A review of blast loading and explosions in the context of multifunctional buildings

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Abstract

This work report forms a part of the Safe Multibygg project, dealing explicitly with antagonistic actions and threats in the form of explosions. Since multifunctional buildings are by nature publicly accessible they are potentially exposed to either deliberate or accidental blast loading from various sources including members of the public or former employees or activists. This report aims to give a broad overview of this subject area and highlights similarities between the challenges which are faced by researchers working in the field of blast and explosion engineering and those working in fire engineering.

Key words: blast loading, multifunctional buildings, Safe Multibygg, statistics, incident reviews, blast load mitigation
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Summary

This report first provides an overview of some statistics of blasts around the world and then gives a discussion of some major bombing incidents which illustrate both the susceptibility of society to explosions as well as the potential destruction and widespread damage which may be caused by such events\(^1\).

The report discusses the physical effects of blasts and how these may be represented in and accounted for in physical models. Parallels are drawn between the current state of the art and research focus of blast engineering with fire engineering— in particular the current changes in the philosophy which are on-going in the two fields and changes to the overall approach of the two disciplines.

Finally, the report contains a brief discussion of approaches for protecting facilities from the effects of blast.

\(^1\) There are many reviews of structural blast loading and design procedures for structures exposed to blast loading. While this report has referenced some of them, it is only the intention that this report should be a starting point for further investigation and discussion. For more detailed information some of the sources which are referenced in this document are comprehensive literature reviews and should be consulted.
1 Recurrence of explosions

Statistics show that there has been an increase in the frequency of bombing incidents by terrorist organisations in recent years\(^2\). For example globally there was a more than 300% rise in bombing incidents between 2004 and 2012 [1], and a 50% increase in suicide bombings, with an accompanying increase in mortality of 30% (for illustration, Table 1 shows injury statistics from a small number of terrorist bombings up until 2000). The current trend for increase in the frequency of terrorist attacks may however be at least partially attributed to bombings in the Middle East [2].

Table 1 – morbidity and mortality of selected terrorist bombings up until 2000, adapted from [2]

<table>
<thead>
<tr>
<th>Date</th>
<th>Target / Location</th>
<th>Deaths</th>
<th>Injuries</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>US Embassy, Nairobi, Kenya</td>
<td>213</td>
<td>&gt;4000</td>
</tr>
<tr>
<td>1983</td>
<td>US Marine Barracks, Beirut, Lebanon</td>
<td>241</td>
<td>105</td>
</tr>
<tr>
<td>1969–72</td>
<td>Belfast, Northern Ireland</td>
<td>117</td>
<td>1532</td>
</tr>
<tr>
<td>1980</td>
<td>Bologna, Italy</td>
<td>73</td>
<td>218</td>
</tr>
<tr>
<td>1975–79</td>
<td>Jerusalem, Israel</td>
<td>26</td>
<td>340</td>
</tr>
<tr>
<td>1985–86</td>
<td>Paris, France</td>
<td>20</td>
<td>248</td>
</tr>
<tr>
<td>1996</td>
<td>Khobar Towers, Dhahran, Saudi Arabia</td>
<td>19</td>
<td>500</td>
</tr>
<tr>
<td>2000</td>
<td>Destroyer USS Cole, Aden Harbor, Yemen</td>
<td>17</td>
<td>39</td>
</tr>
<tr>
<td>1998</td>
<td>US Embassy, Tanzania</td>
<td>11</td>
<td>86</td>
</tr>
<tr>
<td>1988</td>
<td>Jerusalem, Israel</td>
<td>6</td>
<td>52</td>
</tr>
<tr>
<td>1993</td>
<td>World Trade Center, New York, USA</td>
<td>6</td>
<td>548</td>
</tr>
<tr>
<td>1972–80</td>
<td>Northern Ireland</td>
<td>&gt;5</td>
<td>339</td>
</tr>
<tr>
<td>1996</td>
<td>Centennial Park, Atlanta, USA</td>
<td>2</td>
<td>111</td>
</tr>
<tr>
<td>1974</td>
<td>Birmingham, England</td>
<td>2</td>
<td>80</td>
</tr>
<tr>
<td>1991</td>
<td>Victoria Station, London, England</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>1996</td>
<td>Manchester, England</td>
<td>0</td>
<td>208</td>
</tr>
<tr>
<td>1974</td>
<td>Tower of London, England</td>
<td>0</td>
<td>37</td>
</tr>
</tbody>
</table>

Within the context of multifunctional buildings in Sweden a more appropriate thing to do is to consider examples in Sweden alone, where since 1970, there have been a total of 21 bombings associated with terrorist attack, with typically no more than one every two years although in 1991 there were 4 separate incidents [1].

