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The importance of considering realistic blast waveforms and corresponding methods of assessing structural damage when conducting quantitative risk assessments

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Introduction

- The first edition of the CCPS guideline for estimating lethality for building occupants within petrochemical buildings subjected to blast hazards was based on building construction type and peak overpressure
- This method allows for a quick screening of building occupant vulnerability but does not include the effects of the duration of the blast that the buildings are subjected to
- Blast hazards within petrochemical facilities include vapour cloud explosions (VCE), BLEVEs, and bursting pressure vessels
- Vapour cloud explosions can include both deflagrations having long blast durations and detonations having much shorter durations
- The second CCPS edition eliminated this simple table and provided occupant vulnerability as a function of building damage and construction type but did not provide a way to correlate the blast loading with building damage

Introduction

- The missing damage-to-blast correlation must be determined in order to conduct quantitative risk assessments
- A range of simplified tools are available for assessing the response of structural components and whole buildings to blast loads.
  - Single Degree of Freedom (SDOF) models
  - Pressure-Impulse (P-I) iso-damage charts
  - These simplified tools generally do not account for the complex response and failure of real structures or the difference in response to different forms of blast loading
  - Iso-damage charts may be based upon historical data gathered from a range of sources and are often based upon blast damage caused by High Explosive (HE) detonations

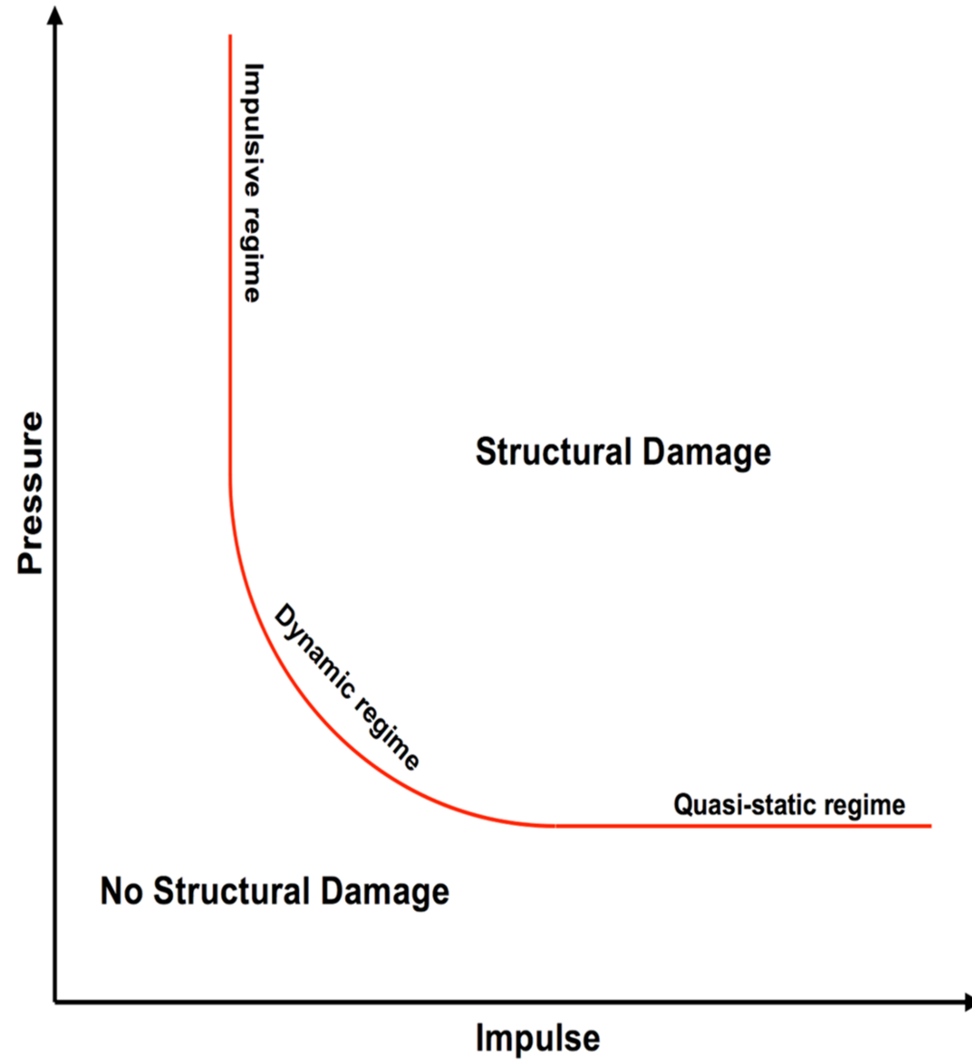
Overview

- This paper briefly presents a detailed assessment of damage to a specific building component caused by a range of blast load waveforms
- The building component is based upon the Northgate Building that was moderately-to-severely damaged during the 2005 Buncefield explosion
- Blast loads resulting from vapour cloud and high explosive detonations are calculated using high-fidelity Computational Fluid Dynamics (CFD) simulations
- Structural response is calculated using Finite Element (FE) simulations
- P-I iso-damage curves are developed using these techniques as well as simplified SDOF methods
- P-I iso-damage charts are presented and the differences between the responses to different blast load forms are highlighted
- The importance of considering the blast load waveform is evaluated

