Likelihood of Progressive Collapse of Buildings from Terrorist Attacks

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ABSTRACT: The paper develops a Probabilistic Risk Assessment model that estimates of the probability of terrorist threat, hazard, damage and loss for progressive collapse of large federal government buildings in the United States. It was found that the existing annual fatality risk for building occupants are lower than acceptable risk criteria, and that progressive collapse is an exceedingly rare event in Western countries. A cost-benefit analysis of UFC and GSA design provisions to mitigate against progressive collapse showed that these design measures only becomes cost-effective when the threat likelihood is a very high one in a thousand per building per year.

1. INTRODUCTION
Terrorist threats against civilian and military infrastructure, particularly buildings, is a concern to the public and government. Improvised Explosive Devices (IEDs), often through the use of suicide tactics and vehicle borne IEDs (VBIEDs) against buildings continue to be the terrorist weapon of choice.

While there have been several structural reliability analyses of structures subject to explosive blast loading, there has been little research to identify the annual risk exposure of buildings to IED Attack (Stewart 2008, 2011). Most vulnerability assessments assume that an IED will successfully detonate and subsequently will reach maximum TNT Equivalency. Despite being conceptually simple devices to design and manufacture, IED performance is highly uncertain. IEDs are typically ‘home made’ and placed under imperfect conditions, causing the potential for failure, as evidenced in numerous failed attempts between 2001 to 2014. Indeed, since 9/11, only one attack consisting of two explosions has occurred in the United States (Boston 2013) and, except for the four bombs on the Underground in London in 2005, no IED attack has been successful in the United Kingdom (Mueller and Stewart 2011a). Notably, these incidents did not involve VBIEDs, presumably due to the complexities associated with achieving a successful IED Attack with these weapons.

There is a clear recognition that uncertainty and variability are associated with many variables describing a structure’s performance, and that this can be accounted for explicitly by the use of probability and structural reliability theory (Stewart 2012). A similar situation arises regarding the human factors associated with IED Attack, including those associated with planning for the attack, target selection, IED selection, placement of the IED, and timing the initiation of the IED (Grant and Stewart 2012).

Given the complexities regarding tactical analysis of building risks from IED Attack, for most circumstances, a more strategic assessment employing a Probabilistic Risk Assessment (PRA) may prove of greater utility. These PRAs could be relatively straightforward, yet provide valuable insight into the cost-effectiveness of
counter-measures to provide protection for critical infrastructure and personnel. Moreover, it provides a basis for the development of evidence-based policy.

The paper describes existing fatality risks from progressive collapse, and then assesses the costs and benefits of design (protective) measures mandated by the United States to mitigate against progressive collapse for federal government (civilian and defence) buildings (UFC 4-023-03, GSA 2014). Hazard, damage, and loss likelihoods, risk reduction, loss, and protective costs are modelled stochastically, which enables the probability that protective measures are cost-effective to be inferred. Where possible, we use actual or representative threat, vulnerability, loss and cost data. Finally, we recognise that the risk and cost-benefit analyses presented herein are preliminary, and based on our best estimates using a limited dataset of terrorist attacks and progressive failure. However, they are instructive, and provide the basis for further research.

2. PROGRESSIVE COLLAPSE PROVISIONS

The 1995 bombing of the Murrah Building in Oklahoma City and the tragic events of 9/11, lead the United States to develop design guidelines to minimise the occurrence of progressive collapse for military and federal government buildings (UFC 4-023-03, GSA 2014). For a full discussion of these standards see Marchand and Stevens (2013). The additional structural frame cost if design incorporates progressive collapse provisions is 9-62% for the case studies presented in UFC 4-023-03 (Marchand and Stevens 2013). However, the additional cost of the building as a whole is only 1-4%.

Progressive collapse is defined as (ASCE 2013) “the spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it.”

