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Assessment of risk reduction strategies for terrorist attacks on structures

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ABSTRACT

Attacks on infrastructure have been a common feature of terrorism over many decades. The weapon of choice is often a Vehicle-Borne Improvised Explosive Device (VBIED) or a person-borne or other type of IED. The consequences of a successful attack in terms of casualties, physical damage, and other direct and indirect costs including societal costs can be catastrophic. Protectives and other risk reduction measures can ameliorate the threat likelihood, vulnerability or consequences. There is a need for a rational approach to deciding how best to protect infrastructure, and what not to protect. Hence, this paper describes a probabilistic risk assessment for the protection of infrastructure from explosive attacks. This includes a description of terrorist threats and hazards, vulnerability assessment including progressive or disproportionate collapse, and consequences assessment. Illustrative examples of the decision analysis consider the optimal risk reduction and design strategies for bridges and the progressive collapse of buildings.

1. Introduction

Acts of terrorism, insurgency, sabotage, or other malevolent events aim to cause damage to structural systems such as buildings, bridges, offshore platforms, process plants, communication towers, pipelines, dams, and others. These events may be classified as extraordinary or low probability – high consequence events. Terrorist attack hazards may include blast loading from explosives or other energetic materials; ballistic impact from munitions and weapons; vehicle, aircraft or ship impact on structures or protective devices such as bollards; uncontrolled discharge from dams; train derailment or other hazards that affect the strength, serviceability or stability of structures.

The number of people killed by Islamist extremist terrorists since 9/11 in the US is about six per year and less than four per year in the UK, while for Canada and Australia, it is two or three in the last decade. The annual fatality risks from terrorism in the developed world are, in almost all cases, less than one in 1 million per year [60]. For the United States from 1970 through 2016, they are one in 4 million per year. For the period from 2002 through 2016, they are one in 39 million per year. For the same period in Western Europe the odds are higher at 1 in 9 million per year. Therefore, they generally lie within the range deemed by regulators internationally to be safe or acceptable and do not require further regulation.

Terrorism though can lead also to large physical damage, direct and indirect economic losses, and social, psychological and/or political consequences unlike that experienced with natural hazards. For example, the 9/11 attacks resulted in approximately $250 billion in loss of life, property damage, and direct and indirect economic consequences, as well as leading to the Wars on Terror in Afghanistan, Iraq and Syria. Hence, decisions on risk reduction strategies need to also be based on the tradeoffs between protective costs and how risk reduction strategies reduce the likelihood and extent of economic, social and other losses. This may be achieved by risk-based decision theory.

Mueller and Stewart [39,40] and Stewart and Mueller [60] assessed the risks, costs, and benefits of homeland security and counter-terrorism strategies for infrastructure protection, policing and aviation security. This paper expands this work, and develops a probabilistic risk assessment for the optimal protection of infrastructure from explosive attacks. This also builds upon the works of Ellingwood [17–18], Stewart [53–54,57], Stewart and Li [59], El Sayed et al. [16], Beck et al. [4–6], and others. Stewart [57] found that the threat likelihood needs to exceed something like one in a thousand or one in ten thousand per building per year for blast-resistant design measures to be cost-effective. Beck et al. [4–6] reached a similar conclusion when assessing the effect of column removal on progressive collapse of low-to-medium height buildings. Similar findings were also found for the protection of bridges [67], and

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when using the Life Quality Index [69]. This paper is also an expanded and improved version of the following documents:

- Annex K to Bases for Design of Structures – General Principles on Risk Assessment of Systems Involving Structures (ISO 13824 [31]) dealing with Terrorism and Malevolent Events.
- Joint Committee on Structural Safety (JCSS) publication: Assessment of Risk Reduction Strategies for Terrorist Attacks on Structures [68].

2. Terrorism risk assessment

The risk assessment necessitates the identification, formulation and modelling of all relevant hazard, damage and failure scenarios which lead to consequences affecting the integrity, stability or functionality of constituents and systems.

The formulation for the risk assessment follows the JCSS document on *Risk Assessment in Engineering - Principles, System Representation & Risk Criteria* [19]. The risks are quantified as the sum of the direct and the indirect risks R_D and R_{ID} associated to direct and indirect consequences. The risks are calculated by aggregating exposures and damage and system failure states, leading to:

$$R = R_D + R_{ID} = \sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} \sum_{m=1}^{n_{SSTA}} \left[C_{ID}(S_m, C_D(\mathbf{C}_l)) \bullet p(S_m|\mathbf{C}_l, EX_k) + C_D(\mathbf{C}_l) \right] \bullet p(\mathbf{C}_l|EX_k) \bullet p(EX_k) \quad (1)$$

where n_{EXP} is the number of exposures, annual exposure probability is $p(EX_k)$, direct consequence probability is $p(\mathbf{C}_l|EX_k)$, n_{CSTA} is the number of constituent damage states, damage state is $\mathbf{C}_l$, direct consequences is $C_D(\mathbf{C}_l)$, n_{SSTA} is the number of system failure states each represented as S_m, probability of system failure is $p(S_m|\mathbf{C}_l, EX_k)$, an indirect consequences is $C_{ID}(S_m, C_D(\mathbf{C}_l))$. This formulation provides the basis the for risk-based optimal protection of structures.

3. Threat and hazard assessment

3.1. Terrorist threats to structures

The exposure probability is calculated with the probability of a threat $p(T_k)$ and the probability of a hazard (exposure) given a threat $p(EX_k|T_k)$:

$$p(EX_k) = p(EX_k|T_k) \bullet p(T_k) \quad (2)$$

The threat constitutes the intent to attack or damage a system involving structures. A threat assessment should allow for the modelling of the k relevant threat scenarios covering the time period of the risk analysis. As discussed in Section 1 this may take on various forms. The nature of the threat will depend on the motive of the attack, target selection, capabilities of the adversaries, their access to materials or equipment, and the damage or loss they are trying to inflict. A threat assessment, typically informed by advice from police and security services, allows reasonable threat scenarios to be described – such as Vehicle-Borne Improvised Explosive Devices (VBIEDs), person-borne IEDs, vehicle impact, etc. Government agencies and standards also provide guidance on threats and hazards to consider (e.g., [20,73]). Analysis of past events is also informative. The Global Terrorism Database [27] is an open-source comprehensive database of 170,000 terror attacks from 1970.