Figure 1a shows global statistics for explosions associated with terrorist attacks, and figure 1b shows statistics limited to only incidents which occurred in Sweden.

\(^2\) Statistics which are cited in this report rely heavily on information which is published in the Global Terrorism Database (GTD) [20]. However, this does not reflect all incidents which have occurred in Sweden. Nevertheless, the statistics which are discussed are considered to be reflective of international trends.
It should be noted also that these statistics do not include examples of accidental explosions or impacts. Accidental explosions may include such events as explosions involving leakages from gas mains or involving materials carried by members of the general public, such as e.g. fireworks. However incidents of this type are rare, especially in multifunctional buildings and any additional explosive load which a member of the public accidentally brings into a building is likely to be so small that it would cause little to no damage. Impact on the other hand is intuitively a more likely scenario, for example impact causing damage to the structure from a vehicle in a bus station, car park or even in a mall. As will be discussed later, once the potential for impact has been identified there are some similarities between impact and blast loading in terms of material response and potential structural damage – although the loading is by its nature more localised. Nevertheless, there are relatively few deliberate incidents involving vehicles (where there was no bomb involved), for example in 2010 there were only 8 attacks globally [1], and the majority of incidents of vehicle impact on building structures are to be considered accidental. Studying accidental incidents can, however, give insight to potential scenarios as such incidents could be recreated deliberately by antagonists.

2 Examples of incidents

Occurrence of explosions is clearly rarer than that of fire. Nevertheless there have been a number of high profile deliberate and accidental events which illustrate the potential for devastation caused by this type of incident. For example the relatively recent large scale incident of the Buncefield disaster, which occurred in the UK in 2005 and which serves to illustrate the wider impact of an explosion in a large industrial site on society. Antagonistically motivated explosions which have affected public or high profile buildings in cities include, notably, the attacks on the world trade centre towers in 1993; the Manchester bombing in 1996; as well as the Oklahoma city bombing in 1995 and the London bombings in 2005.
In addition to this there are also a number of historical or recent accidental incidents where explosions have occurred in apartments – either caused by gas leaks in the case of, e.g. Ronan Point; or by occupant error in the case of more recent events in Philadelphia or New York City.

This section provides a brief summary of a number of events which illustrate the damage which may be caused by both accidental and deliberate explosion incidents. These are only very cursory overviews and for more detailed information the references given should be consulted.

In general, the events are detailed in no particular order, however the incident at Ronan Point is detailed first since, although it was an accidental explosion in a residential building and is therefore of minimal interest for multifunctional buildings, the resulting changes in legislation from the accident are the foundations of what modern structural engineering response to progressive and disproportionate collapse is based upon. When discussing the impact of blast or explosion on a structure, it is impossible not to mention both progressive collapse and disproportionate collapse. The following definitions of these two terms are put forward in order to prevent any ambiguity [3]:

- Progressive collapse may be defined as the collapse of all or part of a structure which is instigated by the failure of a small part of the structure
- Disproportionate collapse may be defined as the collapse of a portion of a structure which is disproportionately large to the initiating event

It should be noted that progressive collapse is usually, although not always, disproportionate; and that by their nature, these definitions are almost entirely subjective.

2.1 Ronan Point (1968)

The case of Ronan Point is incredibly well documented and its effects on the construction industry and how they deal with the potential for blast loading are far reaching. Ronan Point was a block of flats in London, 22 storeys tall, with 5 flats per storey. It was constructed from prefabricated concrete elements using a ‘Larsen Nielsen’ large panel system, originally developed in Denmark [4]. This system comprised floor and wall panels which were lowered onto one another onto exposed bolt heads to provide connection.