The U.S. Department of Defense (DoD) Minimum Antiterrorism Standards for Buildings UFC 4-010-01 states that “new and existing DoD buildings of three stories or more required to comply with these standards, regardless of the standoff distance provided, follow the requirements in UFC 4-023-03 Design of Buildings to Resist Progressive Collapse. Design the superstructures to sustain local damage with the structural systems remaining stable without being damaged to extents disproportionate to the original local damage.” The DoD currently owns or leases 230,000 buildings in the U.S. valued at over $700 billion and comprising over 175 million m$^2$. It is likely that a decent proportion of defence buildings will be three stories or higher. We will assume a modest 5-10% - or approximately 12,000-23,000 buildings.

The United States General Services Administration (GSA) manages nearly 10,000 civilian federal government buildings, including more than 250 federal buildings in Washington D.C. alone. The Facility Security Level (FSL) must exceed FSL III for progressive collapse design to be applied to a new or renovated building (Marchand and Stevens 2013). According to ISC (2013), an FSL of III or more is not difficult to attain for many federal buildings, for example, the Social Security Administration Headquarters, Census Bureau, and Environmental Protection Agency Headquarters have an FSL of III. Clearly, many buildings in the GSA inventory would fit into these categories, particularly those in Washington, D.C. We will assume a modest 25% - or approximately 2,500 buildings require the application of progressive collapse design.

3. PRA MODEL

Annual Fatality Risk (AFR) is expressed as:

\[
AFR = \sum \Pr(T) \Pr(H|T) \Pr(D|H) \Pr(L|D) \quad (1)
\]

where \(\Pr(T)\) is the annual threat probability, \(\Pr(H|T)\) is the conditional probability of a hazard (combination of initiation of an IEDs main charge and the operational aspects of the attack) given occurrence of the threat, \(\Pr(D|H)\) is the conditional probability of damage state (collapse,
glazing damage, etc.), and $\Pr(L|D)$ is the conditional probability of a fatality given occurrence of the damage. The summation sign in Eq. (1) refers to the number of possible threat scenarios, hazard levels and losses.

The Net Present Value (NPV) or net benefit for a protective or security measures is

$$\text{NPV} = \Pr(T) \Pr(H|T) \Pr(L|H) \Delta R - C_{\text{security}} \tag{2}$$

where $\Pr(L|H)$ is the probability of loss conditional on the hazard, $\Delta R$ is the risk reduction attained from protective or security measures, $L$ is the direct and indirect economic loss arising from direct physical damage, loss of life and injuries, and indirect losses such as reduction in tourism, GDP, etc, and $C_{\text{security}}$ is the security cost. Net present value is measured per annum, hence, $C_{\text{security}}$ is an annual cost of security. Equation (2) is a simplification of what is a spatial and time-dependent process, see Stewart (2011) for more details.

In the Western context, IED Attacks causing significant building damage generally result in few casualties and fatalities (Grant and Stewart 2014). Fortunately, progressive collapse is extremely rare, which leads to claims that there are too few incidents to support detailed risk assessments (e.g., Marchand and Stevens 2013). However, this feature is not unique to progressive collapse. Nuclear power plants are also low probability - high consequence systems, with very few catastrophic failures, yet PRA techniques have been widely used to assess the safety and reliability of nuclear power plants for many decades.

4. CASE STUDY - LARGE GOVERNMENT BUILDINGS IN THE UNITED STATES

This case study aims to assess the existing risk to personnel arising from a VBIED Attack upon a large federal government (military or civilian) building in the U.S. where there has not been a direct threat made against the building or its occupants. The building is not designed to UFC or GSA progressive collapse requirements.

4.1. Annual Fatality Risks

4.1.1. Threat Likelihood $\Pr(T)$

Stewart (2008, 2011) has suggested that the annual terrorist threat probability $\Pr(T)$ for large US commercial buildings (excludes government and military buildings), those with greater than five stories, is approximately $5.1 \times 10^{-6}$/building/year, for buildings subject to a non-specific threat.

Ellingwood (2006) suggests that the minimum threat probability may be increased to $10^{-4}$/building/year for high density occupancies, infrastructure close to economic centres, key governmental and international institutions, monumental or iconic buildings or other critical facilities with a specific threat.