If there is no specific threat, which applies to most infrastructure, then Ellingwood [18] and Stewart [52–54] have suggested that a mean occurrence rate for bombing attacks on large U.S. buildings is between 2 $\times$ 10^{-6}/building/year to 8 $\times$ 10^{-6}/building/year. This probability may be increased to 10^{-4}/building/year for key governmental institutions, iconic buildings or other critical facilities with a specific threat [17]. These are mean occurrence rates which assume that attacks and target selection are random. This is unlikely to be the case for terrorist and other malevolent events [18,39]. Nonetheless, they provide a useful starting point for analysis.

As there is high uncertainty associated with threat probabilities, a scenario-based approach based on occurrence of a specific threat may also be useful for a risk assessment (e.g., [45,22]). In this case, Eq. (1) becomes a conditional risk. A set of threat scenarios may be selected to assess levels of conditional risk across a broad spectrum of threats. Another approach to decision-making is also to consider a “break-even” analysis. The variable with the largest uncertainty tends to be the likelihood of an attack. Hence, a decision analysis can be configured such that a risk treatment is acceptable if, for instance, the threat probability exceeds a break-even value. It is then for security and policing agencies to determine if they believe the threat probability does or does not exceed this value. A benefit of this approach is that the threat probability need not be known to high accuracy; for example, if security agencies estimate the threat probability to be in the region of 1 in 1000 to 1 in 10,000, and the break-even value is 1.4 $\times$ 10^{-2} then the threat probability is clearly lower than the threshold, and this may justify no additional protective measures.

The main terrorist threat to structures remains the IED. The probability that an IED will inflict damage is about 20% for terrorists in Western countries, whereas the probability that a terrorist or insurgent IED attack in the Middle East will be successful is more than three times higher mainly because there is more opportunity for IED operational skills and explosives to be acquired [23–24]. This may help explain why no terrorist has been able successfully to detonate a bomb of that sort in the United States since 2001, and the explosions in Brussels in March 2016 marked the first time terrorists have been able to kill with explosives anywhere in Western Europe in over a decade. For more details on the nature of the terrorist adversary see Mueller and Stewart [39–40] and Stewart and Mueller [61].

Most of these IED attacks involved a Person-Borne Improvised Explosive Device (PBIED) containing less than 10 kg of explosives [41]. This is not unexpected, as an analysis of bomb incidents has found that most IEDs are less than 5 kg [76]. It is important to note that design threats specified by government and security organizations is often based on what is possible. Hence, according to Don Williams, a leading blast consultant in Australia, “*Consideration should be given to what is ‘probable’ rather than ‘possible’*” [77].

3.2. Hazards – explosive blast loading

The hazard is the expected loading or demand given the threat like e.g. the structural force resulting from a vehicle impact or airblast from an explosion. The hazard probability should be calculated accounting for the process of realising the threat which is e.g. for an IED the manufacturing, the placement and technical reliability of the detonation mechanism. The hazard probability can be modelled discretely, distributed or as a hazard curve. For example, the likelihood that a terrorist bomb or IED will successfully detonate and reach its full energetic potential is less than $p(EX_k|T_k) = 20\%$ for attacks in Western countries [24].

The main hazards from terrorism that may affect structural performance are explosive blast and fragmentation loading, and vehicle impact. The latter is unlikely to be a serious hazard for large structures, however, it is the governing load case for designing and assessing the effectiveness of vehicle impact barriers and bollards. Hence, the hazards of interest are blast overpressure, primary fragmentation of the device, debris (secondary fragmentation) of the building structure and components, and thermal effects arising from detonation of explosives.

Fragmentation as a hazard to the building and its occupants is beyond the scope of the present paper. However, a brief overview is provided. Modelling of primary and secondary (debris) fragmentation hazards is difficult due to the many parameters that must be taken into account. Primary fragmentation hazards (such as shrapnel from car body and engine parts from a VBIED) pose a significant hazard to people exposed directly to an IED (such as on a street), but are unlikely to cause severe structural damage to a building. However, secondary fragmentation from the building itself, particularly glazing, may be a significant safety hazard to building occupants (e.g., [42]).

The detonation of high explosives releases a significant amount of energy, which heats up the immediate environment as well as producing gas. The violent expansion of these hot gases creates blast waves in any air surrounding the explosive. Fig. 1 shows the pressure–time curve for the detonation of high explosives. The explosive yield of high explosives is measured in terms of TNT equivalence where 1 kg of TNT is 4.2 MJ (e.g., [29,2]), see Table 1.

More details on accidental and malevolent explosive blast loading, including event frequencies, are available from design standards ISO 10252 [29], ISO 13824 [31], ASCE/SEI 59-11 [2], UFC 3-340-02 [75], etc. and in numerous texts.

3.2.1. Airblast modelling

Explosive blast loading is uncertain and variable. The sudden release of energy following detonation of an explosive is a complex phenomenon with temporal and spatial variability associated with the emanation of a shock-wave.

Important sources of variability are (i) model uncertainty and (ii) inherent or aleatory uncertainty (e.g., [71]). However, it is not possible to separate these effects from explosive field trials – i.e., aleatory and epistemic uncertainties cannot be distinguished from field trials. Hence, model uncertainty is defined as the accuracy of predictive load models including inherent variability. Two other important sources of variability are equivalent explosive mass (W) and range or distance from the explosive (R).

Explosive blast loads may be predicted from (i) empirical or (ii) Computational Fluid Dynamics (CFD) modelling. These models may be applied to interior or external explosions, although data on modelling and inherent uncertainties are limited at this point in time to empirical methods for exterior blast loading.

The most widely used empirical method for exterior free-field detonations is the Kingery-Bulmash [34] model used in ISO 10252 [29], ASCE/SEI 59-11 [2] and other design codes and manuals to estimate exterior blast loads on buildings assuming that the explosive detonates on or near to the ground. It is thus considered a free-field hemispherical charge detonating against a reflecting surface, and reflections from other structures are not considered. Blast pressures may be estimated as an incident (side-on) pressure (or overpressure) or a reflected pressure. A reflected pressure arises from the blast wave hitting a solid surface, and so is the loading of interest when modelling the structural response to blast. On the other hand, simplified structural damage criteria are often

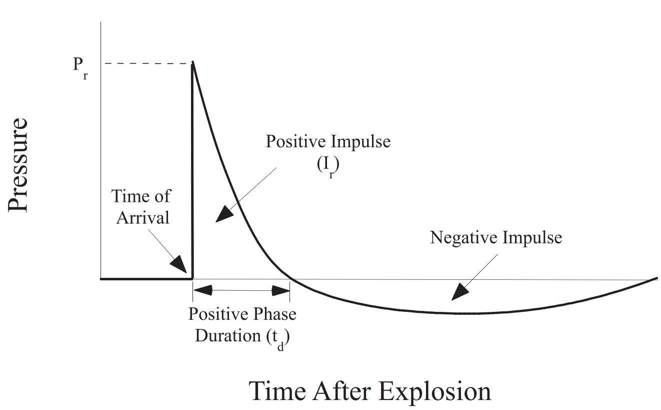

Fig. 1. Idealized Pressure-Time History Curve Showing Peak Reflected Pressure (P_r) and Impulse (I_r).