Buncefield VCE:
Damage to RC cladding panels on Northgate Building

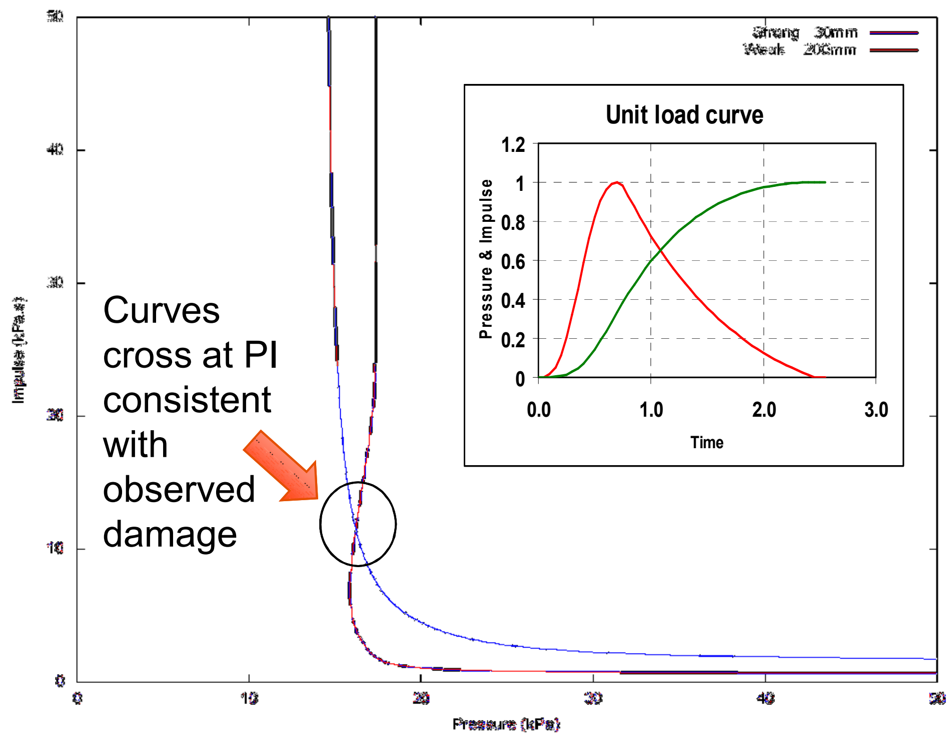
Pressure-Impulse (PI) iso-damage curves

- Simple and often used means of relating structural damage to transient (blast) loading
- Peak pressure, impulse and duration of loading are accounted for
- A single curve is a transition from one damage level to another. A set of curves represents a range of damage levels
- Curves can be generated analytically, numerically or by physical testing but are specific to the shape of the applied load curve



Buncefield VCE:
Damage to RC cladding panels on Northgate Building

- Two sets of near-identical RC panels
- Slightly different levels of reinforcement: two different damage levels.
- Discrepancy in damage “brackets” the unknown applied loads which can be back-calculated:



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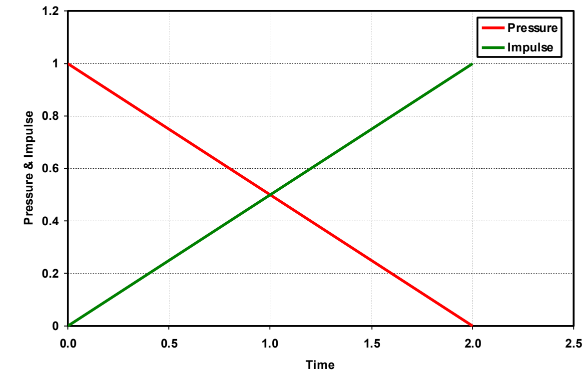
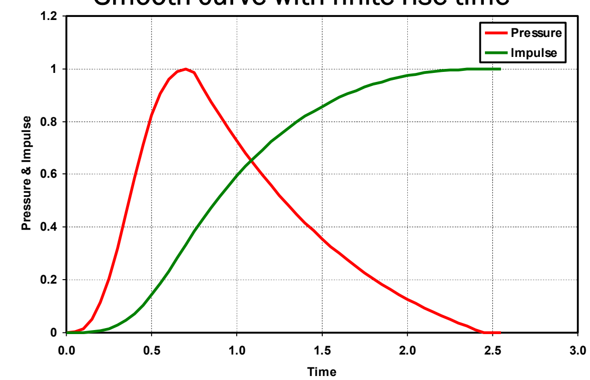
Shape of the blast waveform

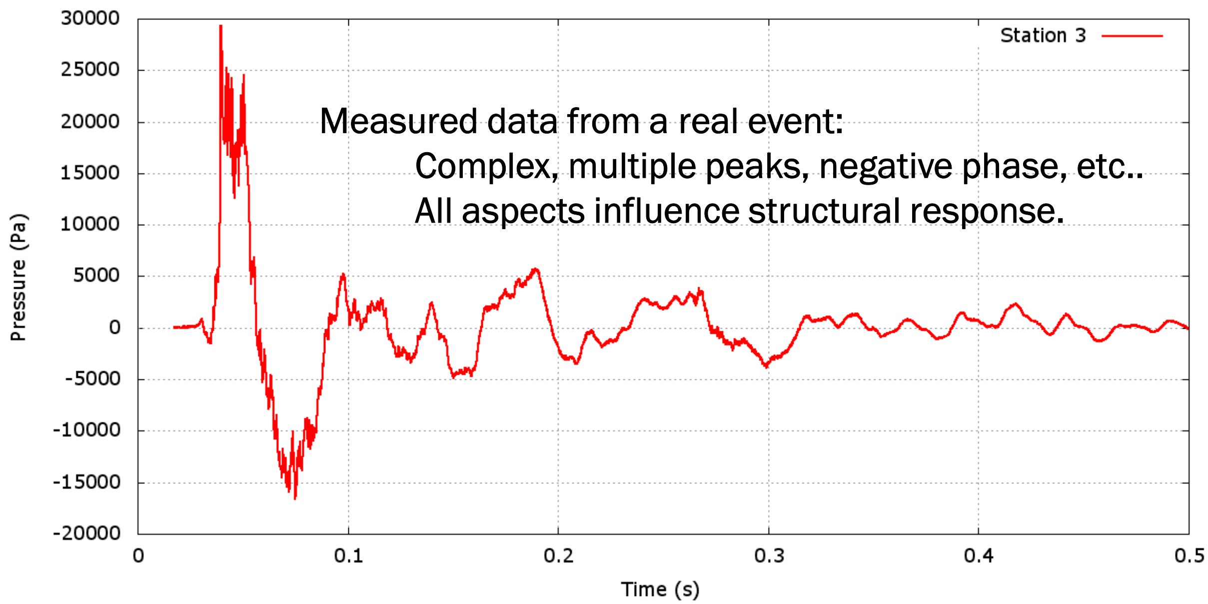
- The shape of the blast waveform is important: structural response is different for different blast forms.
- Simplifying assumptions regarding the blast waveform can result in significant inaccuracies in predicted structural response.

