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

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This paper briefly presents a detailed assessment of damage to a specific building component caused by a range of blast load forms. The building component in question 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.

Keywords: VCE, vapour cloud explosion, P-I diagram, CFD, finite element, structural damage

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.

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. These tools include Single Degree of Freedom (SDOF) models and 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.

The objective of this paper is to illustrate the differences in these methods of damage assessment and in particular highlight the differences in response from VCE compared to HE and the problems of using P-I iso-damage charts derived from HE data alone.

Single Degree of Freedom Analysis Methods

Biggs (1964) originally described the use of SDOF and in particular developed the approach of representing complex structures with a lumped mass equivalent SDOF system. These methods essentially allow the equation of motion of the system to be derived either analytically or numerically depending upon the complexity of load and resistance functions. The method has been variously developed for assessing the response of structures to HE blast loading by Baker (1983), Smith (1994) and Cormie (2009).

Solution of the equation of motion for a single degree of freedom system can be accomplished by various means as described in Cormie (2009). However, blast engineers are usually only concerned with the calculation of the final state rather than a detailed deflection-time history. This allows for the use of energy balance methods to determine the overall limits of response. For example, where the load duration is long compared to the response period of the structure, usually termed the Quasi-Static loading regime, it is possible to equate the total work done on the structure to the total strain energy developed in the structure, an overall displacement function can be assumed for the structure which in turn allows the calculation of the maximum displacement. Similarly, where the load duration is short compared to the response period of the structure, usually termed the Impulsive loading regime, it is possible to equate the impulse delivered to the structure to the kinetic energy of the structure and so determine the displacement of the structure to be assessed. The region between the Impulsive and Quasi-Static asymptotes is known as the Dynamic regime or Pressure-Time regime. In this regime the natural period of the structure and the duration of the loading are similar, therefore the form of the induced response is directly dependent upon the form of the loading time history.

This, in turn leads to the concept of Pressure-Impulse (P-I) iso-damage curves. It is possible to represent these Impulsive, Quasi-Static and Dynamic response regimes as curves of constant damage plotted on graphs of pressure and impulse. Figure 1 shows a typical non-dimensional P-I curve. With this graph it is possible to simply describe the end state of an equivalent SDOF to an arbitrary pressure-time loading. However, it must be remembered that the shape of this P-I curve is dependent upon the form of the pressure-time history applied to the equivalent SDOF system.

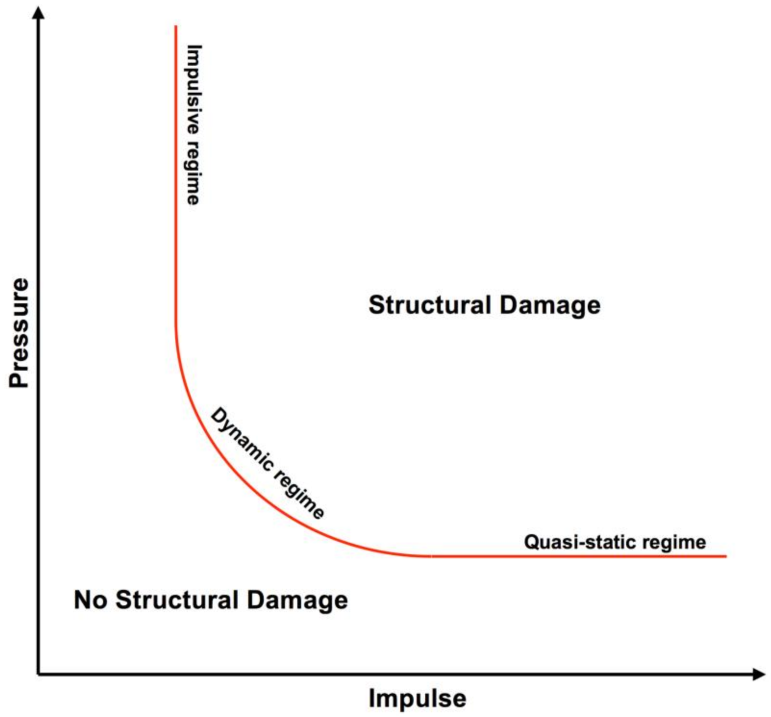

Figure 1. Non-dimensional P-I iso-damage curve.

Structural component level damage assessment: precast reinforced concrete cladding panel

Precast reinforced concrete cladding panels are widely used in the British construction industry. These panels generally form the exterior of a building and are therefore part of the architecture of the building and not just a structural component. The result is that the form and appearance of these panels can vary significantly. To reduce weight these panels can have void spaces or can be constructed with a beam grillage supporting a thinner slab. Sometimes the exterior surface concrete will be coloured, textured or patterned for aesthetic reasons. Commonly these panels are faced with brickwork. However, the underlying structural behaviour is reasonably consistent amongst the range of cladding styles. Generally, the cladding panel is simply a reinforced concrete slab attached to the primary building structure on two or more sides.

For the purposes of this paper a specific structural arrangement was analysed based upon a real structure that was subjected to an accidental large vapour cloud explosion. The structure chosen for this analysis was the Northgate building (Northgate House) in Hemel Hempstead, UK. This building was subjected to a large vapour cloud explosion resulting from an accident at the Buncefield oil storage and transfer depot, Hemel Hempstead, on 11 December 2005. This event is well-documented elsewhere and this paper only considers the reinforced concrete panels which were used to clad the outside of the Northgate building.

The cladding panels used on the Northgate building were typical of those used throughout Britain in commercial/industrial buildings. The primary panel structure consisted of a reinforced concrete slab approximately 7m long by 2.2m high by 0.36m thick and spanned horizontally between the columns of the supporting structure. Along the top and bottom of the slab there were thicker beam sections that were more heavily reinforced than the slab itself. Spanning vertically between the two beam sections there were concrete “ribs” which defined a number of void spaces which were filled with a lightweight foam. The panels were faced with brickwork that was supported on a steel angle section that was itself anchored onto the bottom beam section of the panel. Figure 2 shows views of these cladding panels after the accident.