Table 1
Equivalent TNT Mass for Typical Explosives (adapted from [72]).

Explosive	Equivalent TNT Mass		Overpressure Range (MPa)
	Peak Pressure	Impulse	
TNT	1.00	1.00	Standard
ANFO	0.87	0.87	0.03–6.90
Composition C4	1.20	1.19	0.07–1.38
	1.37	1.19	1.38–20.7
H-6	1.38	1.15	0.03–0.70
PETN	1.27	1.27	0.03–0.69
Tritonal	1.07	0.96	0.03–0.69

based on values of incident pressure (e.g. [21]).

3.2.2. Model uncertainty and inherent variability

The Kingery and Bulmash [34] model provides a very good prediction of blast loads from bare (uncased) explosives in a free-field environment. Stewart et al. [64] measured the pressure and impulse from 90 free-field explosions of mass of explosive of up to 1.8 kg leading to 593 pressure and impulse observations. When combined with other data this leads to model uncertainties as shown in Table 2. These free-field data represent the “simplest” scenario and is thus an indication of the minimum variability for airblast parameters. In the absence of specific data, CFD models tend to have high accuracy leading to model uncertainty with no bias and a COV of 0.05 (e.g., [35].

3.2.3. Variability of equivalent explosive mass

The following discussion of variability of W and R is illustrative only (hypothetical), and will describe the type of information that is required to help quantify airblast variability. For more practical examples see Stewart [55–56,58].

The equivalent explosive mass is estimated as

$$W = W_{TNT} \times W_{mass} \quad (3)$$

where W_{TNT} is the TNT effectiveness factor, and W_{mass} is the actual mass of explosives.

The TNT effectiveness factor recognizes that the equivalent TNT mass of an explosive can vary due to variations in constituents and mix proportions during manufacture. Variability may also arise from variability of charge shape, casing effects, placement and type of detonators, etc.

The charge mass (W_{mass}) may be known for a military weapon or explosive ordnance, but less so for malevolent or terrorist attacks. There may be variability in W_{mass} due to weighing and mixing tolerances, human error in the mass selected or used, or uncertainty about predicting the amount of explosives to be used by terrorists.

The coefficient of variation of equivalent explosive mass (V_W) is approximately

$$V_W = \sqrt{V_{TNT}^2 + V_{mass}^2} \quad (4)$$

where the coefficients of variation V_{TNT} and V_{mass} are considered to be statistically independent. Most design and assessment guidance is

Table 2
Airblast model uncertainties for bare charges [64].

	Mean	COV	Distribution
Pressure:			
$0.59\ m/kg^{1/3} \le Z \le 3.0\ m/kg^{1/3}$	1.06–0.005Z	0.1175–0.0125Z	Lognormal
$3.0\ m/kg^{1/3} < Z \le 6.0\ m/kg^{1/3}$	1.06–0.005Z	0.08	Lognormal
Impulse:			
$0.59\ m/kg^{1/3} \le Z \le 3.0\ m/kg^{1/3}$	0.99	0.222–0.054Z	Lognormal
$3.0\ m/kg^{1/3} \le Z \le 6\ m/kg^{1/3}$	0.99	0.06	Lognormal

Note: Z is scaled distance defined as $Z = R/W^{1/3}$ expressed as $m/kg^{1/3}$.

deterministic, and so information about COVs are never considered and so are often unknown. However, COVs may be estimated from expert judgements of tolerances or upper and lower limits of variability.

Home-made explosives exhibit considerable variabilities. For example, the amount of ANFO (ammonium nitrate fuel oil) that can be carried in a vehicle bomb is uncertain, but an assessment of most likely masses may be postulated by security agencies. A security agency may believe the mass tolerance for a VBIED is a 95% confidence limit of ±25%, and further assuming that this variability in mass is described by a lognormal distribution then the mass COV of ANFO is $V_{mass} = 0.14$. If the security agency believes that the size of the VBIED threat is known with certainty, then $V_{mass} = 0.0$.

The W_{TNT} factor for commercially produced ANFO may be taken from Table 1 as $W_{TNT} = 0.87$. However, home-made ANFO and other explosives are likely to experience a high variability in TNT equivalency, as the explosive output is highly sensitive to the constituent materials and mix proportions. For example, if it is expected that a terrorist-made ANFO will have a low TNT factor of 0.6, with lower and upper bounds of 0.35 and 0.90, then if these limits represent the 95% percentile bounds of a lognormal distribution, V_{TNT} is 0.23. If $V_{mass} = 0.14$, then Eq. (4) leads to$V_W = 0.27$ for a terrorist VBIED. Note, however, that it is not possible to present herein actual information or intelligence relating to the quality of home-made explosives. This type of information could be postulated by security agencies taking into account the quality of the explosives and the capabilities of the terrorist.

3.2.4. Variability of range

The location of a terrorist IED is difficult to predict, but if the target is known, then minimum stand-off from a facility (building, bridge, etc.) is obtained from knowledge of the site (roads, parking), access control (security gates, bollards) and perimeter security. For instance, if it is assumed that the final location of a VBIED will be a maximum of one car width (2.5 m) from the desired detonation location, then if the 95% confidence limits of achieving this is ± 2.5 m then the standard deviation is approximately 1.25 m assuming a normal distribution. If the mean range is 10.0 m, then$V_R = 0.125$. A remotely detonated personnel-placed IED or a suicide bomber can locate the IED more precisely, leading to a lower V_R.

3.2.5. Variability of other parameters

Temperature and atmospheric pressure have less influence on blast pressures and impulses than W and R. Hence, their variability has little effect on airblast variability. The variability of other parameters may be obtained from other sources. For example, airblast variability of a cylindrical shaped explosive charge is near double that of a spherical-shaped charge [51].

3.2.6. Exposure or hazard curve

The exposure *EX* may also be represented as a hazard curve similar in concept to natural hazard curves – i.e., a cumulative distribution function of the load or exposure. For example, if the threat scenario is the detonation of a small VBIED comprising 250 lbs (115 kg) of homemade ANFO, there are variabilities associated with the charge mass, its manufacture, and blast loading model uncertainty. Fig. 2 shows the resulting hazard curve of peak pressure on a structure located 50 m from the detonation location (e.g., [63]).