We can look at this another way. Progressive collapse design provisions seem applicable to something like 20,000 military and civilian government buildings in the United States (see Section 2). If there is one VBIED threat against one of these buildings per year, and the threat involves an VBIED large enough to cause progressive collapse if the attack is 100% successful, then the annual threat probability is $\Pr(T) = 5 \times 10^{-5}$/building/year. In reality, the threat to large U.S. federal government buildings has not been observed as approaching one serious threat per year.

Since 9/11, 55 cases have come to light of Islamist extremist terrorism, whether based in the United States or abroad, in which the United States itself has been, or apparently has been, targeted (Mueller 2014). Eight of these cases, or one case every two years, involved planning to detonate a VBIED against a building - only one of the targets was a federal government building. We will be conservative and assume two VBIED threats against approximately 20,000 large government buildings over the period 2001 - 2013 results in $\Pr(T) = 8 \times 10^{-6}$/building/year.

4.1.2. Hazard Likelihood $\Pr(H|T)$

Hazard likelihood $\Pr(H|T)$ in Eq. (1) can be further devolved to explicitly address complexities involved in IED Attack:
\[
\Pr(H|T) = \text{PSM}_{D&M} \times \text{PSM}_{Ops} \times R
\]

where PSF\text{D&M} is the Performance Shaping Factor (PSF) for design and manufacture of an IED, PSF\text{Ops} is the PSF for the operational aspects of the IED Attack, and R is the baseline reliability of the IED (i.e. IED design and manufacture to military standards).

Grant and Stewart (2012) describe the process for developing PSFs to characterise the human factors effects affecting IED Attack, and identified that PSFs were affected by National Culture, Organisational Culture, and Training or Education.

Grant and Stewart (2012) also found that the baseline reliability (R) is high, 92% for a mobile phone initiated VBIED. However, PSF\text{D&M} and PSF\text{Ops} can be as low as 52% and 21%, respectively, for terrorists operating in Western countries. In other words, the likelihood that an IED attack will cause damage or casualties is approximately 15-20% for terrorists operating in Western countries. Clearly, PSFs have a considerable effect on hazard likelihood.

In order to progress our model we require a large body of IED incident data. One open source database from which data is available, the Global Terror Database (GTD), is collated by the National Consortium for the Study of Terrorism and Responses to Terrorism (START) at the University of Maryland (START 2010). The dataset contained over 5300 incidents of IED Attack worldwide in the period 1998 - 2008, with 220 of these incidents involving significant building damage arising from a broad range of IED attacks, including Vehicle and Personnel Borne IEDs that were placed in and around buildings. Note that the GTD 2010 contains detailed descriptors of damage and loss only for the period 1998 - 2008.

A more recent study considered the GTD dataset for the US domestic and Western environments by considering how many IED Attacks were successful (caused >USD$1 million economic damage and/or casualties) compared to how many IED Attacks were perpetrated in the period 1998 - 2008 (Grant and Stewart 2014). For the U.S. it was found that \(\Pr(H|T) = 15\%\). Note that this is lower than for the Western average of \(\Pr(H|T) = 23\%\), that is, IED Attacks in the US are less likely to succeed than for other areas in the Western world.

The likelihood that a one tonne or larger IED (which would be needed to cause progressive collapse) would successfully detonate, and reach maximum energetic output will be lower than 15%, particularly taking into account the difficulty of obtaining explosives and preparing them for maximum energetic output. This is particularly apt for ‘home made’ Ammonium Nitrate Fuel Oil (ANFO).

A triangular probability distribution is used to represent uncertainty of \(\Pr(H|T)\), see Table 1 and Figure 1.

<table>
<thead>
<tr>
<th>Probability Likelihood</th>
<th>Low</th>
<th>Mid</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Pr(H</td>
<td>T))</td>
<td>0%</td>
<td>15%</td>
</tr>
<tr>
<td>(\Pr(D</td>
<td>H))</td>
<td>0%</td>
<td>7%</td>
</tr>
<tr>
<td>(\Pr(L</td>
<td>D))</td>
<td>85%</td>
<td>93%</td>
</tr>
<tr>
<td>(\Pr(L</td>
<td>H))</td>
<td>0%</td>
<td>7%</td>
</tr>
</tbody>
</table>

Figure 1: Triangular Distribution.