Figure 2. Photographs of blast damage to Northgate building showing detached cladding panel and flexural failure.

An interesting feature of the response of these panels during the blast was that two different manufactured batches of panels exhibited significantly different responses. There was one set of panels that showed only minor damage while another set of panels showed heavy damage. The heavily damaged panels showed what would be considered a failure in the form of a severe crack running vertically at mid-span. This difference was attributed to a minor difference in the quantity of reinforcing steel in the panels. A study conducted by Weidlinger Associates Ltd and prepared by the Steel Construction Institute (SCI) (2009) for the Health and Safety Executive Explosion Mechanism study used P-I diagrams generated using idealised blast load definitions and SDOF models of the cladding panels to back-calculate the pressure load time-history applied to the façade of the Northgate building during the event. It was concluded that a pressure load curve characterised with a finite rise time, long duration pressure with a peak pressure of around 17kPa, an impulse of 11kPa.s, and a duration of around 1.4s would result in the damage observed on-site. It was also concluded from the observed damage to the whole building and the surrounding area that all of the panels in question would have received a similar level of pressure loading from the blast. However, the Buncefield Accident Investigation Board has yet to be able to determine conclusively what the form or magnitude of the blast loading was in this location. There has been significant debate over whether the Buncefield explosion involved a deflagration, a detonation, or a more complex combination of the two with involving deflagration to detonation transitions (DDT) in parts of the stoichiometric portions of the cloud.

This paper attempts to expand upon that previous study by illustrating the importance of considering a more realistic blast waveform.

Pressure-Impulse iso-damage curves based upon simple waveform and SDOF

The assessment presented by SCI (2009) describes the development of a non-linear, inelastic SDOF model of the cladding panels. Simplified pressure loads of the form described above with scaled duration and magnitude were then applied to the SDOF model. The predicted permanent deflection of the panel according to the SDOF model was then used as a damage metric to generate iso-damage contours. The study assumed that the observed damage to the Northgate "weak" and "strong" panels was a result of the same load and sought to determine if it was possible to determine the form and magnitude of the pressure load function that could cause the observed damage. Various forms of pressure load function were assessed including shapes typical of a HE event and a VCE event. The study concluded that the only unique solution was the result of a VCE style event. Figure 3 shows the derived P-I diagram for the "weak" and "strong" Northgate panels and the corresponding unique solution.

Figure 4 shows P-I iso-damage curves from 0mm (onset of permanent deformation to 300mm maximum permanent deformation) for the stronger of the two cladding panel designs. This plot shows only a close-up of the dynamic response region of the P-I parameter space. The other components of this plot will be described below.

Realistic blast load waveform from CFD calculations

The P-I iso-damage relationships defined by Figure 4 are based upon the assumptions inherent in the shape of blast load waveform and the SDOF model of the cladding panel. The main objective of this paper is to illustrate the importance of considering a more realistic and complex waveform. To that end a series of numerical simulations are conducted using the VCFD Computational Fluid Dynamics software, Hassig (2016). Wesevich (2016) describes the use of the VCFD code for simulating vapour cloud explosions. The simulations conducted here considered a range of vapour cloud sources and combustion scenarios that were initiated near a range of generic building shapes. The pressure-vs-time predicted on the faces of those buildings were recorded. Figure 5 and Figure 6 show contour plots of peak pressure from two such simulations.

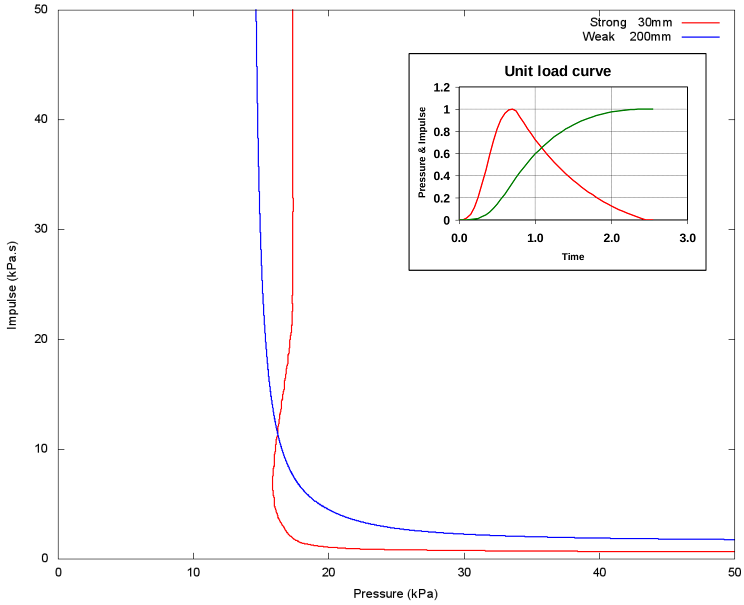

Figure 3. Iso-damage curves predicted by SDOF model, applied loading as idealised vapour/dust explosion form, showing onset of failure for strong panel and 200mm permanent deflection for weak panel, idealised positive-phase only waveform.

A generic scenario was found that subjected the buildings to peak-pressure and peak-impulse within the dynamic response region of the cladding panel. Figure 4 shows the Pressure Impulse pairs extracted from the VCFD simulations and Figure 7 shows the corresponding pressure-vs-time curves for five of these points. The pressure-vs-time curves produced by this scenario have a smooth positive-phase with finite rise time and a similar subsequent drop back to ambient pressure. However, these loads also include a significant negative phase. The peak negative pressure and impulse are generally of similar magnitude to the positive phase. This is obviously important when predicting structural response. It is also significant that the durations of the positive and negative phases are of a duration that is similar to the natural period of the cladding panels; certainly within the dynamic response region of the P-I damage chart. The "P-I pair" for each of these curves refers to the peak positive phase pressure and the peak positive phase impulse only.