4. Vulnerability/damage assessment

The probabilities of the system and constituents damage and failure states should be quantified in conjunction with the relevance of the consequences. The probabilities of system damage state given exposure and constituents damage states $p(S_m|\mathbf{C}_l, EX_k)$ and the probability of a damage given exposure $p(\mathbf{C}_l|EX_k)$ should be available depending on the explosives, impact or other hazard exposure scenarios and varying parameters. Such curves can be assessed by using standard probabilistic methods and/or statistics.

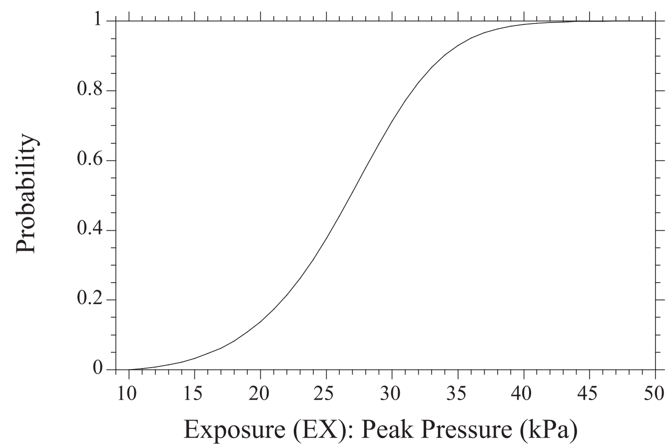

Fig. 2. Blast loading hazard curve for a VBIED comprising 115 kg of home-made explosives.

4.1. Fragility/vulnerability modelling for structural damage

The likelihood and extent of structural damage may be obtained from engineering models, empirical guidelines, or past experience. An accurate prediction of structural damage can be obtained from detailed structural engineering models to infer specific damage levels such as window breakage, column or wall collapse, etc.

Experience suggests that the non-linear finite element analysis (FEA) models developed for concrete, steel and masonry buildings are accurate for blast-resistant design. Strain rate dependent constitutive models for steel, concrete and masonry are also readily available in the literature. LS-DYNA, AUTODYN or other software may be used as the computational tool as they are widely used FEA programs that use explicit time integration to analyse the non-linear dynamic response of three-dimensional structures. These and similar packages can include material and geometry non-linearity with a non-linear time history analysis to obtain the dynamic load–deflection response.

Damage may also be predicted from Pressure-Impulse (P-I) curves that are widely available for many structural elements including glazing. Added to this are single and multi degree of freedom models. Finally an indication of the vulnerability of buildings is possible using some simple to use damage models. The United States Federal Emergency Management Agency *Reference Manual to Mitigate Potential Terrorist Attacks Against Buildings* [21]provides damage prediction for unstrengthened buildings (i.e., conventional construction, not designed to be blast-resistant) subject to above ground explosions.

There will be considerable uncertainty and variability in (i) blast loads and (ii) structural response and these sources of uncertainty may be represented by random variables, some of which may be spatially correlated. Model uncertainty is typically low and uncertainty of structural response dominated by parameter sensitivity. The variability and uncertainty of many system response parameters such as material properties and dimensions have been the subject of many studies and are readily available for building structures. The very high strain rates of material properties is significant (and highly non-linear) which will likely lead to high variability of material stiffness and strength.

The probability of constituent damage given exposure to a hazard $p(\mathbf{C}_l|EX_k)$ may be represented as fragility curves derived from standard probabilistic methods. The derivation of these curves may be challenging, for example, structural response to explosive blast loading is dependent on pressure and impulse. Hence, a suite of bespoke fragility curves is needed to probabilistically describe the complex interactions between pressure, impulse and structural response for a situation where charge mass and standoff are known. Fig. 3 shows typical fragility curves

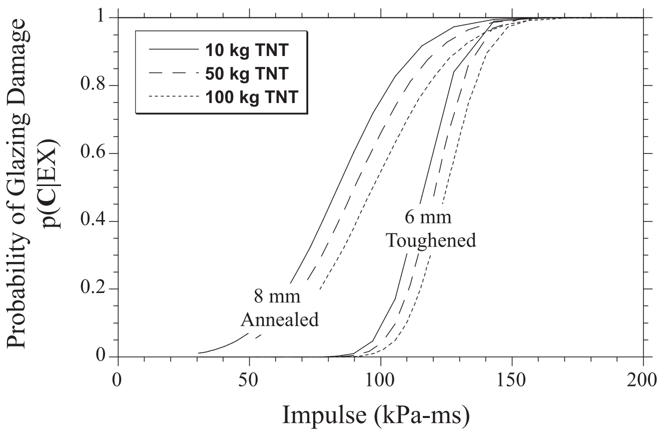

Fig. 3. Fragility curves for glazing damage (adapted from [62]).

for explosive blast damage to annealed and toughened glazing, where hazard and structural response are random variables and the threat is a VBIED.

4.2. Progressive collapse

Risk assessment for "progressive" or "disproportional" collapse under terrorist action involves all terms of Eq. (1). Risk mitigation against systemic progressive collapse is achieved by working on three fronts:

(A) to control the hazard or reduce its rate of occurrence (term $p(EX_k)$ in Eq. (1);
(B) to control or limit initial damage states (terms $p(\mathbf{C}_l|EX_k)$ and $C_D(\mathbf{C}_l)$); and
(C) to control or limit systemic damage propagation (terms $p(S_m|\mathbf{C}_l, EX_k)$ and $C_{ID}(S_m, C_D(\mathbf{C}_l))$).

Terrorist threats and hazards (A) were addressed in Section 3. Initial damage states (B) were addressed in Section (4.1). This section addresses point (C). Design approaches against progressive or disproportionate collapse can be classified as direct or indirect [74,26,15]. The indirect design approaches account for prescription of minimal levels of strength, continuity, and ductility. System behavior and progressive collapse consequences are not explicitly considered. The direct approaches consider progressive collapse in a more explicit way and can be divided in two branches. The Enhanced Local Resistance (ELR) is an event-dependent approach, where the strength of potential target elements is increased, such that they survive application of the abnormal loading. Increasing the strength, ductility or robustness of a column to withstand the blast wave of a terrorist bombing is one example. The Alternate Path Method (APM) is an event-independent approach involving discretionary removal of potential target elements. The structural system is strengthened to form alternate load paths or "bridges" over the removed elements. The APM approach is illustrated in a frame building example in Section 7.2. Updated review summaries of current progressive collapse modelling and understanding are given by Adam et al. [1] and Kiakojouri et al. [33].