Simplified external HE:
Triangular with instantaneous rise



Simplified external VCE:
Smooth curve with finite rise time





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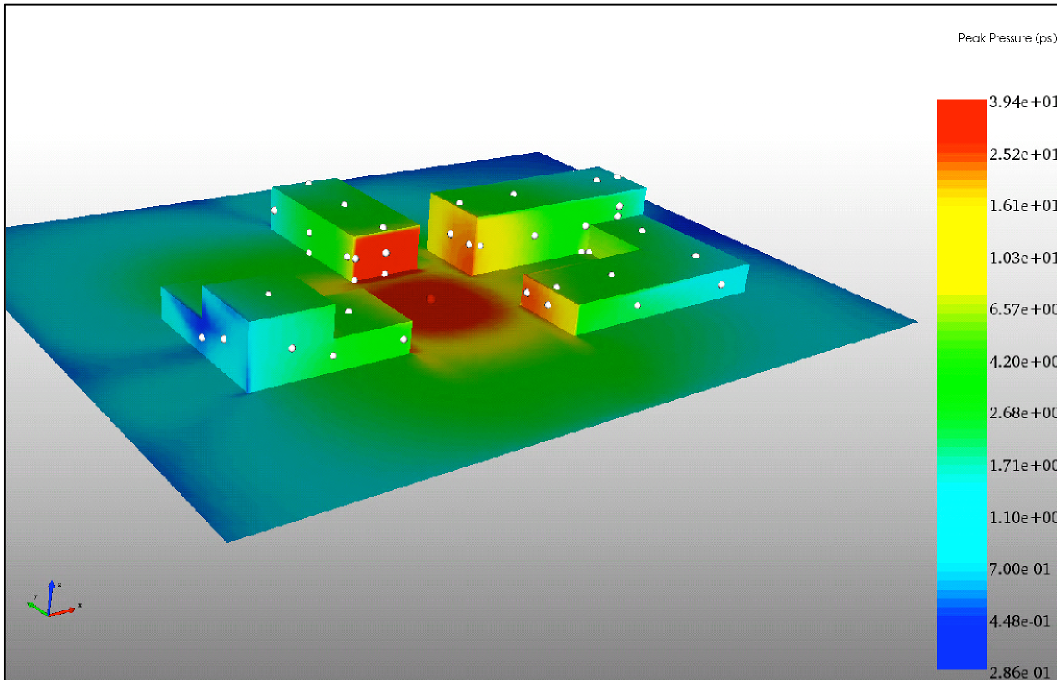
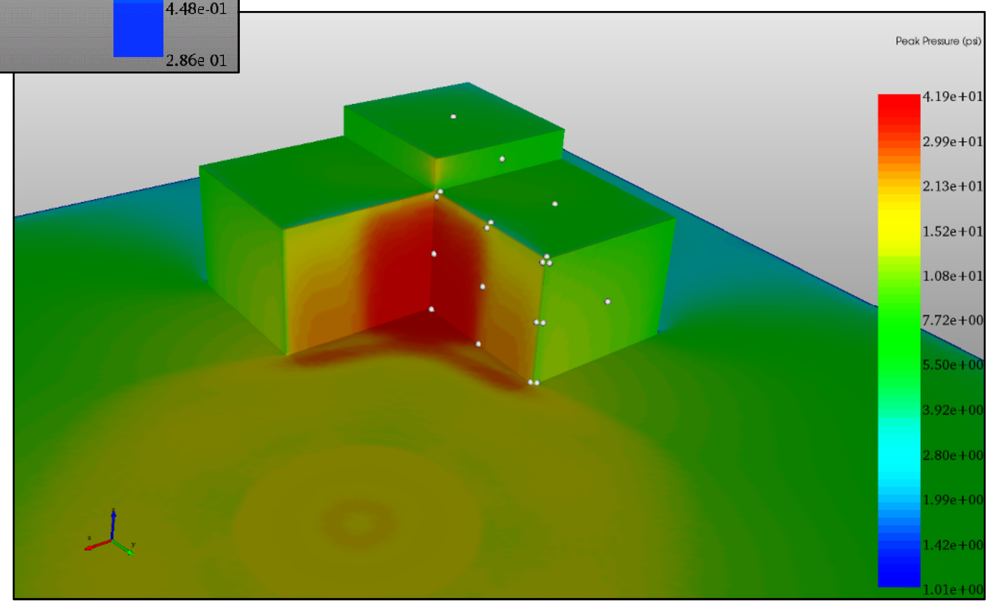
VCFD: numerical simulations of generic VCE scenarios



- A range of generic geometries and VCE scenarios were run to extract “realistic” pressure waveforms
- Using the Thornton Tomasetti VCE FacilityBlast software (a “first-principles” CFD code)
- Multiple VCEs, multiple buildings, multiple virtual pressure gauge locations

- Generate a database of realistic VCE blast waveforms in order to investigate the influence on structural response. Waveforms include the effects of channeling, re-entrant, and shielding effects on buildings