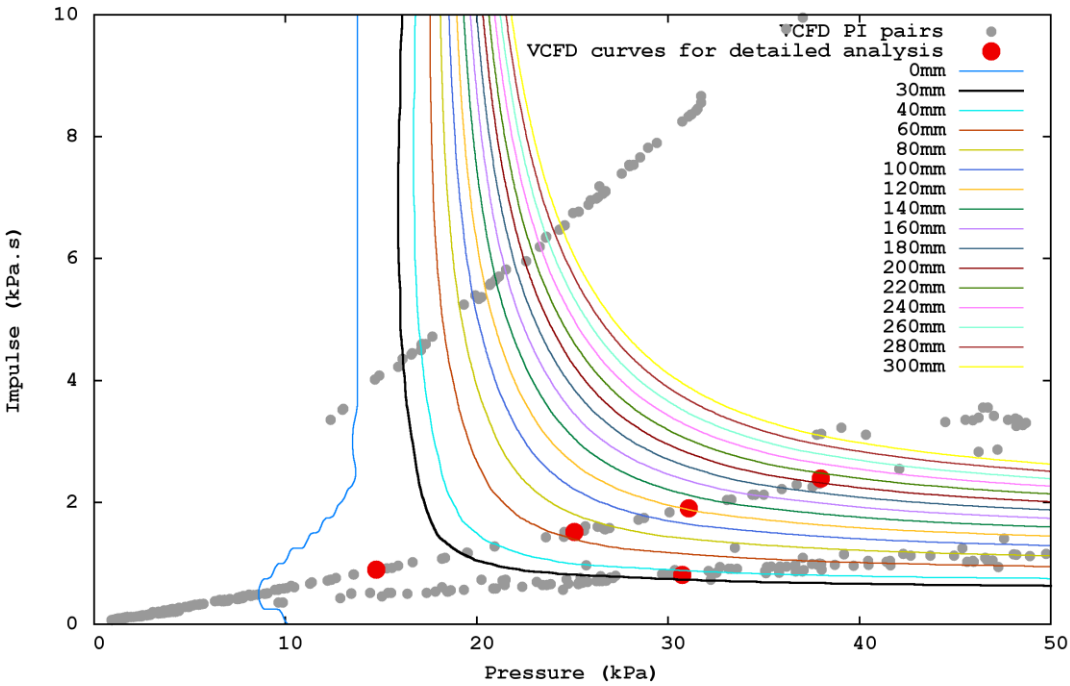

Figure 4. P-I iso-damage curves for reinforced concrete cladding panel, also showing location of P-I pairs from CFD simulations and locations of pressure-time curves chosen for further analysis.

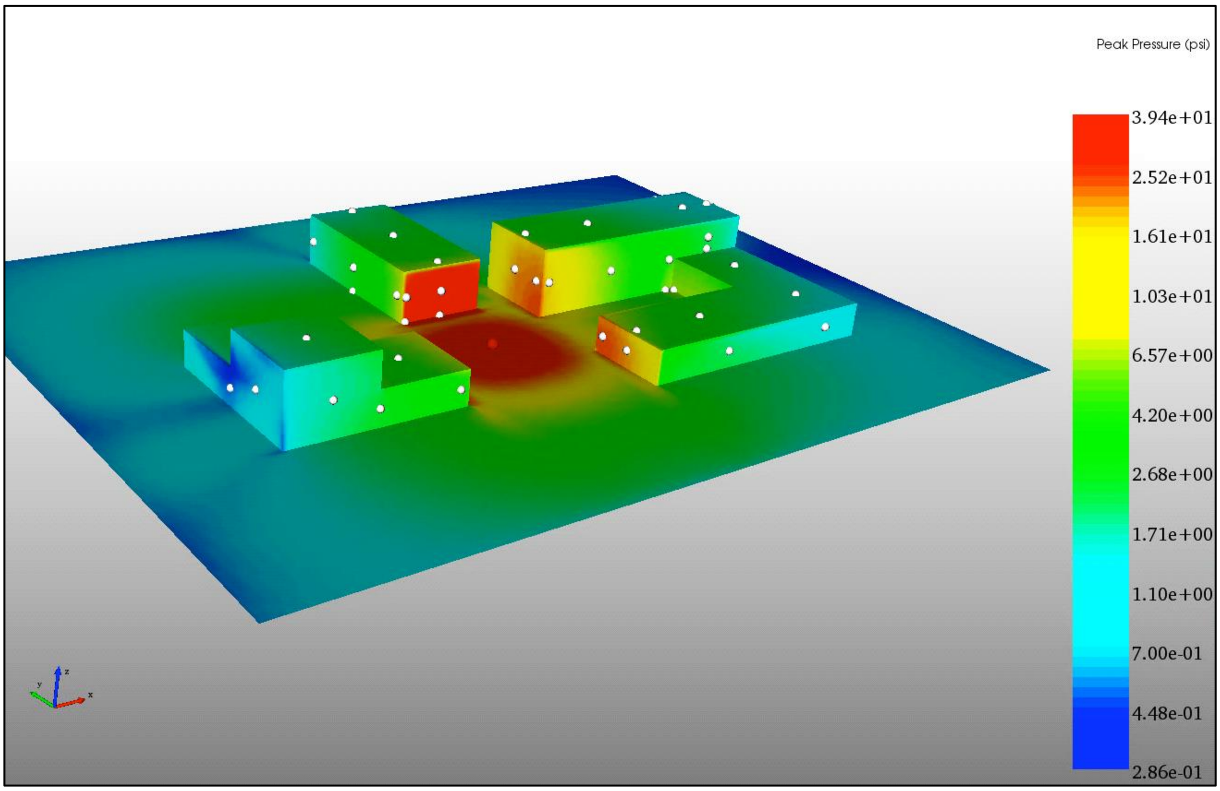

Figure 5. Typical peak-pressure contour plot from VCFD simulation of vapour cloud explosion (units are psi, 1psi = 6895Pa).