For beams of regular RC frame structures, the mechanisms providing additional resistance against progressive collapse, under sudden removal of a vertical load carrying member, are well understood. The different load paths produced by these resisting mechanisms are fully dependent on system behavior. Stage 1 of the resisting mechanism is the usual bending action of beams, under conventional gravity loads. At this stage bending behavior is mainly elastic, with the occasional appearance of flexural cracks. If a column is suddenly removed, bending moments increase significantly due to the double span effect, leading to reinforcement at beam ends to yield, characterizing elastoplastic or inelastic behavior. If sufficient lateral restraint is provided (mainly by adjacent columns), the beam can go into compressive arch action (stage 2), where additional stiffness and load-carrying capacity are mobilized, by way of increased compressive axial forces. Past the point of peak load capacity in compressive arch action, snap-through instability occurs due to yielding of steel rebars and crushing of concrete, significantly reducing the load-bearing capacity. If the beam cannot redistribute axial loads, due to insufficient restraint by lateral columns or rupture of reinforcements, it will fail. Yet, if lateral restraint is provided and reinforcements are still functional, the beam will enter a catenary stage, which is characterized by axial loads turning from compressive to tensile. The limit of stage 2 is the tensile strength of rebars, which will eventually rupture.

5. Consequence assessment

The consequences of a terrorist attack includes (i) direct consequences $C_D(\mathbf{C}_l)$ due to constituent and system damage and (ii) indirect consequences $C_{ID}(S_m, C_D(\mathbf{C}_l))$ such as (a) loss of life, (b) business losses, loss of tourism, reduction in GDP, etc. and (c) social losses as the effect of the level of fear and anxiety within society (and perhaps on civil liberties). The consequences are interconnected, for example, a fearful public may be reluctant to travel and contributing to business and tourism losses, or may be reluctant to invest. Total losses from terrorism are not significantly affected so much by loss of life or physical damage, but by the fear they generate that can lead to large indirect and social losses [39].

The probability that an individual is killed in a damaged building is, in most cases, quite low. Stewart [52] showed that this is a low 0.03% for occupants of the World Trade Center bombing in 1993, 45.1% for the 1995 Oklahoma City bombing, 6.9% for the 2001 World Trade Center attacks, and 0.8% for the 2001 attack on the Pentagon. However, for total progressive collapse without pre-warning the fatality rate would be near 100%, but some will be rescued from voids in the collapsed building.

The cost of physical damage is relatively straightforward to estimate if extent of damage is known. The estimation of indirect and social consequences of extreme events such as terrorism or natural hazards is well studied and guidelines exist for their estimation (e.g., [48]).

However, a unique feature of terrorism is the desire to terrorise or psychologically affect individuals, society or government. These consequences may be minimized by individual and societal resilience, and not to self-inflict larger losses by risk-averse behaviour or over-reacting to an attack (e.g. [39]).

VBIED attacks on the World Trade Center in 1993 and Oklahoma City in 1995 resulted in several billion U.S. dollars of losses. However, very few terrorist attacks exact such damage. Analysis of the GTD shows that of 219 terrorist bombing incidents in the U.K., 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 up to US$ 2 billion [39].

The 2001 attack on the Pentagon resulted in repair costs of US$500 million, compensating the families of the 184 victims reached US$1.4 billion, and when additional costs of social and business disruptions, etc. are included the total loss approaches US$10 billion [39].

The attacks on the World Trade Center caused close to US$250 billion (inflation adjusted to 2022) in total losses including $25 billion for loss of life (value of statistical life or VSL = US$7.5 million), $40 billion in direct physical damage including rescue and clean-up costs, and social and indirect losses to the economy reaching up to $175 billion due to people's reluctance to travel, invest, feeling confident about the future, and other risk-averse behaviour [39]. The 9/11 attacks on the World Trade Center represent very much an outlier of losses from terrorism, and are the largest in history.

All relevant consequences should be quantified and discounted with an appropriate discount rate applicable to decision scenario, system boundaries and time horizon.

6. Modelling, assessment and ranking of risk reduction strategies

An efficient management of terrorism risk reduction strategies requires a prediction, an analysis and an optimization of information acquirement and mitigation strategies before implementation. This is facilitated by the utilization of the pre-posterior decision analysis based on the Bayesian probability, utility and decision theory.

Risk reduction strategies need to be framed into a set of relevant decision scenarios building upon a risk analysis (structural system states and direct and indirect consequences, see previous Section). Risk mitigation strategies by physical actions encompass e.g., structural strengthening, barriers to shield against the placement of explosives and consequence reduction measures (see e.g. [67,69]. These physical actions may be classified into system state and consequence reduction actions and should contain relevant uncertainty and cost modelling (e.g., [65]).

Information acquirement strategies should be (1) relevant for the system states and (2) be developed to support the implementation of the physical system state and consequence reduction actions. Both the relevance and the support of the action implementation constitutes a precondition for information value facilitating that information acquirement strategies can be optimized before implementation [65–66]; see also further conditions on information utilization in [43]. The modelling of the information should encompass the type of information (e.g., direct or indirect, see [65]), the information acquirement process and operation related uncertainties, and costs for information acquirement system design, installation, operation and renewal.

Risk reduction strategies are assessed in terms of their cost-efficiency, i.e., the risk reduction including the expected strategy costs, and compliance with life safety and risk acceptance criteria and requirements by law. Risk acceptance criteria should be derived with the marginal life safety principle (MLSP), see Faber [19]) and ISO 2394 [30]. The objective function representing the decision scenario for maximizing the risk reduction for a specific decision maker should incorporate a risk assessment and the decision variables associated to the risk reduction strategies. The preferences of a decision maker should be included for a descriptive decision analysis; for a normative decision analysis or linear utility functions, the decision maker preferences may be omitted [9].

The ranking of risk reduction strategies is based on decision theoretical optimality, i.e., the strategy with the lowest risks and expected costs is ranked first. Positive effects on the vulnerability, robustness and resilience in the scope of the decision analysis can be demonstrated. For transparency, the analyzed scenarios and the specifications, calibrations, assumptions, and limitations of the probabilistic information, action and system performance models should be transparently documented.

7. Illustrative examples

7.1. Large and iconic bridges

A decision scenario for the risk reduction of a large and iconic bridge (e.g., the Queensferry Crossing, Scotland with a cost £1.35 billion or $1.9 billion [11] or the Golden Gate Bridge valued about $1.6 billion [28] under terrorist threats is formulated. The risk reduction strategies are counter terrorism protection measures and control, i.e., information acquirement via surveillance and consecutive bridge closure [68].