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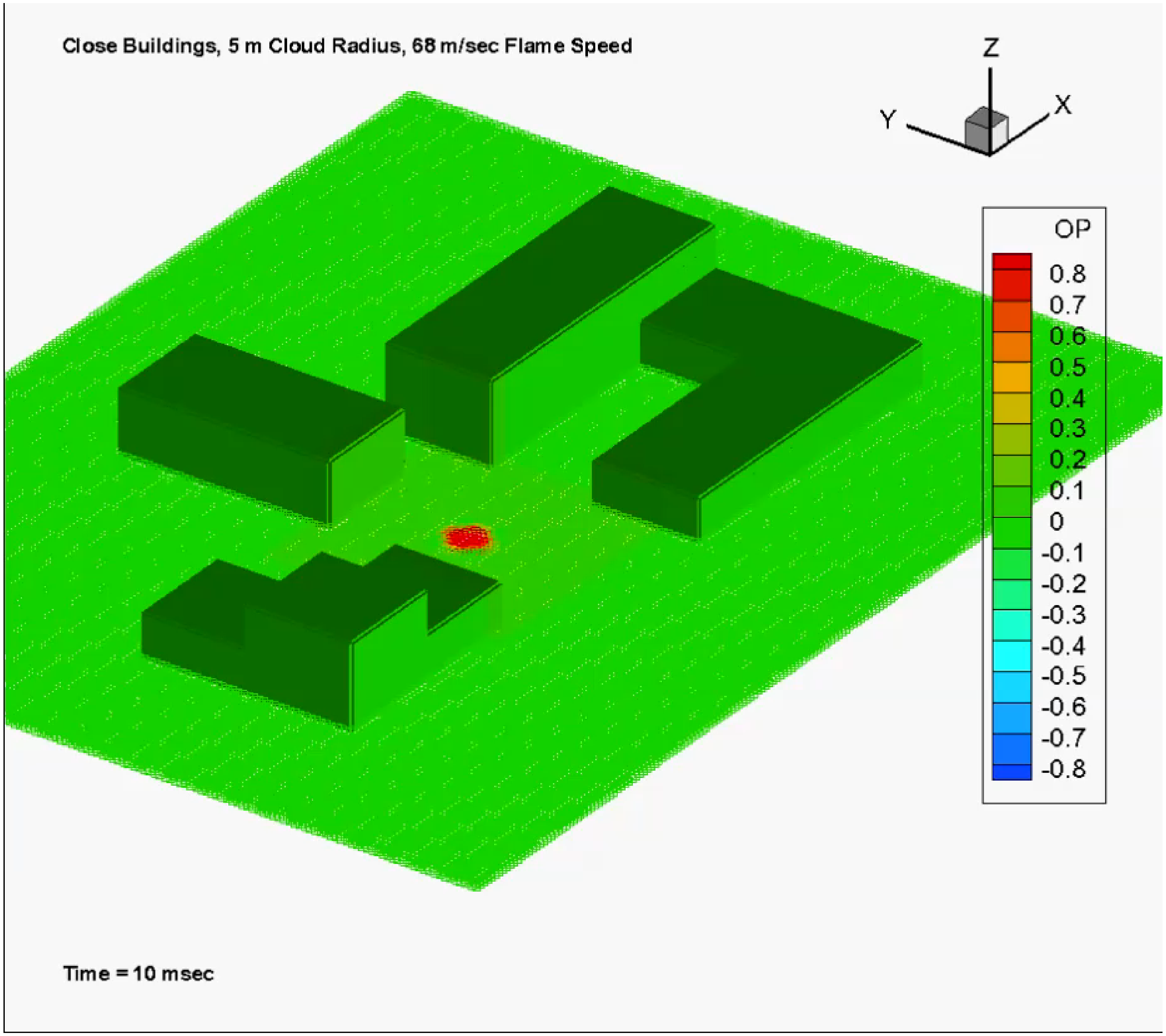
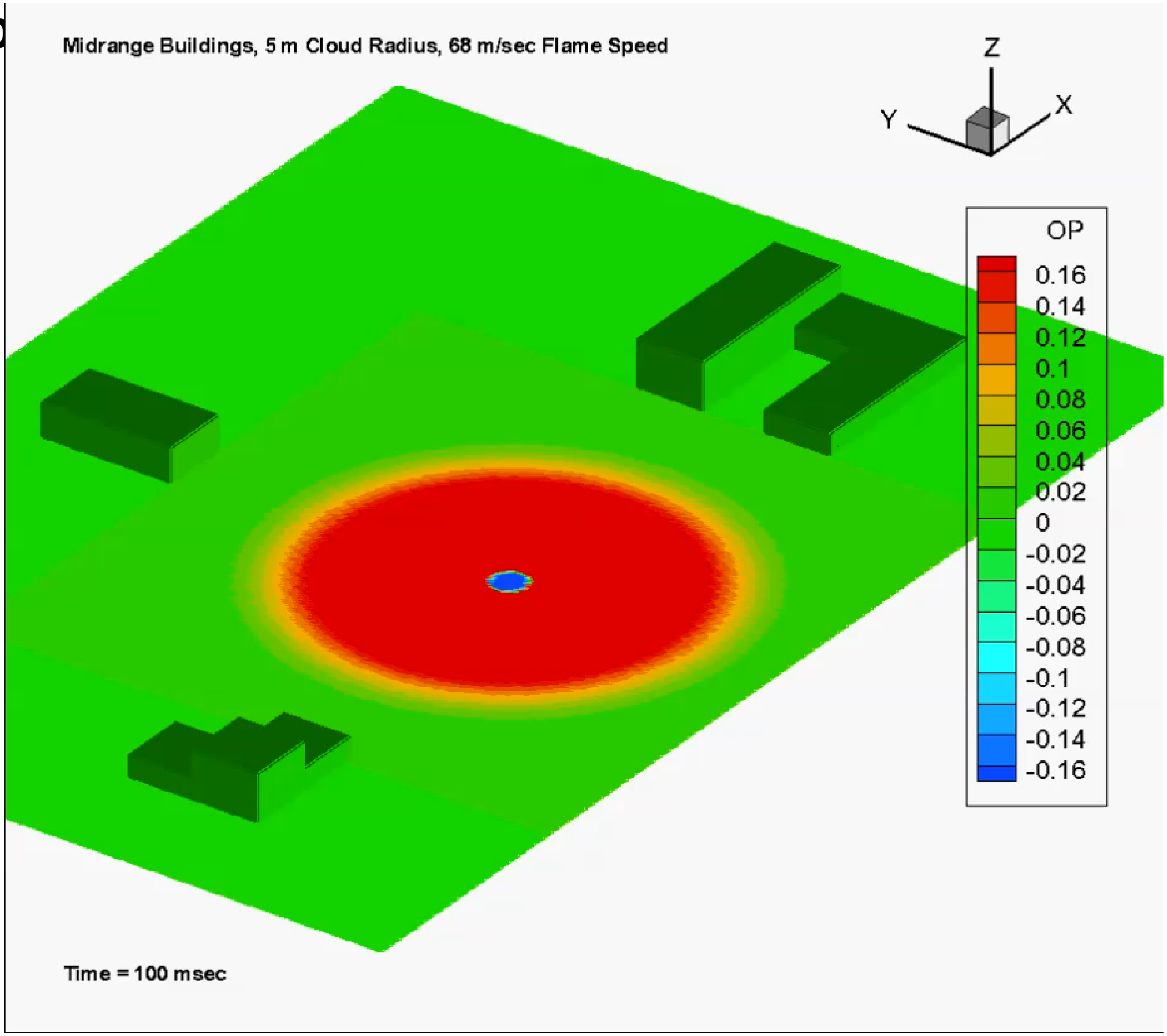
VCE FacilityBlast overpressure (psi) animation: close