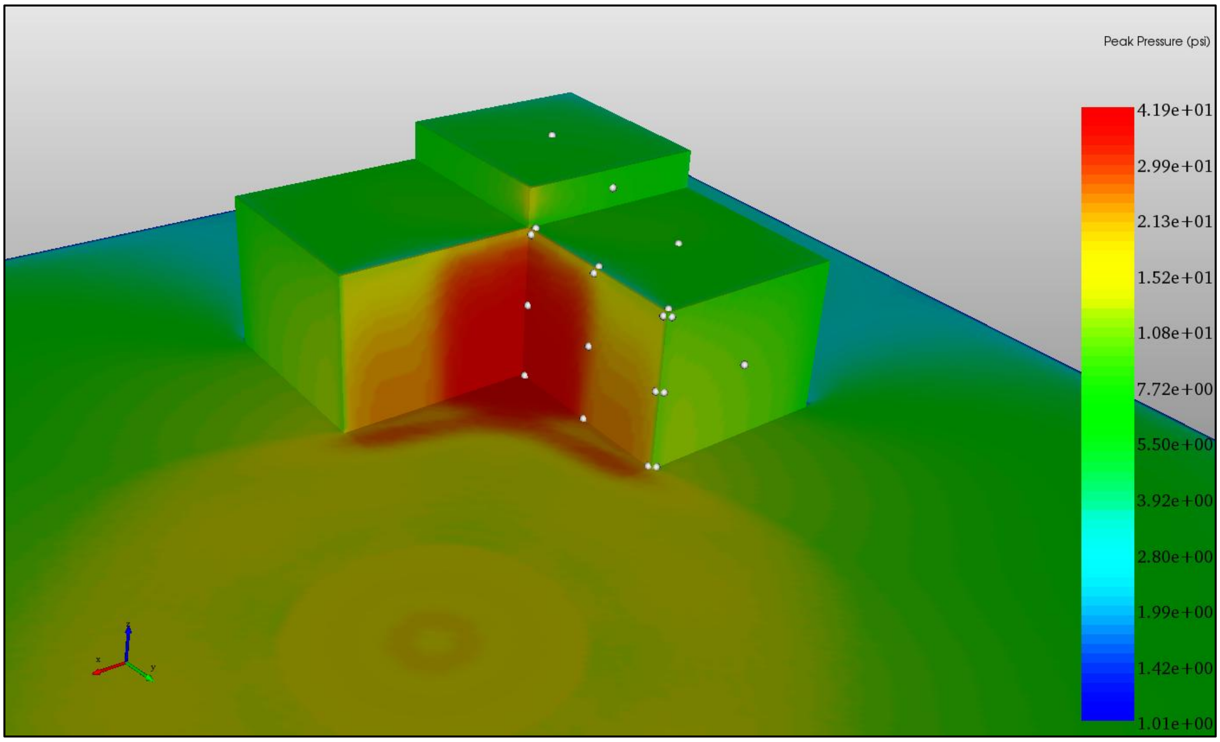

Figure 6. Typical peak-pressure contour plot from VCFD simulation of vapour cloud explosion (units are psi, 1psi = 6895Pa).

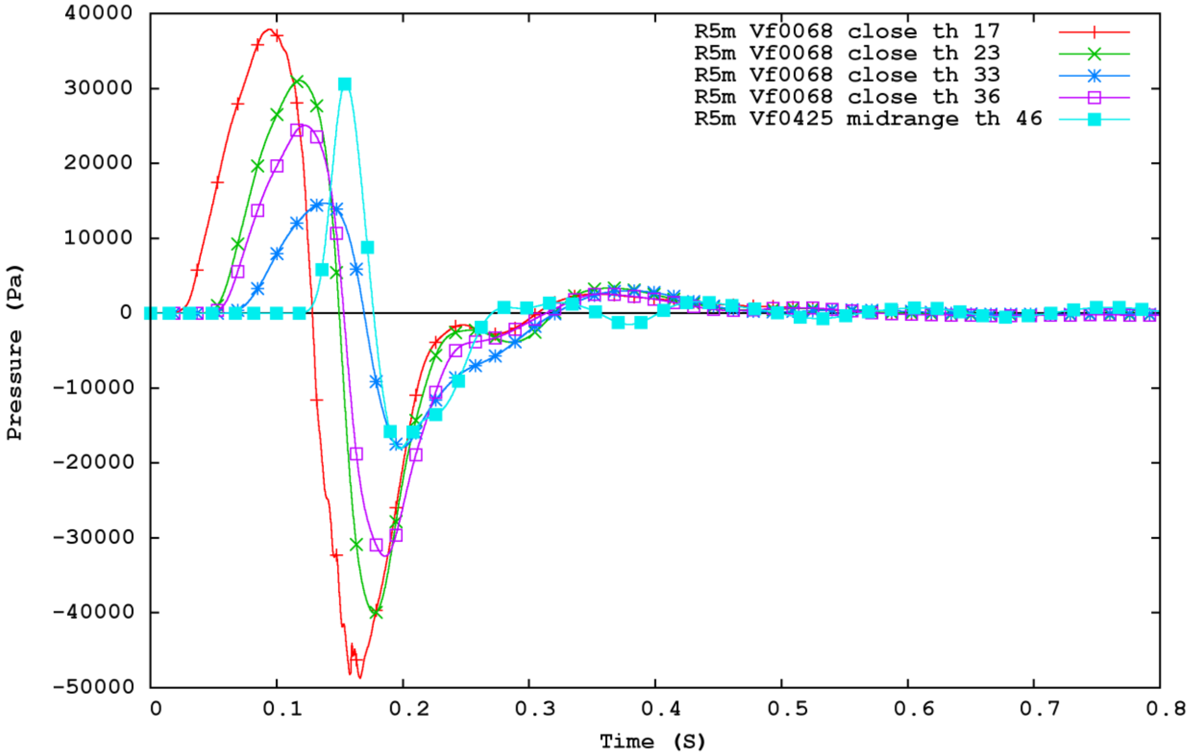

Figure 7. Pressure-vs-time curves from VCFD simulations used for more detailed structural assessments, extracted from various locations on buildings subjected to blast.

Simplified blast waveforms for comparison

A set of five pressure-vs-time curves was selected from the VCFD simulation results for further analysis. The peak positive phase pressure and impulse was extracted from each curve. For comparison, for each P-I pair an equivalent simplified blast load curve was also defined which had the same peak positive phase pressure and impulse as the curves resulting from the CFD simulations. The simplified load curves shown in Figure 8 have the same peak pressure and peak impulse as the more complex CFD derived load curves.