4.1.3. Damage Likelihood \(\Pr(D|H)\)

The likelihood of progressive collapse will be very low. This is partly due to the large size of a VBIED necessary to cause progressive collapse, and also the robustness of many structures against progressive collapse.

The evidence to date shows that no modern
or well-designed tall or large building has fully collapsed as a result of an VBIED; the 4,000 kg truck bomb on the Marine Barracks in Beirut in 1983, and the several tonne truck bomb in Oklahoma City in 1995 caused partial progressive collapse. Moreover, experience in the UK shows that intense blast loadings cause little structural damage to reinforced concrete (RC) or steel framed buildings designed to modern codes. Most damage occurs to the building facade, particularly glazed areas (Smith and Rose 2002). This is not to say, though, that blast loadings cannot cause severe structural damage, such as that experienced by the Murrah Building in Oklahoma City. However, in this case, partial collapse of the building was caused by disintegration of a critical column causing progressive collapse. If the building had been designed as a Special Moment Frame for earthquake design then loss of floor area would have been reduced by between 50-80% (Corley, et al. 1998). Damage to the Pentagon on September 11 2001 was contained by the structures’ resilience to progressive collapse, namely, its continuity, redundancy and energy-absorbing capacity (ASCE 2003). This is why progressive collapse provisions are now being incorporated into US design codes (UFC 4-020-01, GSA 2014). Hence, with the exception of extraordinarily large blasts, a moment resisting RC or structural steel frame designed and detailed for alternative load paths should provide significant structural resistance to prevent collapse.

Numerical and stochastic modelling of multi-storey buildings to explosive blast loads and the likelihood of progressive collapse reveal that Pr(D|H) is 0-10% for a 250-900 kg VBIED detonated within 20 m from a 10 storey building (Kelliher and Sutton-Swaby 2012), and removing a ground floor column of a 31 storey building causes a Pr(D|H)=16% probability of total collapse (Le and Xue 2014). This assumes of course, that the VBIED is located in very close proximity to a structural column, a task not made easier by the ever present bollards and other anti-vehicle barriers.

Words of estimative probability are supplied in Table 2 (adapted from Fletcher 2011), and they are then applied to damage and loss rates. As a mid-point estimate, we assume that likelihood of complete progressive collapse is ‘almost certainly not’ given the difficulty in manoeuvring a truck sized VBIED in close proximity to a building’s supporting column, and according to Table 2 Pr(D|H)=7%. An upper bound may be 30%.

Table 2: Words of Estimative Probability.

<table>
<thead>
<tr>
<th>Probability</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Certain</td>
<td>100%</td>
</tr>
<tr>
<td>Almost certain</td>
<td>93%</td>
</tr>
<tr>
<td>Highly probable</td>
<td>85%</td>
</tr>
<tr>
<td>Probable</td>
<td>75%</td>
</tr>
<tr>
<td>Chances about even</td>
<td>50%</td>
</tr>
<tr>
<td>Probably not</td>
<td>30%</td>
</tr>
<tr>
<td>Almost certainly not</td>
<td>7%</td>
</tr>
<tr>
<td>Impossible</td>
<td>0%</td>
</tr>
</tbody>
</table>

4.1.4. Loss Estimates Pr(L|D)
The probability that an individual is killed in a damaged building is, in most cases, quite low. However, for total progressive collapse the fatality rate would be near 100%, noting that there would be some survivors rescued from voids in the collapsed building.

It would be ‘almost certain’ that a person in a collapsed building would be killed, so mid-value for Pr(L|D)=93%, with a lower value of Pr(L|D)=85% for ‘highly probable’ of a fatality.

This paper assumes damage D is total progressive collapse, so the mid-value of expected fatalities given an attack is Pr(D|H)Pr(L|D) is 6.5%. If we defined D as partial or total collapse, then Pr(D|H) would increase, but Pr(L|D) would decrease as then not everyone in a building would be in danger. The resulting product Pr(D|H)Pr(L|D) would thus remain relatively unchanged.

4.1.5. Acceptable Risk

The consensus risk acceptance criteria for involuntary fatality risk to an individual is that annual fatality risks smaller than $1 \times 10^{-6}$ are
deemed as negligible and further regulation is not warranted (Stewart and Melchers 1997).