VCE FaciltiyBlast overpressure (psi) animation: midrange b



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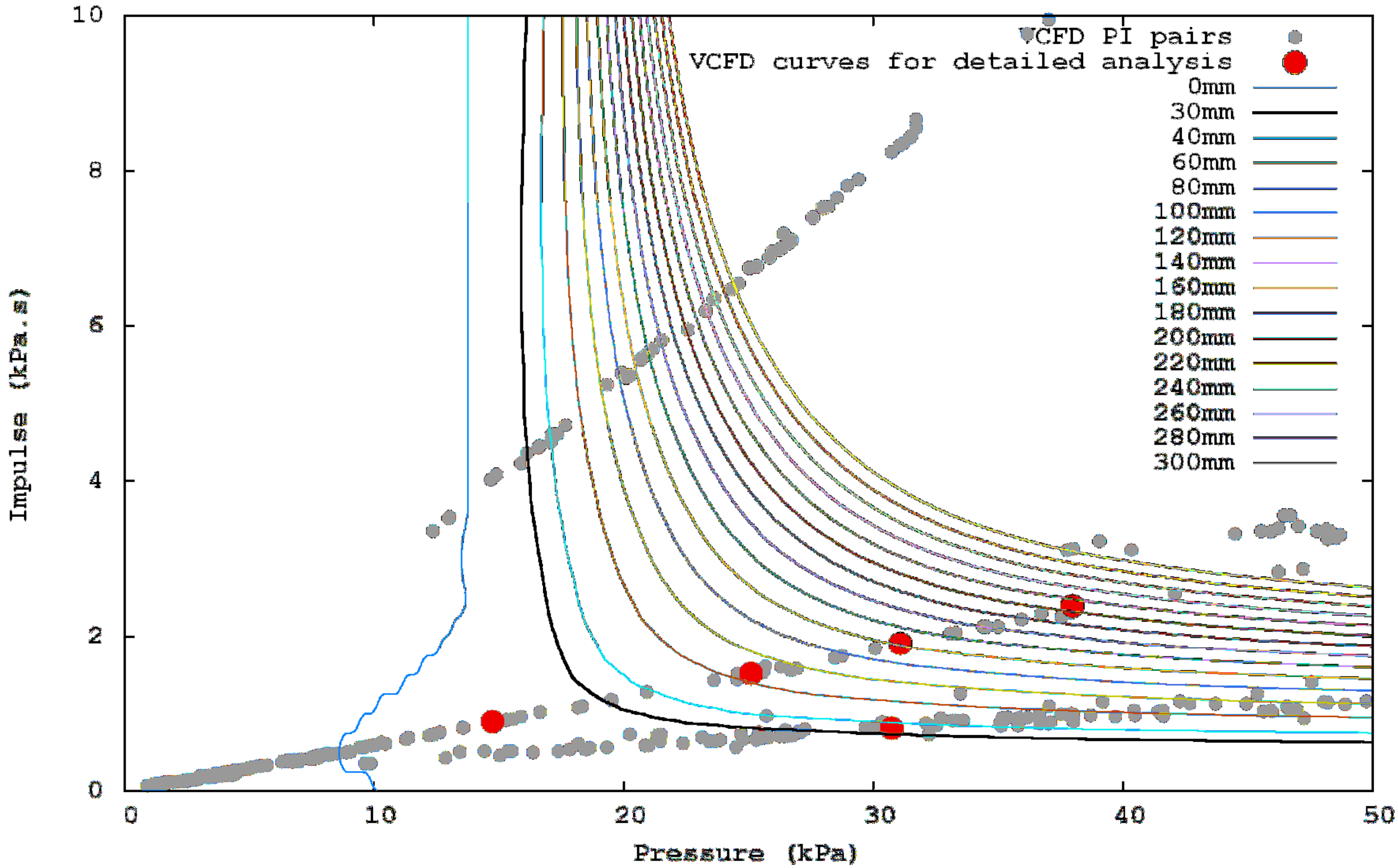
Calculated PI iso-damage curves for RC cladding panel (idealised VCE and SDOF)
Locations of VCFD PI pairs for detailed consideration



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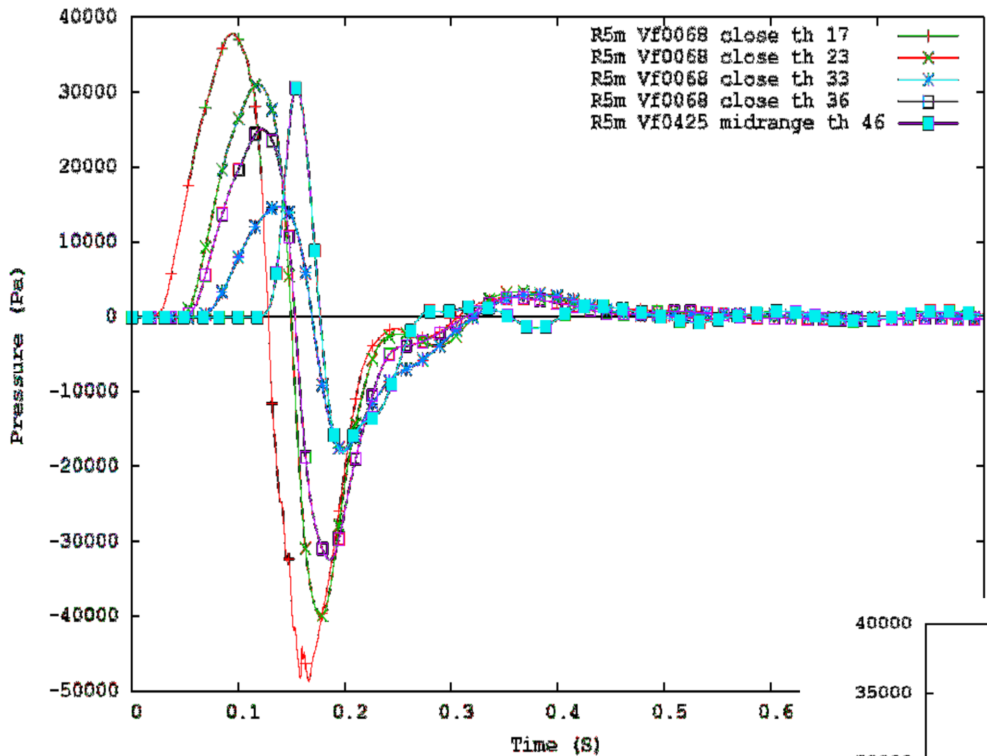
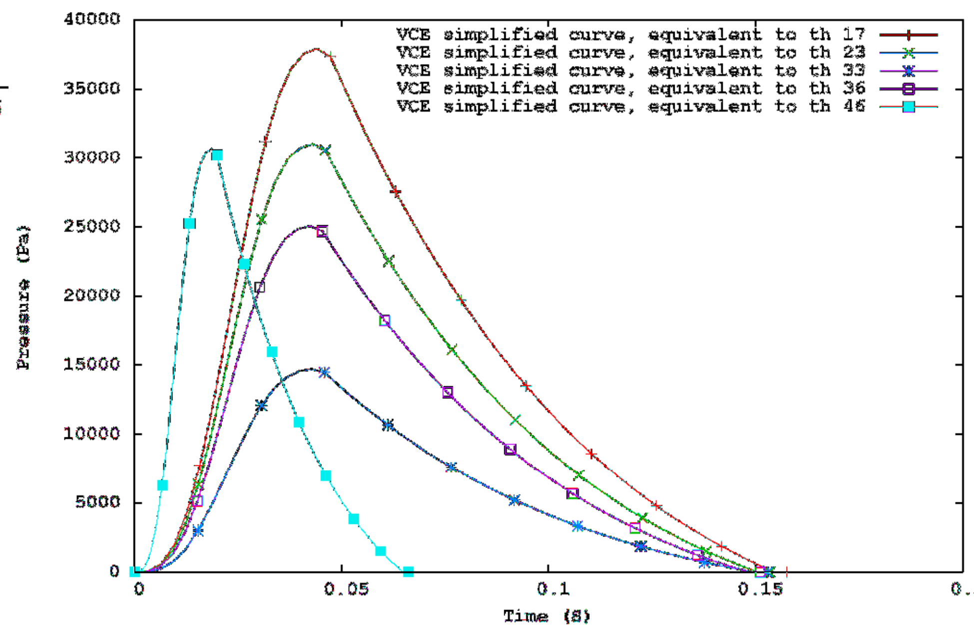
Pressure-vs-time curves, “realistic” and simplified