The probability of a collapse due to a terroristic attack with an Improvised Explosive Device (IED) is calculated with the probability of a threat, the conditional probabilities of a hazard given the threat and the bridge collapse. The threat probability is (publicly) largely unknown and thus a range of threat probabilities is analyzed. The conditional probability of a hazard given a threat may be evaluated by considering statistics of the construction, placement and donation of an IED. Such probability is governed by the high fraction of human factors [25]. The probability of a bridge collapse given an IED detonation is assessed to be high due to the considered scenario with a large amount of explosives, relatively skilled terrorists and that iconic bridges may have a low redundancy and a highly utilized structural system.

Counter terrorism protection measures for bridges encompass e.g., strengthening by fiber-reinforced polymers (FRPs), additional steel reinforcement during design, adding lateral supports, and vehicle barriers. A risk reduction measure-cost-relationship has been established in Thöns and Stewart [68] ranging from 0.01% to 0.2% costs related to the bridge value (over a design life of 100 years at a 4% discount rate) and a risk reduction between 7.5% and 95.0% (based on [10;49]). The risk reduction measure-cost-relationship models a linear cost relationship for a low to moderate risk reduction. For a high risk reduction, an over-proportional cost increase is modelled.

The control strategy encompasses surveillance information and bridge closure in case of a threat indication. Surveillance information is modelled with its precision, i.e., the indication and no-indication probabilities of threats, and the surveillance system investment, operation and renewal costs. The surveillance information performance and cost model covers various strategies [13,8,32,14,70,78,49] from low-cost systems (with 0.7 detection probability and costs of 6.0 k€ per year) to high-cost systems with a high detection probability (0.97, investment costs of 150 k€ and with 46 k€ yearly operational expenses). According to this model, higher detection probabilities are achieved with an over-proportional costs increase.

The bridge closure has the purposes of attack prevention and eventual explosive charge detection, location and deactivation activities. The bridge closure leads to a reduction of the consequences for bridge collapse due to a lower number of vehicles on the bridge and consequently less fatalities; however, additional costs according to bridge traffic network importance [49] and [50] are included.

The decision scenario is formulated for an authority responsible for the safety of a large scale and iconic bridge. The objectives of the decision maker are to minimize total risks and costs for society and the bridge users and to implement efficient risk mitigation strategies. The risk analysis and the decision scenario are depicted in Fig. 4. The decision scenario contains the strategy “Protect”, which is modelled with a probabilistic system state action influencing the bridge failure probability. The strategy “Control” consists of an information acquirement by a surveillance system, the outcomes “No Threat” or “Threat” and the consequence reduction action: bridge closure. The consequence reduction action is subjected to implementation uncertainties.

Fig. 5 contains the risks and expected costs for the risk reduction strategies “Protect” (left) and “Control” (right) and for three distinct annual threat probabilities ($p(T)$). With these figures, the optimal strategies in terms of performance (risk reduction for “protect”; indication probability for “control”) and costs are identified (see arrows in Fig. 4). The optimal strategies shift towards a higher performance and over proportional higher costs for higher threat levels. This behavior is more pronounced for the strategy “Protect”. It is found that for all threat levels, the optimal “control” strategy is more cost efficient than the “protect” strategy. For a threat probability of 0.9×10^{-2}, an optimal “Protect” strategy can be identified. However, the risk reduction is only marginal pointing to a low significance of this strategy. It should further be noted that the probability of cost efficiency for this strategy is below 50% [68]. The analysis of risk reduction strategies of a large and iconic bridge subjected to terrorist threats show that high performance and expensive protection measures are optimal and significant for threat probabilities larger than 2.0×10^{-3} per bridge per year. More efficient in terms of risk reduction, significance and cost efficiency can be surveillance and consequence reduction strategies. Optimal control strategies should have a threat indication reliability higher than 94%. Below

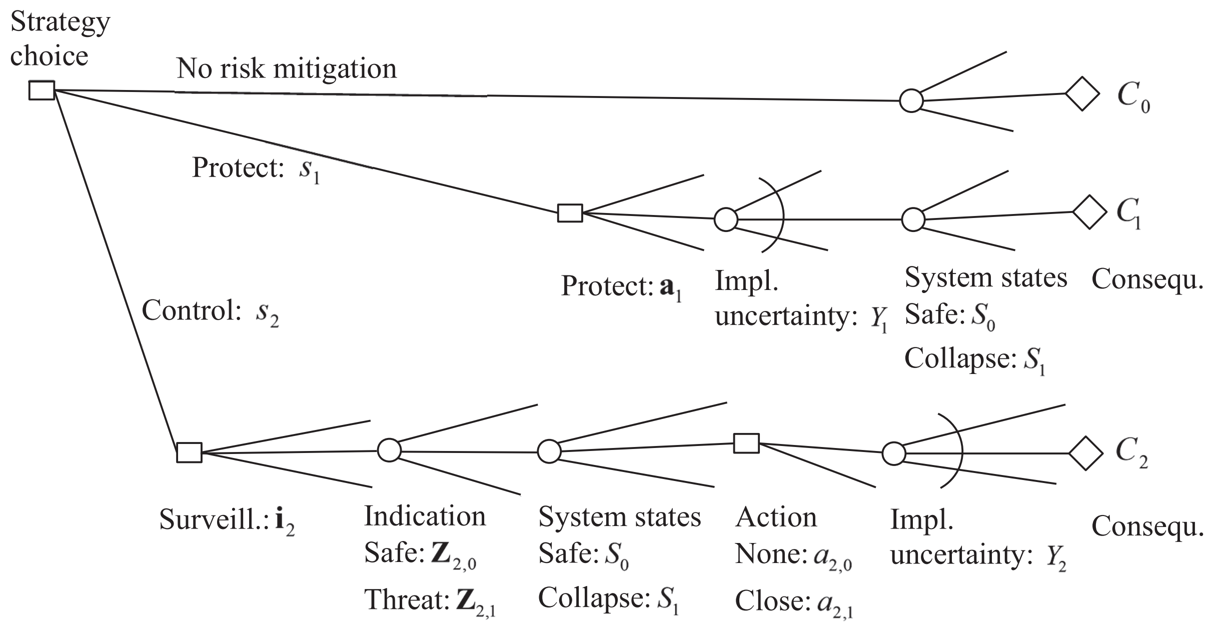

Fig. 4. Risk analysis and decision tree for the "Protect" and "Control" strategies with the system state action "protect" and the consequence reduction action "bridge closure".

