations in the rebound peaks.
- Literature sourced data deviate from our current results and overpredict the damage evolution. Current results exhibit good repeatability.
- The Winfrith model can predict the initial and some of the subsequent peaks-troughs and is qualitatively more aligned to the global response.
- Ongoing work has sought to better calibrate the K&C model as it allows for greater application for the analysis of confined concrete.
- The percentage or reo is seen to have a dramatic effect on the blast response, increasing the reo diameter from 10 mm to 12 mm reduced the peak displacement but also compressed the structural response frequency.



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Future direction

- Conventional and high strength concrete panels were blast tested using NFPBS.
- New blast testing of fibre (Dramix) reinforced concrete is yet to be finalised, alongside qualification of concrete strength through laboratory testing.
- The multi-disciplinary team is utilising a number of techniques that leverage their respective expertise and facilities to accelerate the development of these panels and building predictive models.