- Pressures on structures (not free-field)
- Realistic VCE waveforms tended to include a large negative phase
- This negative phase has a significant influence on the final state of loaded structures – demonstrated shortly

- Simplified VCE waveforms with peak pressure and impulse identical to the realistic curves above



Structural response simulations

Analysis methodologies:

- Simplified methods can be used: SDOF models for example.
- More sophisticated approaches may be taken: detailed Finite Element simulations for example.
- Simplified blast load waveforms can be used, or more realistic CFD derived waveforms could be used.

- Consider the following three analysis approaches with varying degrees of simplifying assumption:

Analysis approach	Pressure load waveform	Structural response calculation
1	VCE, simple, positive phase only	SDOF model
2	VCE, complex CFD derived curve	SDOF model
3	VCE, complex CFD derived curve	Detailed FE model

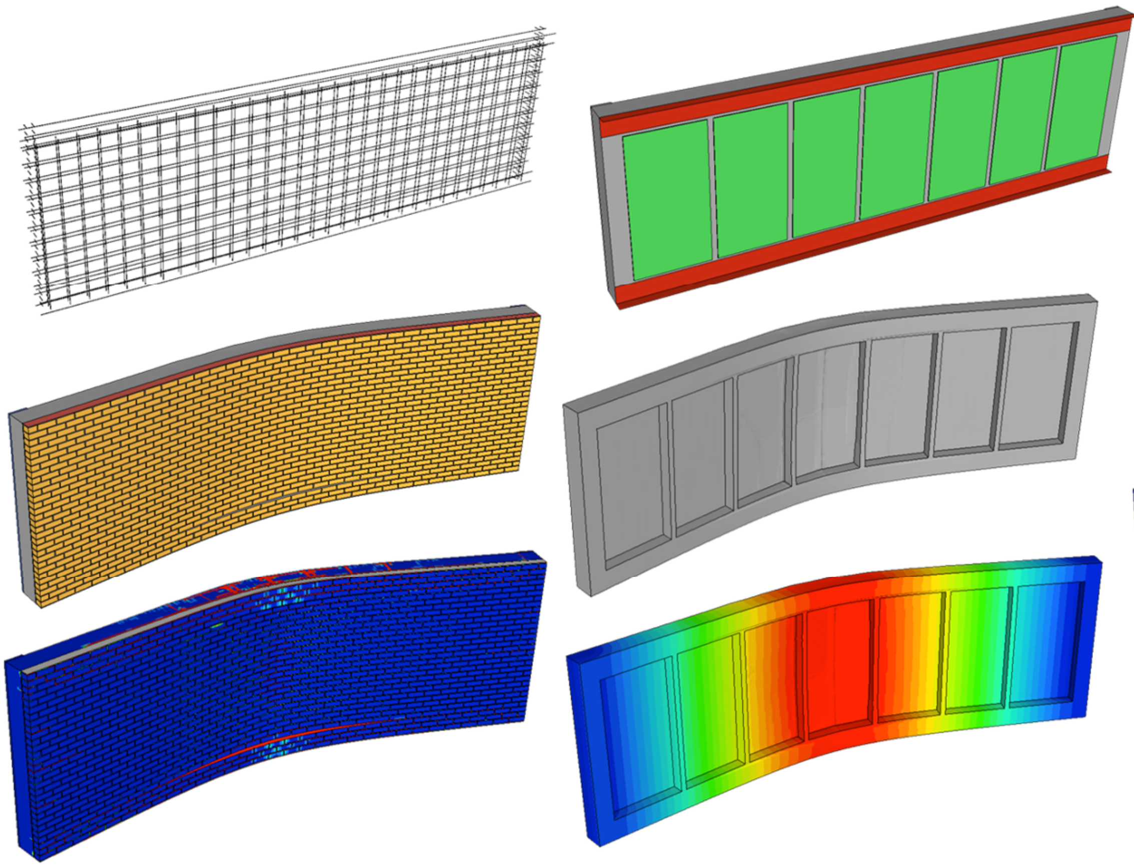
- How significant are the differences in predicted structural response?