In the morning of 16th may 1968 there was an explosion in one of the flats on the 18th floor. The explosion was a result of a gas leak in the kitchen, which was ignited in the morning when the tenant, Ivy Hodge, struck a match to light the stove. As well as causing damage to non-load bearing internal partitions, the explosion blew out one of the external load bearing walls from the building [5]. The removal of the load bearing wall resulted in the floors above collapsing onto the 18th floor, with the impact of this collapse causing further failure of the floors below. Four people were killed and 17 injured in the accident. A plan of the flat where the explosion originated, both before and after the explosion is shown in Figure 2 a) and b).
The end result was the partial collapse of the floors of one corner of the building almost all the way down to the ground.

Naturally, reaction to the incident was strong with several causes being explored before it was concluded during enquiry that the main fault was in the type of construction, as described in parliamentary debate [6]:

“The Tribunal find that this behaviour of the building was inherent in its design and was not due to faulty workmanship. They state that progressive collapse after such an accident can be avoided by the introduction of sufficient steel reinforcement to provide effective ties at the joints between the structural components, and by so arranging the components that loads can be carried in alternative ways if a failure occurs.”

The UK parliamentary secretary, ministry of housing and local government in 1968 (lord Kennet)

The conclusions of the enquiry into the Ronan Point incident resulted in the implementation in the UK Building Regulations of clauses which were intended to address the risk of disproportionate collapse. The UK was one of the first countries in the world which had regulations dealing with disproportionate collapse, and for many years was one of very few countries with such regulations [7]. The guidance has been improved since it was first introduced however it has not changed substantially in principle, and is included in codes of practice for different materials. The current guidance includes the following recommended options [8]:

- Provision of vertical and horizontal ties
- If vertical tying is not practicable, provision of alternative load path(s) in the structure to cope with the notional removal of the untied vertical member in each storey in turn
- If it is not possible to bridge over the missing member, limit the risk of collapse to the minimum of either 15% of the area of the storey or 70m²
- If, on removal of a member, the risk of collapse cannot be limited, design of that member to withstand an applied load of 34 kN/m².
2.2 WTC (1993)

On February 26th 1993, 4 men drove a van containing a bomb into the 2nd level basement car park underneath the world trade centre in New York. The bomb was detonated shortly after noon and killed 6 people, injuring over 1000 [9].

The damage caused by the bomb was considerable, including damage caused to the concrete slab up to 3-storeys above the level where the bomb went off and down to 3 levels below. As well as damage to the concrete slab, steel columns were damaged and had lateral bracing destroyed by the explosion. In addition to structural damage, ancillary equipment including water mains and air conditioning were also damaged in the attack [10].

Despite the considerable extent of the damage, the building was repaired and remained in use until 2001 when the well documented aircraft impact into both WTC1 and WTC2 occurred, ultimately resulting in their collapse [11].

2.3 Oklahoma (1995)

The Oklahoma City bombing in April 1995 was a major attack on US soil carried out by a domestic terrorist. Reports vary, however around 167 people were killed and between 648 and 782 were injured [2, 12]. A truck bomb carrying around 2,177 kg of fertiliser and fuel oil destroyed 3 columns at the front of the Murrah Federal Office building in Oklahoma, a 9 storey reinforced concrete framed building [12]. The three destroyed columns were supporting a transfer girder, which in turn supported additional columns and floors at higher levels. Without the support of the columns the transfer girder failed, leading to a progressive collapse mechanism as the columns and floors above failed [3]. The level of destruction to the building was huge, see Figure 3, and there was widespread damage to vehicles and buildings in the blocks around the bomb site. The Murrah building was ultimately demolished within 2 months of the bombing [12].
In the aftermath of the bombing, a vulnerability assessment of federal facilities was carried out and a standard comprising a set of 52 minimum security features was developed for federal buildings covering perimeter, entry, interior security and security planning [12].

2.4 Manchester (1996)

On Saturday June 16th in 1996, a car bomb was detonated in Manchester City Centre. With a mass of 1,500 kg the bomb caused considerable property damage. However because of the emergency response to advance notification of the bomb, the city centre was evacuated and no one was killed, although over 200 were injured by the effects of the blast, including injury resulting from broken glazing falling from buildings around the origin of the explosion. A dozen significant buildings suffered severe structural damage and around one half of these had to be demolished. Secondary effects of the bomb were significant, including displacement of residents and businesses and the closure of key city streets for up to 18 months [14].