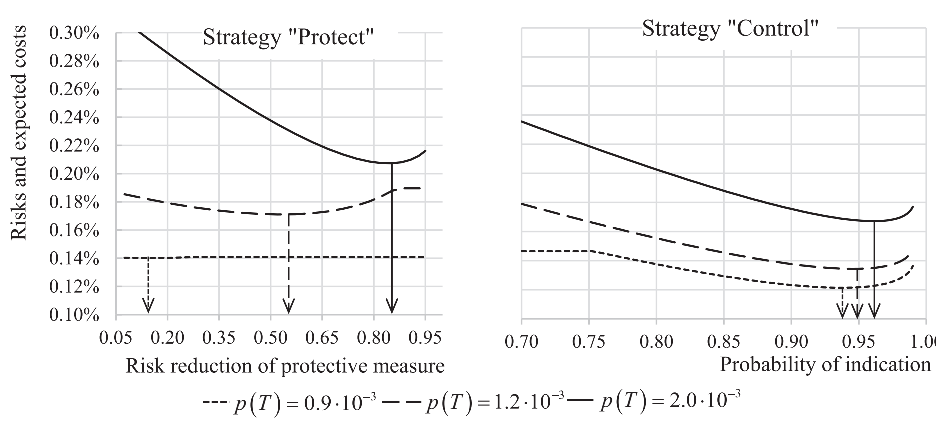

Fig. 5. Risks and expected costs in dependency of protection and control performance for different annual threat probabilities. The optimal strategies are marked with arrows.

a threat level of 0.9×10^{-3}, risk reduction strategies should be carefully assessed for their optimality, significance and probability of cost efficiency.

7.1.1. Attack of the Crimean Bridge

The analyzed scenario of an iconic bridge attack has become more relevant with the 2022 attack on the Crimean Bridge over the Kerch Strait between the Crimean Island and the Russian mainland. The 19 km long Crimean bridge is the longest bridge in Europe with a building cost of about $3.7 billion. The bridge consists of a road bridge with two independent bridge decks for each direction and a separate rail bridge supporting two ballasted rail tracks. The bridge entrance is security controlled and a X-ray scanner for lorries is in operation. The bridge has been heavily used for providing economic and societal connections and since the Russian invasion of Ukraine it is also an important link for military supplies.

On October 8, 2022, a massive blast occurred in about the middle of the bridge between the main arch span over the Kerch–Yenikale shipping channel and Tuzla Island. The blast led to five fatalities and the collapse of one lane of the road bridge, damage to the other direction lane and the ignition of an oil tanker train on the railway bridge passing coincidingly. The fire was extinguished and the rail bridge did not collapse. Reports showed that the bridges were still partly serviceable, however, there was very limited freight traffic on the road and rail bridges. As a consequence, ferry operations restarted. Repair is in progress with time projections ranging mid to end 2023 (see Caprani and Rigby [12]), and news reports in Wikipedia "Crimean bridge explosion" 2023).

The attack on the Crimean bridge confirmed the attractiveness of iconic bridges for attackers and that attackers may be skilled. In comparison with the analyzed scenario (Section 7.1 and Thöns and [56]), the following observations are made:

1. Scenario and threat probability

At this stage it is not possible to characterize the attack as the act of insurgents (or some may claim, terrorists), or accidental detonation of explosives or munitions in the trucks. Given the rather unclear attack motivation, an assessment of the threat probability may become impossible; however, the threat probability to infrastructure in countries at war should be rather high. For a high threat probability, risk mitigation analyses (Section 7.1 and Thöns and Stewart [56]) point to the effectiveness of risk mitigation strategies towards high performing and expensive strategies (see also Section 7.1, Fig. 5).

2. Explosive device performance and collapse probability

Consistent with the assumptions in the analyzed scenario (Section 7.1) is that the probability of a bridge collapse given a hazard is high due to a high amount of explosives and skilled attackers. However, the collapse only happened to one direction lane of the road bridge. The other direction lane was only damaged due to its separated structural design. The completely separated rail bridge was subjected to a high fire and train load but did not collapse.

The seemingly sophisticated attack scenario may point to a rather high explosive device performance, i.e., a high probability of a hazard given a threat.

3. Consequences

The indirect consequences could be on the lower end of the triangularly distributed consequences (factors to the bridge value between 5.0 and 25.0 with a mode at 10.0; see Thöns and Stewart [56]. The indirect consequences encompass a comparably low number of fatalities, only partial road bridge collapse and partial serviceability limitation counteracted by the restarted ferry operation. The presumably low indirect consequences and the prevented full loss of the Crimean link can mainly be attributed to the bridge layout namely the separated road rail bridges and the separated road bridge decks. However, if the bridge had load and traffic restrictions, and more traffic was transferred to ferries, then the indirect costs may be more substantial.

4. Security system operation

If it is assumed that a bomb loaded truck passed the security control, which should have been capable of detecting the explosives especially by using the X-ray scanner, then circumvention of the surveillance strategies was part of the plot. The determination of the indication probabilities may need to be revised, or socio-technical measures should be taken to exclude such a bypass of security.

7.2. Progressive collapse of buildings

In contrast to iconic bridges, regular frame buildings are representative of the “usual” structures, constructed in large numbers around the world. One relevant design question here is: Is it cost-effective to strengthen usual structures so that they support loss of a column (or other load-bearing element) due to a terrorist attack or other accidental actions? What level of threat or hazard probability would justify such spending? This example, taken from Beck et al. [4–6], tries to answer these questions based on a risk analysis, considering the progressive collapse probabilities following loss of a load bearing element. Hence, the example focuses on the system failure states term in Eq. (1), $p(S_m|\mathbf{C}_l, EX_k)$, and on the system failure consequences $C_{ID}(S_m, C_D(\mathbf{C}_l))$.

When regular frame structures suffer loss of one or more (say, $n_{r,c}^0$) columns, of $n_{r,s}^0$ stories, as illustrated in Fig. 6, progressive failure may propagate upwards, by formation of bending-hinge mechanisms; or it can propagate horizontally, by crushing/instability failure of adjacent columns. If adjacent columns fail, damage increases to $n_{r,c} = n_{r,c}^0 + 2$; if not arrested, damage may again propagate upwards by beam bending mechanism, or horizontally by further adjacent column crushing/instability with $n_{r,c} = n_{r,c}^0 + 4$, and so on, until progressive failure is arrested, or until complete frame collapse. When horizontal damage propagation is instantaneous, a pancake-type collapse is observed. The interplay between these failure modes is controlled by structural detailing, such as reinforcement continuity, tying system, structural fuses, etc.; but it is also controlled by the safety factors of beams and columns, and/or by the strengthening of beams and columns to counter act the initial damage. Damage consequences $C_{ID}(S_m, C_D(\mathbf{C}_l))$ can be assumed proportional to the plan area affected by each failure mode.