4.1.6. Results

A life-safety risk analysis is considered for VBIED threats to large federal government buildings, and that these buildings have not been designed to UFC or GSA progressive collapse provisions. The existing risk is stochastic due to the stochastic nature of hazard, damage and loss likelihoods. Hence, the probability that annual fatality risk exceeds the acceptance criteria of $1 \times 10^{-6}$ can be estimated. Table 3 shows that there is zero likelihood of existing risk exceeding acceptable risk for annual threat probabilities less than $8 \times 10^{-6}$/building/year, and is only 25.3% for the highest observed threat likelihood of $5 \times 10^{-5}$.

<table>
<thead>
<tr>
<th>Pr(T) /building/year</th>
<th>Mean Annual Fatality Risk</th>
<th>Pr(AFR $&gt; 1 \times 10^{-6}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2 \times 10^{-6}$</td>
<td>$3.0 \times 10^{-8}$</td>
<td>0%</td>
</tr>
<tr>
<td>$8 \times 10^{-6}$</td>
<td>$1.2 \times 10^{-7}$</td>
<td>0%</td>
</tr>
<tr>
<td>$5 \times 10^{-5}$</td>
<td>$7.5 \times 10^{-7}$</td>
<td>25.3%</td>
</tr>
<tr>
<td>$1 \times 10^{-4}$</td>
<td>$1.5 \times 10^{-6}$</td>
<td>62.4%</td>
</tr>
</tbody>
</table>

4.2. Cost-Effectiveness of Protective Measures

4.2.1. Loss Likelihood Pr(L|H)

A large VBIED attack on a building is unlikely to cause progressive collapse. Section 4.1.3 showed that a mid-estimate for damage (progressive collapse) likelihood is 7%. Hence, in this case, we assume that Pr(L|H) = Pr(D|H) and is modelled as a triangular distribution as per Table 1. Note that if progressive collapse were not to occur, the likelihood of loss of life, property damage and other direct and indirect losses would be considerable. However, progressive collapse provisions will not reduce the casualties, damage to adjacent properties, loss of tourism and consumer confidence, etc. Hence, these losses cannot be reduced by progressive collapse provisions and so are excluded from the cost-benefit analysis conducted herein.

4.2.2. Loss L

The 2004 attacks on trains in Madrid, and the 2005 attacks on underground trains and a bus in London caused $2-5$ billion in losses. Losses from VBIED attacks on the World Trade Center in 1993, and Oklahoma City in 1995 come to several billion dollars. It is important to stress, however, that very few terrorist attacks exact damage on the scale of these. Analysis of the GTD shows that of 219 terrorist incidents in the U.K. involving explosives, only two inflicted damage that the GTD considered “catastrophic” - a bombing in London that killed three people in 1992 and the 1993 London financial area bombing, each causing losses of $1$ to $2$ billion. The 2001 attack on the Pentagon caused up to $10$ billion in losses, and the attacks on the World Trade Center close to $200$ billion. For more details see Mueller and Stewart (2011a,b).

The 9/11 attacks on the World Trade Center represent very much an outlier of economic and social losses from terrorism, and are the largest in history. A more reasonable upper bound is $10$ billion, and a lower bound of $1$ billion. This is modelled as a uniform distribution.

4.2.3. Risk Reduction $\Delta R$

We assume considerable risk reduction for UFC and GSA progressive collapse provisions. Low, mid and high risk reductions are 80%, 90% and 100% modelled as a triangular distribution. This is conservative, and one that will bias the results in favour of finding that progressive collapse provisions are cost-effective.

4.2.4. Cost of Protective Measures $C_{security}$

Marchand and Stevens (2013) show the additional cost of construction when progressive collapse provisions in UFC and GSA guidelines are incorporated in the design of the building. In this case, by ensuring that the building is stable when one exterior supporting column is removed from the structure. The additional costs range from $633,000$ for a 7 storey RC framed building, to $196,000$-$502,000$ for a 4 storey steel framed building. When annualised over a 50-year design life at a 4% discount rate the
annualised additional cost is $10,000 to $30,000 per building. The costs are likely to be higher for larger buildings. Nonetheless, we assume that \( C_{\text{security}} \) is modelled as a uniform distribution between $10,000 - $30,000 per building per year.