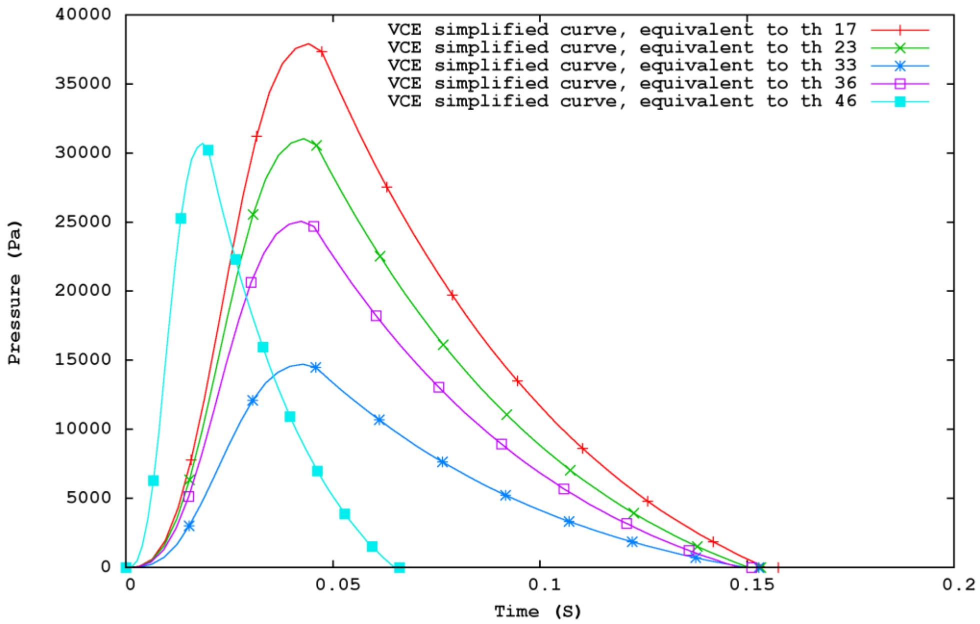

Figure 8. Simplified pressure-vs-time curves with equivalent positive phase peak pressure and impulse as those from VCFD simulations.

Structural response predicted by SDOF and high-fidelity Finite Element model

Each of the five example load curves derived from the VCFD simulations and the five corresponding simplified load curves were applied to the SDOF panel model. The primary output from these models was mid-span deflection of the panel as a function of time. For comparison, the VCFD derived load curves were also applied to a detailed Finite Element (FE) model of the panel.

The NLFLEX solver described by Vaughan (1983) was used to conduct the detailed FE simulations. NLFLEX is an explicit large deformation finite element solver designed specifically for simulating blast effects on structures. The purpose of this paper is not to present validation of numerical codes but the NLFLEX and VCFD solvers are well validated and details can be found in the usual literature.

The detailed FE model of the panel included explicit representations of the concrete, reinforcing steel, bricks and mortar, steelwork, and insulation foam of the cladding panel. The blast pressures were applied simply as a uniform, time-varying, pressure on the front face of the panel. Figure 9 shows selected views of the FE model. More details of the FE model can be found in SCI (2009). A selection of images showing the FE model response to a typical load case are shown in Figure 10.