2.5 London (2005)

The London bombings in July of 2005 were comprised of 4 suicide bomb attacks all targeting public transport systems. The 4 bombs were contained in rucksacks and were estimated, based on CCTV footage of the bombers, to weigh between 2 and 5kg [15]. The first three bombs detonated at the same time, approximately 8:50 am, on three different underground lines; the fourth bomb was detonated just under an hour later on a double decker bus close to Kings Cross station. In total 52 people died and 770 were injured [2].
2.6 Buncefield (2005)

On Sunday the 11th of December 2005, in the early morning, an oil storage depot in the UK experienced a number of explosions, at least one of which was very large, caused by the overfilling of a storage tank and the subsequent release of approximately 300 metric tons of unleaded petroleum fuel [16]. Although damage caused by the incident indicated high overpressures, reports also suggest a slow flame front rate, more associated with a deflagration than a detonation\(^3\). This behaviour has been attributed to a slow flame front comprising periods of rapid combustion interspersed by periods of slower combustion [17].

As a result of the extensive flame spread and the high overpressures, significant damage was caused to houses and vehicles up to a 3.75 km radius from the facility. In total 761 houses suffered some king of structural damage. The total estimated damage bill was in excess of $1.5 billion [16]. Luckily no one was killed.

An image of the Buncefield site before and during the incident is shown in Figure 4 below [18].

![Figure 4 - Buncefield site prior to incident and showing the major fires that followed the explosion [18]](image)

2.7 Other recent incidents

A survey of recent news articles highlights the frequency of accidental explosions in the home which can lead to significant property destruction, with an impact which is perhaps similar to that which was seen in Ronan Point (although these are all smaller buildings, and therefore damage was limited by the size):

- On the 29th of July 2013, an explosion occurred involving a terraced house in south Philadelphia. No one was killed, however 8 were injured and one home was entirely destroyed and three others suffered partial collapse [19].
- In New York on July 11th 2013, a woman set off 20 canisters of bug bombs in an apartment without turning off a pilot light. The flammable fumes ignited.

\(^3\) Explosions may be characterised as either a deflagration or a detonation. Deflagrations are characterised by sub-sonic velocities of the flame front and small side-on overpressures. Detonations are characterised by supersonic propagations of the blast wave and significantly higher side-on overpressures. For example, in a 10m radius unconfined deflagration speeds of 84 m/s have been observed with an overpressure of 0.1 atmospheres. Conversely in a stoichiometric hydrogen cloud detonation, blast front velocities of 1968 m/s and overpressures of 15.6 atmospheres have been observed [20].
destroying windows on three storeys of the apartment building. No one was killed however 12 people were injured [21].

- In Reims in France, an explosion reportedly caused by a gas leak partially destroyed a 5-storey block of flats, killing 3 people in April 2013 [22].
- In Buenos Aires, Argentina, on the 6th of August 2013 an explosion reduced 9 storeys of a 10 storey building to a pile of rubble just 5 or 6 metres high [23]. The cause of the explosion is believed to be a gas leak, although the cause of this leak is unknown at the time of writing. At least 19 people died from the accident, with 2 people still missing, again at the time of writing [24].

3 Physical effects of blasts on structures

Blast loading is not considered in a separate part of the structural Eurocodes, as opposed to fire, loading from which is addressed in Part 1-2 of Eurocode 1, specific design considerations for fire are addressed in Part 1-2 of the material specific structural Eurocode documents. Nevertheless there are several national and international guidance documents which detail the steps which are required when designing structures for blast loading. These are analogous to the steps which are required when predicting structural response to fire or other forms of extreme, transient, loading. In summary, predicting the blast damage to a piece of equipment or structure involves [25]:

- Calculating the time history of the blast wave produced in the air, for both the explosion pressure and the dynamic pressure;
- Calculating the time history of the load acting on the structure as a result of interaction with the blast wave
- Calculating the response of the structure to this loading

For comparison, in structural fire engineering the same steps may be summarised as:

- Calculating the time history of the temperatures inside of a building based upon the fuel load, its distribution if appropriate to the analysis, and the ventilation conditions
- Calculating the time history of the temperatures within the structure as a result of interaction with the fire
- Calculating the response of the structure to this loading

Since structural elements undergo large inelastic deformations under blast loading, complexity in analysing the response of blast-loaded structures arises because of the need to consider the effect of high strain rates as well as non-linear inelastic material behaviour [26]. In addition to this it has been recognised that there is a need to consider alternative load carrying mechanisms which might not be of interest under ‘normal’ gravity loading [27].