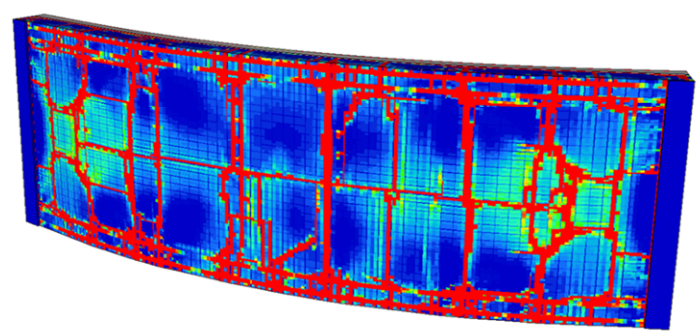
Example of detailed Finite Element simulation of single cladding panel

- Simulations conducted using the Thornton Tomasetti NLFlex explicit transient Finite Element solver
- All relevant details accounted for

Detailed structural simulations include:

- Concrete
- Rebar
- Steel angle sections
- Brick and mortar cosmetic facing
- Foam insulation
- Connections to supporting structure





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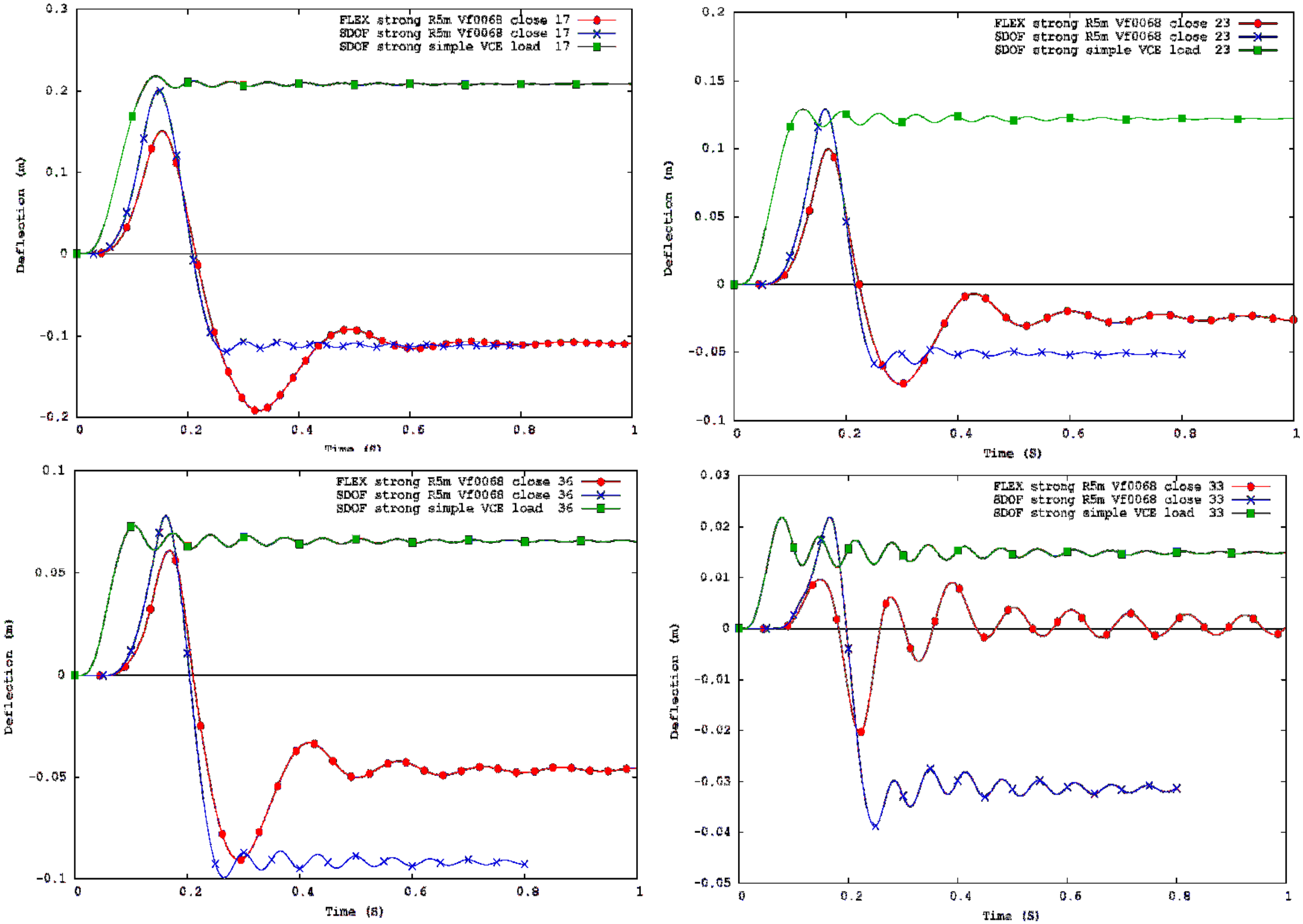
Deflection-vs-time, three different levels of approximation, 4 load cases



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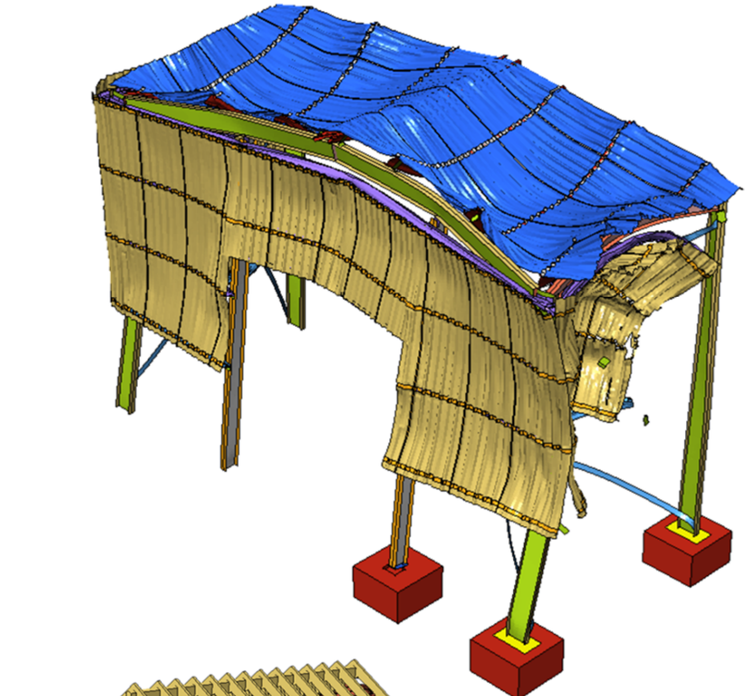
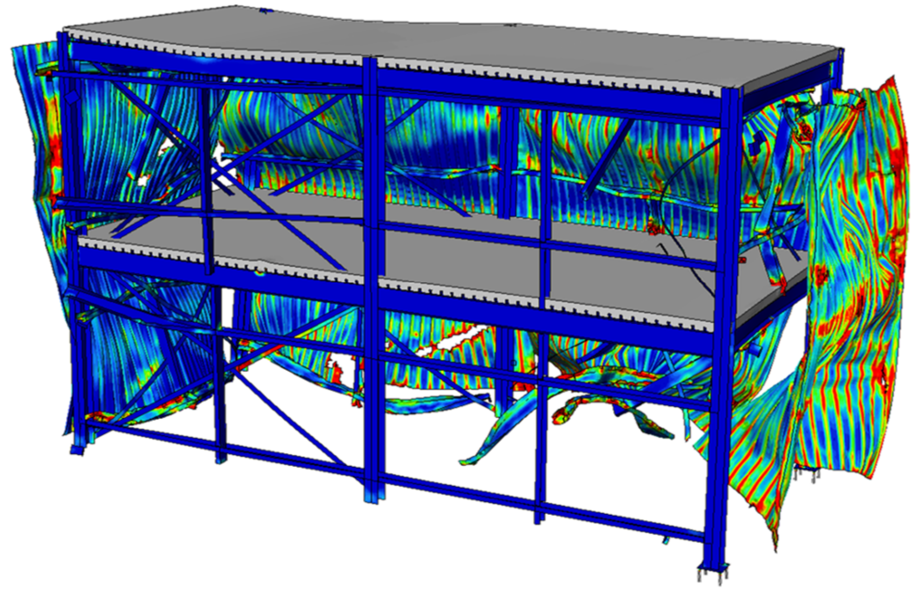
Deflection-vs-time, three different levels of approximation, 4 load cases