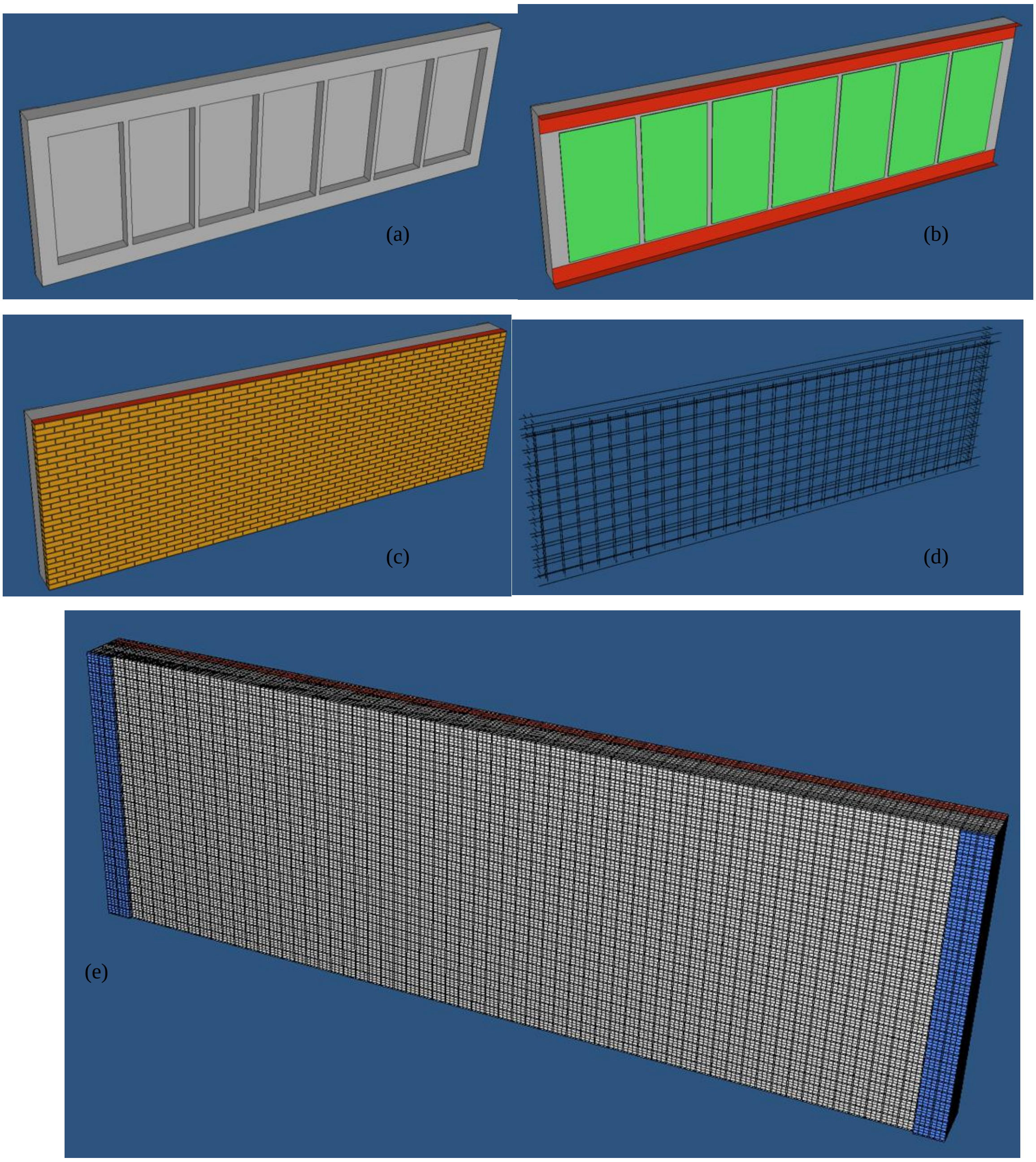

Figure 9. NLFLEX finite element model of cladding panel, (a) concrete, (b) concrete, steelwork and insulation foam, (c) brickwork facing, (d) steel reinforcement, (e) rear face showing boundary elements and spatial discretisation.

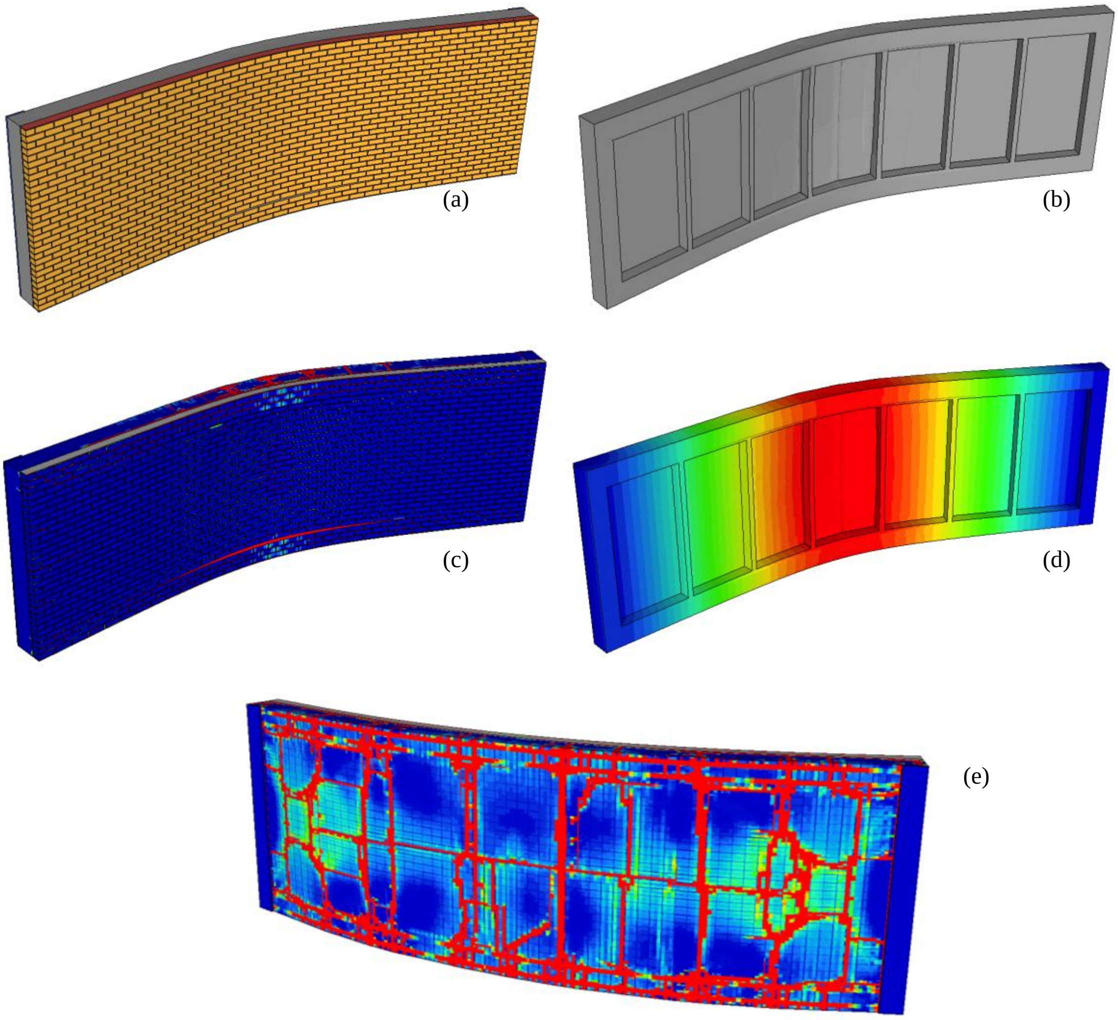

Figure 10. NLFLEX finite element model of cladding panel, results plots from typical analyses, (a) deformed shape, (b) deformed shape showing concrete material only, (c) contours of constitutive model damage parameter, (d) contours of displacement. (e) contours of constitutive model damage parameter.

These analyses produce three structural response predictions for each of the five selected P-I locations, as summarised in Table 1. The deflection-vs-time response of the panel for each P-I location are shown in Figure 11 (a) to (e).

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

Table 1. Combinations of pressure load waveform and structural response methods for comparison.