3.1 Time-history of blast waves

An explosion is defined as a large scale and sudden release of energy, normally associated with the extremely rapid ignition of a highly combustible material. The sudden energy released into a gas volume results in a rapid expansion of the volume. Most of the damage resulting from an explosion is caused by a layer of compressed air which forms in front of the gas volume which contains most of the energy released by the explosion. The wave of compressed air moves outwards as the blast wave front expands. As the compressed layer moves outwards the blast wave results in an almost
instantaneous increase in incident pressure to a value significantly above the ambient atmospheric pressure. This is referred to as the side-on overpressure. As the compressed air layer passes, the overpressure decays and after a short time, the pressure behind the front may drop below the ambient pressure. This is illustrated in Figure 5 below.

Figure 5 – peak side-on overpressures resulting from a blast wave, adapted from [26]

To determine the magnitude of the impulse from any blast loading, the magnitude of the peak side-on overpressure must be determined. This varies with the distance (or radius) of the object or building in question from the centre of the charge, R, and the mass of explosive expressed as an equivalent mass of TNT, W. These two variables are combined to a scaled distance factor, Z:

\[ Z = \frac{R}{W^{1/3}} \]

The peak side-on overpressure (in bar) is then commonly expressed as a function of the scaled distance factor thus:

\[ P_{so} = \frac{6.7}{Z^3} + 1 \quad P_{so} > 10 \text{ bar} \]
\[ P_{so} = \frac{0.975}{Z} + \frac{1455}{Z^2} + \frac{5.85}{Z^3} \quad 0.1 \leq P_{so} \leq 10 \text{ bar} \]

The duration of the positive phase of the side-on overpressure / time relationship may be expressed as a function of the scaled distance factor and the charge weight, Z and W. As the stand-off distance increases, the duration of the positive-phase blast wave increases resulting in a lower-amplitude, longer-duration positive specific impulse. Means of calculating the duration of the positive pressure phase may be found in literature [28] and are not included in this discussion for brevity.

As a shockwave encounters an object or structure in its path, the incident peak overpressures, \( P_{so} \), may be amplified by a factor which depends on the intensity of the shock wave, and for large explosives at normal incidence these reflection factors may enhance the incident pressures by as much as an order of magnitude [26]. This effect is of significance not only on the incident overpressures resulting from explosives which are placed inside of a room or a building, but also on the side-on overpressures in urban environments. Urban geometry and city layouts will channel blast loading along streets, confining the expanding gas volume and increasing pressure loads [29].

The effects of blast on an element depend on its size and orientation to the direction from which the side-on overpressure is coming. For example, massive structures with a large surface area facing the blast wave will be subject to a large pressure difference between the exposed and unexposed faces whereas thin structures will be subject to drag-loading
as the shock wave passes them and the pressure at the front and sides quickly equalises [25].

### 3.2 Interaction between the blast and structure

The degree of damage resulting from an explosion can be graphically determined from a pressure impulse diagram, where the impulse is defined as the integral of the side-on over pressure vs time diagram over the duration of the positive specific impulse, see figure 6. In this diagram, Pressure-impulse lines are drawn which represent an equivalent level of damage for varying combinations of pressure and impulse. A qualitative assessment of blast damage can be made by considering the area bounded between two pressure-impulse lines [30].

Alternatively, a more advanced analysis may be carried out, however the type of analysis must take account of the frequency of the structure and the duration of the blast wave. There are three distinct loading regimes in the pressure impulse diagram: the impulsive loading regime, the dynamic loading regime and the static loading regime [25]. These are shown in Figure 7. The loading regime for analysis is dependent upon the ratio of the natural frequency of the structure and the duration of the blast wave. For example, flimsy structures with very low natural frequencies will respond quickly to blast loading, and any analysis must take place over the very short timescales associated with the blast wave duration in the impulsive loading regime. Conversely, heavy stiff structures with high natural frequencies may be analysed assuming a quasi-static loading regime. Where the blast wave duration is similar to the natural frequency of the structure then a dynamic loading assessment must be carried out.