4.2.5. Results of Cost-Benefit Analysis

The mean NPV, mean benefit-to-cost ratio (BCR), and probability that NPV>0 are shown in Table 4. For a high threat probability of \( 1 \times 10^{-4} \) per building per year there is a net loss of more than $11,000/building/year, meaning that $1 of cost buys only 46 cents of benefit. As expected, the probability that protective measures against progressive collapse are cost-effective is less than 1% for realistic threat probabilities. The threat probability has to approach one in a thousand for high surety that protective measures are cost-effective.

<table>
<thead>
<tr>
<th>( \Pr(T)/\text{building/year} )</th>
<th>Mean NPV</th>
<th>Mean BCR</th>
<th>( \Pr(\text{NPV}&gt;0) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 2 \times 10^{-6} )</td>
<td>-$19,980</td>
<td>0.01</td>
<td>0%</td>
</tr>
<tr>
<td>( 8 \times 10^{-6} )</td>
<td>-$19,350</td>
<td>0.04</td>
<td>0%</td>
</tr>
<tr>
<td>( 5 \times 10^{-5} )</td>
<td>-$16,050</td>
<td>0.23</td>
<td>1%</td>
</tr>
<tr>
<td>( 1 \times 10^{-4} )</td>
<td>-$11,620</td>
<td>0.46</td>
<td>10%</td>
</tr>
<tr>
<td>( 1 \times 10^{-3} )</td>
<td>$62,050</td>
<td>4.44</td>
<td>83%</td>
</tr>
</tbody>
</table>

5. DISCUSSION

Tables 3 and 4 suggest that reducing the annual probability of threat would be the most effective countermeasure to reducing the effects of VBIED Attacks upon buildings. Mueller and Stewart (2011) conclude that protecting against essentially random conventional terrorist attacks is futile; and that only target sets where quite large physical, economic, psychological and/or political consequences may warrant specific protective measures. Moreover, spending on policing and intelligence measures (such as the Federal Bureau of Investigation) to warn or prevent terrorist attacks is likely to be the more cost-effective countermeasure as this would have the greatest impact on the threat probability for buildings (Mueller and Stewart 2011a, 2014).

Terrorist threats continue to evolve. Our assessment has been heavily reliant upon historical open-source data and as a result it has not been possible to consider all of the complexities associated with VBIED Attacks upon buildings. One significant reason for this is the low frequency of terrorist incidents in Western countries that cause significant damage to buildings. It is entirely possible that threat, hazard and loss probabilities could change significantly as a result of a series of large-scale, well designed and planned terror events. Or perhaps more likely, the catastrophic attacks on September 11 2001 were an aberration rather than a harbinger of things to come, as evidenced by the low incidence of terrorist attacks in the U.S. since 9/11. However, although there is no guarantee that the terrorism frequencies of the past will necessarily persist into the future, there seems to be little evidence terrorists are becoming any more destructive, particularly in the West. In fact, if anything, there seems to be a diminishing, not expanding, level of terrorist activity and destruction at least outside of war zones (eg. Mack 2008).

Despite this, our assessment was quite conservative and provides a valuable starting point to better understand the risks associated with VBIED Attacks upon buildings. This work is important to inform decision-makers and ensure that effective cost-benefit analysis can be conducted, particularly should the threat of VBIED Attack become a significant influence upon building design and construction standards into the future.

6. CONCLUSIONS

A probabilistic risk assessment can be effectively used to identify the risks associated with VBIED attacks to buildings. Existing annual fatality risk for large federal government building occupants are lower than acceptable risk criteria, and that progressive collapse is an exceedingly rare event in Western countries. UFC and GSA design provisions to mitigate against progressive collapse showed that they only become cost-effective when the threat likelihood is a very high one in a thousand per building per year. The
co-benefit of protective measures may be considerable if strengthening a building to be more blast-resistant has the co-benefit of reducing the risks from seismic, vehicle impact, or other hazards.

7. REFERENCES
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