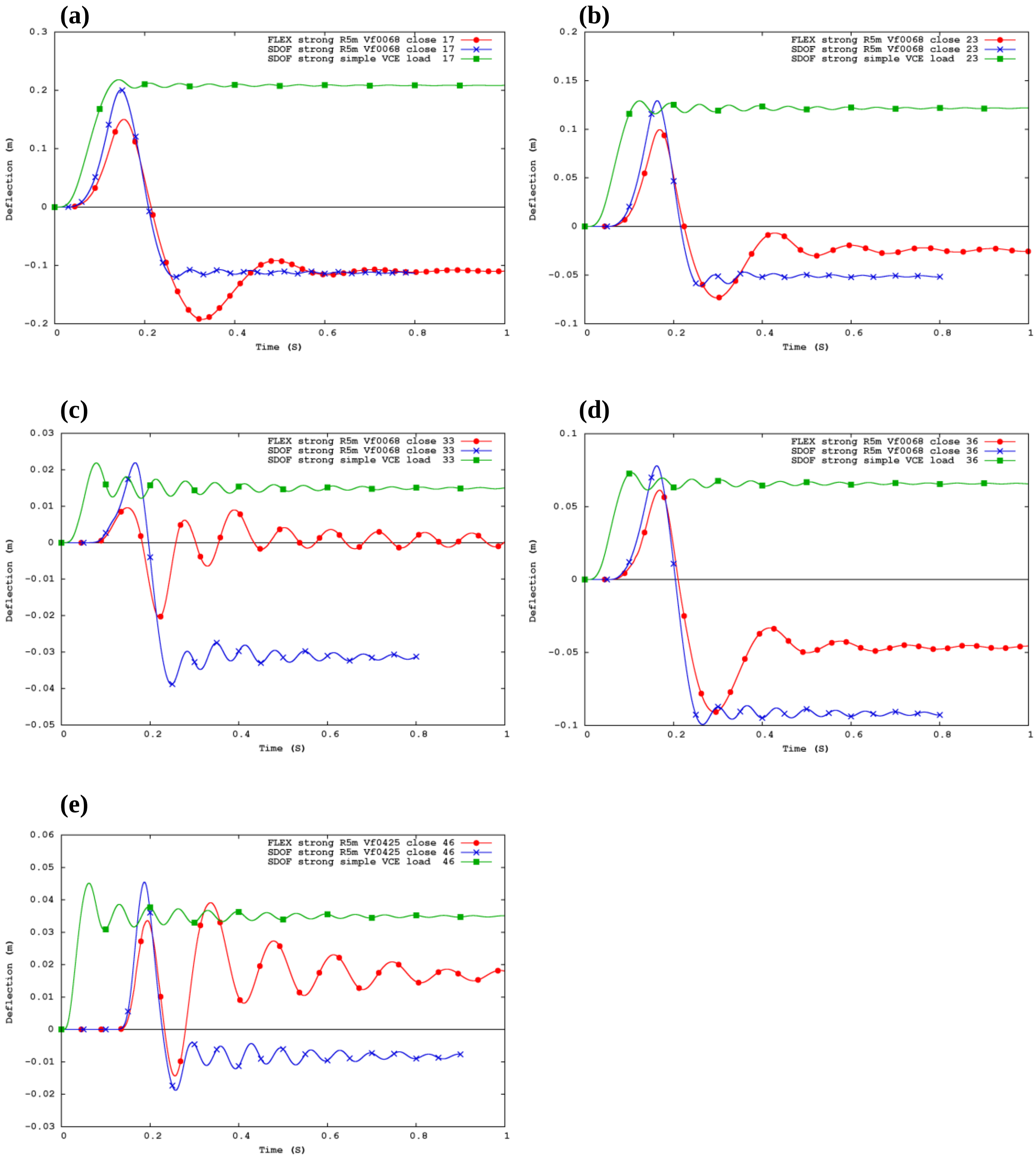

Figure 11. Deflection-vs-time response of cladding panel, predictions according to three different analysis methods, (a) input time history no.17, (b) input time history no.23, (c) input time history no.33, (d) input time history no.36, (e) input time history no.46

Discussion

The analyses conducted here considered only five locations in the P-I parameter space, locations within the dynamic response regime of the structure being assessed. Three different structural response predictions were made using simple or complex loading and simple or complex structural models, according to Table 1. All three response predictions at each P-I location are directly comparable and are plotted together in Figure 10 (a) to (e).

Upon inspection of Figure 11, it is clear that the three different approaches to predicting the blast load and structural response provide three significantly different results for the range of loadings assessed. This outcome was expected and intentional as illustrating the magnitude of the variations was an objective of this exercise. It is beyond the scope of this paper to describe all details of the SDOF, CFD, and FE models used in this exercise; more details can be found in the references previously specified. The SDOF approach, the CFD code and the FE solver are all well validated and verified methods and implementations and can be shown to accurately model well-posed problems when used appropriately.

However, in this particular example, the differences in results do not stem from the numerical and algorithmic procedures used but from the level of idealisation used in the definition of those analyses.

The most obvious difference in the predicted responses is due to the large negative phase present in the complex waveforms, a detail that is not accounted for in the simplified load curves. Using simplified load curves with only a positive phase resulted in final panel deflections that were always positive, *i.e.* away from the ignition point. When the negative phase is accounted for, the final panel deflections are more likely to be negative, *i.e.* towards the vapour cloud.

In these models it has been assumed that the negative phase pressure can be applied in the same manner as the positive phase: as a uniformly distributed pressure on the front face of the cladding panel. On a real building it may actually be necessary to apply negative phase loading to the back face of the cladding panel, depending upon the form of the construction.

Comparison of the initial phase of the response shows that initial predicted deflections are similar for each of the analysis methods. However, comparison of the predicted permanent deflections in the panel at the end of each analysis show considerable differences. For the example shown in Figure 11 (a), the FE and SDOF models with the complex blast load applied predict near identical permanent deflections of around -120mm but the SDOF model with a simplified blast load applied predicts a permanent deflection of around +200mm.

For the example shown in Figure 11 (e), the three assessment approaches predict permanent deflections of around -10mm, +15mm and +35mm. There is clearly such a large discrepancy here that the results would not be particularly useful in a real world assessment. The negative phase in the complex blast loading, the natural period of the cladding panel, the relatively low level of damage, and the level of detail considered by the SDOF and FE models, all contribute to this observed wide variation of results.