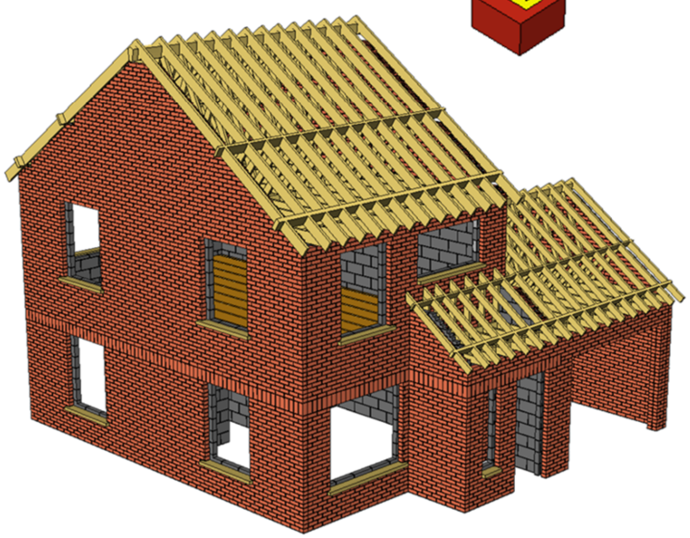
Observations:

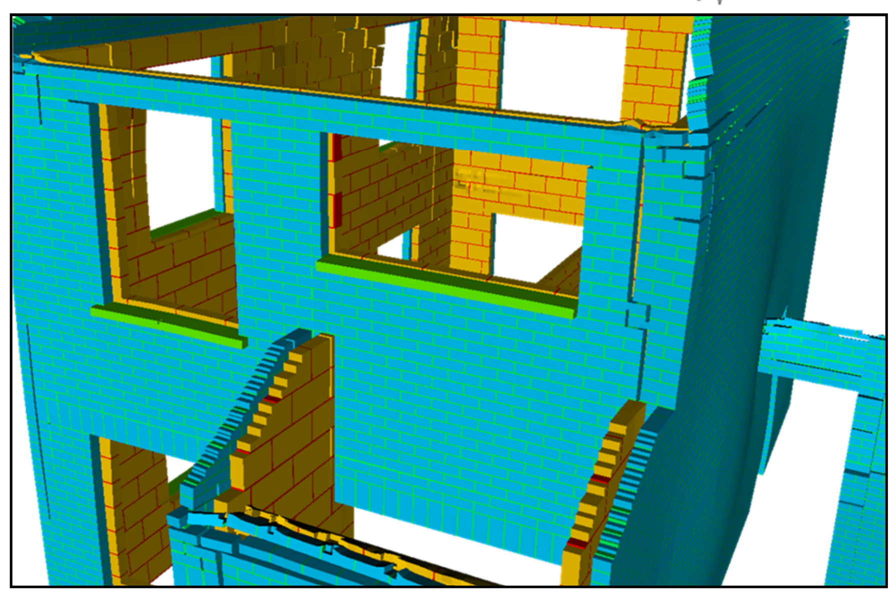
- Three different analysis methods (with varying levels of approximation) produce significantly different predictions of structural response, even for this relatively simple example structure
- Peak deflection is the most consistently predicted result but can still vary by a factor of 2 depending upon the methodology used
- Final deformed shape (prediction of final damage), can vary massively. In the examples used here a difference of +100mm to -200mm final deformation was observed
- The most significant parameter is the blast waveform. The shape of the rise to peak and the magnitude of the negative phase were important factors in the example. When there is no negative pressure phase, there is no late-time negative deflection
- The structural representation is also important. Simplified SDOF models cannot replicate real-world complexities of non-trivial structures. Material strength and plasticity models can be modeled more realistically with FEA models than with SDOF models

Real examples where structural details and blast waveform could not be readily simplified, validated by full-scale tests









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Conclusions

- This paper has described a comparison of the deflection time histories of a simple reinforced concrete panel when calculated using a SDOF analysis method, with a simplified and more complex loading function as well as a more detailed FE analysis using a complex loading function
- All methods predict peak responses that are broadly similar
- However, the final state or permanent residual deformation is highly dependent upon the form of the pressure-vs-time curve
- Different results are predicted for the different complexity of assumed loading

Conclusions (cont.)

- The primary conclusion here is that the full pressure-vs-time curve of blast loading is significant when assessing structural response
- Simple peak-pressure to damage relations and slightly more complex pressure-impulse damage relationships should only be used with extreme caution and only when the potential error magnitudes are understood
- Specifically, published P-I iso-damage charts should be used only where the form of the loading that generated those charts, or the loading basis for the P-I curves, is fully understood
- It is recommended that before finalizing consequence and quantitative risk assessment based facility siting studies, that the more significant buildings whose damage characterizations are closely above or below critical damage thresholds, be looked at using more rigorous CFD and FEA based analytical tools before finalizing the facility siting study, and making expensive plant decisions to mitigate or lower societal or maximum individual risk at the facility
    - Personnel relocation
    - Strengthen (blast harden) buildings
    - Adjust process
    - Install detection

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