![Figure 6 – pressure impulse diagram for a single degree of freedom elastic system with an ideal blast wave, adapted from [25]](image)

Finally, it should be noted that uncertainties associated with blast load calculations and time-dependent deformations are not inconsiderable and their effect on any design calculation should normally be taken into account. Unfortunately, there does not seem to be a comprehensive framework to account for this despite there being several suggestions to apply, for example, the PEER framework [31] to blast loading [32]. On the other hand, this uncertainty is such that often building elements are reduced to an ideal elasto-plastic single degree of freedom system for analysis, reducing the complexity of any calculation which is to be performed.
3.3 Design strategies for limiting the effects of blast

There is a Unified Facilities Criteria which has been published by the US Department of Defence for the design of structures for accidental loading which gives detailed information about the design of concrete and steel structures for blast loading [33]. According to this document, design strategies for designing structures to resist the impact of terrorist actions include the following:

- Maximising standoff distances
- Preventing building collapse
- Minimising hazardous flying debris
- Providing an effective building layout
- Limiting airborne contamination
- Providing mass notification

Maximising stand-off distance clearly addresses the magnitude of the side-on overpressure through the relationship described in §3.1 above. Similarly, providing an effective building layout limits the potential damage by affecting, for example, the ability to place or deliver an explosive device or even potentially by reducing the reflection factors thereby reducing the magnitude of any impulse from the incident pressure. Preventing building collapse from a structural design perspective typically relies upon the guidance which is briefly described above in reference to the Ronan Point incident. However as with structural fire engineering there is an invigorated interest in the response of structures to blast loading. It is hard to pinpoint where this focus on rational design of structures for blast loading begins. However many of the research areas which are being explored are analogous to the avenues which are currently being explored in structural fire engineering as described in more detail below.

Some authors highlight the lack of a relationship between real structural response and the nature of the tying force requirements, as well as a lack of consideration of ductility requirements in elements as a shortcoming of the current provisions [7]. These shortcomings have been the focus of recent research; for example considering the contribution of catenary action to structural resilience and its ability to help to prevent disproportionate collapse [34]; or by considering ductility of connections and other structural details and how this impacts structural robustness [35]. This and other current research is discussed, e.g., in output from COST Action 26: Urban Habitat Constructions under Catastrophic Events [27].

In addition to the consideration of ductility in connections and the effects of membrane action, other authors have proposed the use of a braced frame at the upper level of multi-storey buildings to prevent progressive collapse by providing an efficient alternative load transfer mechanism [36]. Finally, researchers at Imperial College London have proposed a simple assessment methodology of the susceptibility of structures to sudden column loss [7, 37].

4 Discussion

The majority of property damage from external explosions is caused by reflected pressure acting on facades. This is evidenced by the explosions in Oklahoma, Manchester and Buncefield. This leads to window breakage, often causing injury, as seen from secondary injuries reported following the Manchester bombing.
Where the blast impacts upon the structure then significant damage can occur: from the disproportionate collapse seen at Ronan Point to the progressive collapse mechanisms observed at both Ronan Point and in the Oklahoma bombing. Other serious structural damage can be caused without leading to disproportionate or progressive collapse, as evidenced by the world trade centre bombing in 1993 or the Manchester bombing or Buncefield. It is important to note, however, that in the majority of cases discussed progressive or disproportionate collapse has not been evidenced to be an issue, which suggests either that the regulatory changes which followed, e.g. Ronan Point have been successful in limiting damage caused by blast, or that the affected buildings were not susceptible to disproportionate collapse either through design or as a result of the nature of the explosion itself.

There is, however, a clear motivation for considering the effects of blasts on buildings which fall under the definition of multifunctional. Not only from a perspective of life safety but also from a perspective of business continuity. Despite the apparently low frequency of occurrence of such events in Sweden, global trends suggest that instances are on the rise and any implications of this should be considered in future planning. Design of structures for blast loading has apparently seen great progress in recent years. This is almost certainly aided, as in structural fire engineering, by the proliferation of software and computational capacity which can be used for engineering analysis, alternative mechanisms are being explored which both help in rationalising building design as well as identifying potential ‘weak points’, such as connections which may not provide enough ductility in the event of large displacements. Many of the opportunities and challenges which are faced in structural design for blast loading are similar to those which are current in structural fire engineering, such as uncertainty in the loading; as well as difficulties in analysis arising from the complexity of material and member behaviour under large displacements and high strain rates.
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