The purpose of this simple exercise was not to prove or disprove the validity of the simplified load curves, CFD simulations, SDOF models or the explicit finite element models, but to highlight the potential magnitude of the different predictions that could be obtained by these methods, even when considering a structural component as simple as a single reinforced concrete cladding panel. In real-world problems with complex multi-component buildings with a wide range of construction types that are being assessed, extreme care must be taken when making assumptions about the applied blast loading and the complexity of the structural response.

It has been shown that modern computational analysis techniques, CFD and FE modelling, can be used to predict the level of damage inflicted on buildings by large scale airblast events. For example, Hoing (2008) reports an assessment of a range of typical "British Commercial Building" construction types when subjected to large scale high-explosive airblast loading. It was shown using blind predictions of physical tests that the damage inflicted to three different construction types could be predicted with an accuracy of around 20% (within one damage category on a scale of five categories). In order to predict the form and magnitude of damage inflicted it was necessary to model the true pressure-vs-time loading on all faces of the buildings, including inside faces in some cases, as well as fine details of the structure such as masonry cavity walls, bolted connections on steel frames *etc.* Some images from those analyses are reproduced in Figure 12. A similar study looked at the response of typical British residential buildings; example images are also reproduced Figure 12. In that study it was found that blast venting through window openings and internal pressurisation of the structure was an important aspect that had to be accounted for in order to accurately predict the structural response. When the structural damage is dependent upon such fine detail, it is not possible to predict the response using simplified load curves and simple structural models: highly detailed simulations are required.

Much empirical data is available regarding the P-I iso-damage response of common structural forms, such is the well-known Jarrett curves, Jarrett (1968). The curves presented by Jarrett considered damage to brick buildings and were based upon bomb damage observed during World War II. Due to the fact that these P-I curves were based upon real-world damage of real-world blast loading, with all the inherent complexities of structural form and blast waveforms, the Jarrett curves could be expected to be quite accurate but only for assessing the response of brick buildings in London to WWII bombs. The same curves should not be considered valid for vapour cloud blast loading on any other construction type. Similarly, P-I charts for building damage derived from nuclear tests should not be used for small scale HE loading scenarios as the blast load waveforms are significantly different.

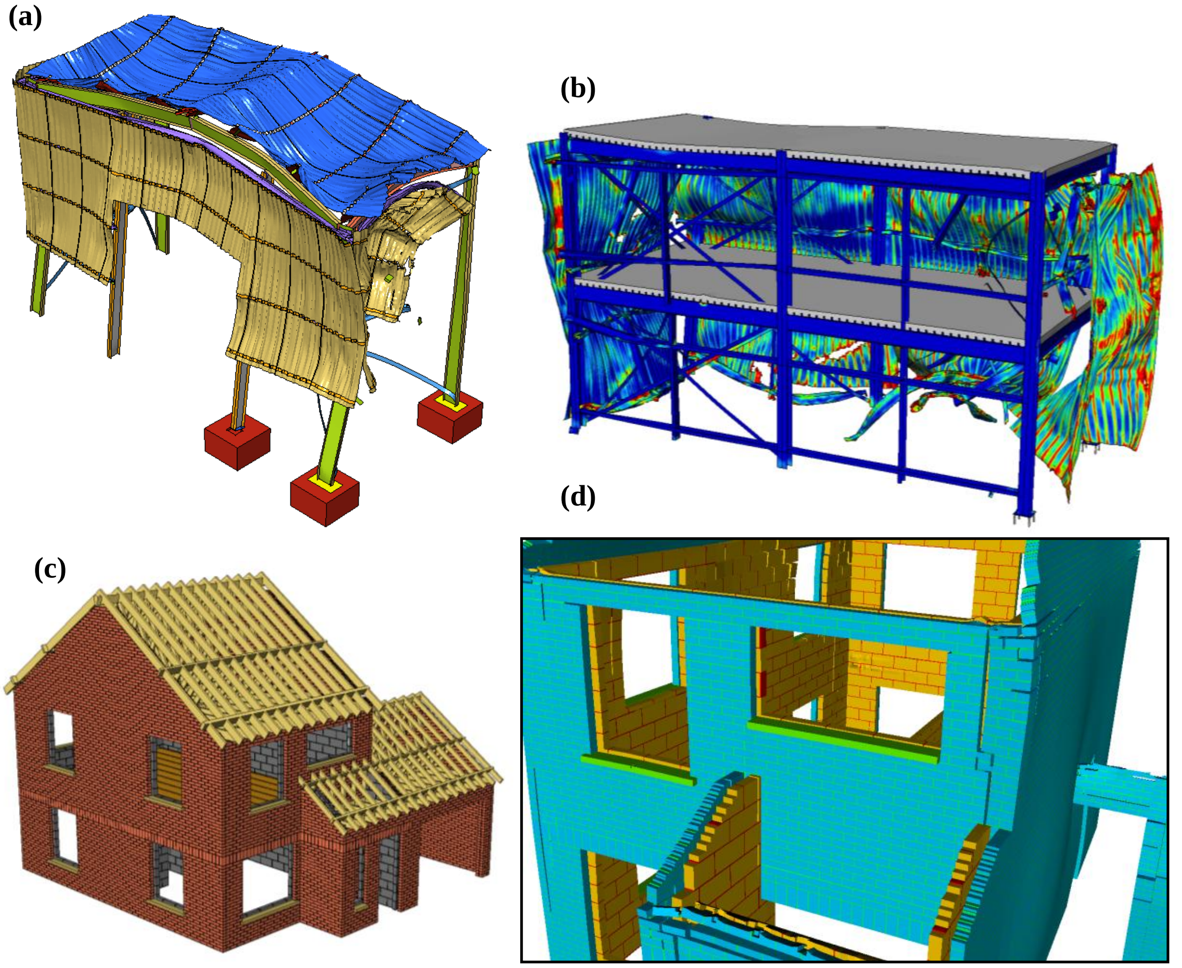

Figure 12. Examples of more complex and detail sensitive structural response models: (a) steel portal frame with insulated cladding, (b) steel moment frame with precast floor and roof system and insulated cladding, (c) residential building finite element model, (d) predicted damage to brick/block structure of residential building.

Conclusion

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 loading assumed.

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.

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