Beck et al. [4–6] addressed the above problem by looking for the minimum total expected risk (Eq. (1)), including the costs for strengthening beam and column elements to support initial damage of different magnitude. A probability was assigned to the discretionary element removal prescribed in codes [73–75,26,15]. Because of the large uncertainty related to variability of explosive mass and range, and to the survivability of a RC column exposed to such an explosion, as described in Section 3, the initial damage probability p_{LD} was treated as an independent parameter:

$$p_{LD} = \sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} p(\mathbf{C}_l|EX_k) \bullet p(EX_k) \quad (5)$$

Parameter p_{LD} is determined from a risk analysis addressing all potential hazards and threats, considering structure ownership, use and surrounding environment [7]. Treating p_{LD} as an independent parameter allows the hazard/threat risk analysis to be de-coupled from the mechanical progressive collapse analysis.

The hint to this approach was the observation that the optimal reliability-based design of structural systems is strongly dependent on many non-structural (social, political, organizational) factors [3,36–38,7,79], which include the terrorist act of bombing a building.

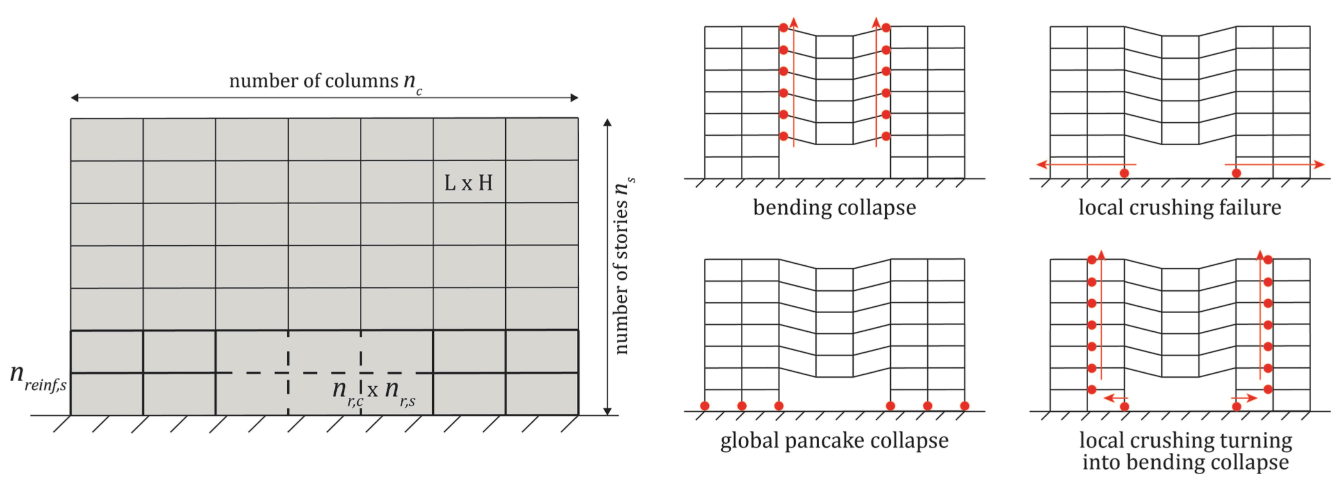

Fig. 6. Regular structural frame with n_c columns and n_s stories subject to (a) initial damage and (b) possible system damage states.

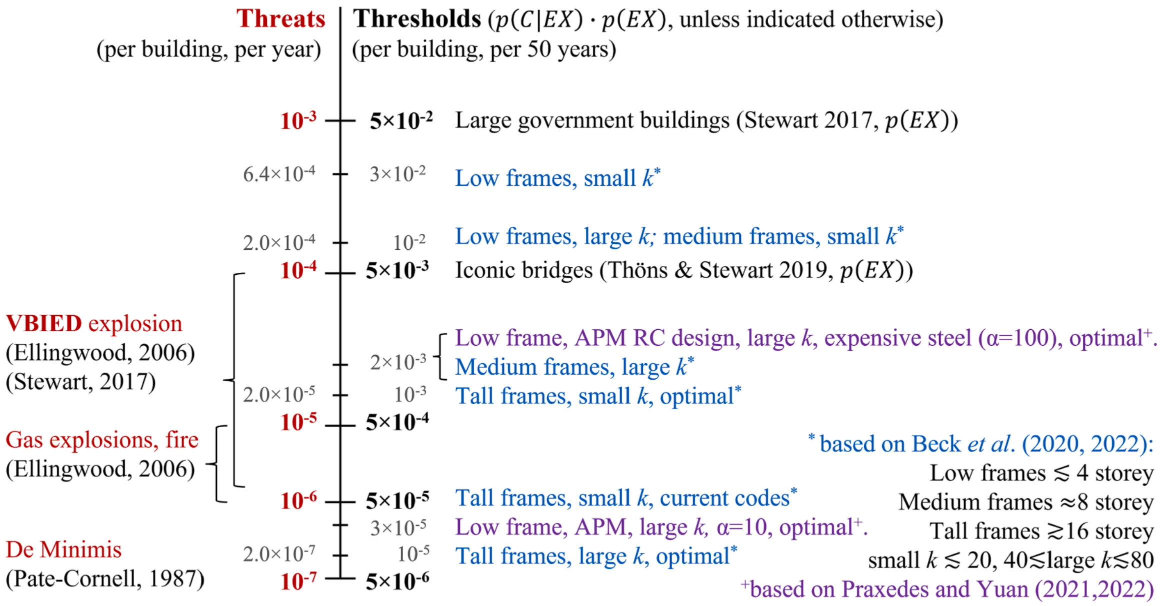

Fig. 7. Summary of threat and threshold probabilities evaluated by different authors [4–6,17,18,44,46,47,54,67] (updated from [6]), k = failure cost multiplier.

Moreover, Beck et al. [4–6] considered the normal loading condition (*NLC*) as one of the "hazards" in Eq. (1):

$$R_{TOTAL} = \sum_{m=1}^{n_{SSTA}} [C_{ID}(S_m, C_D(\mathbf{C}_l)) \bullet p(S_m|LD) + C_D(\mathbf{C}_l)] \bullet p_{LD} + \sum_{m=1}^{n_{SSTA}} [C_{ID}(S_m, C_D(\mathbf{C}_l)) \bullet p(S_m|NLC)] \bullet (1 - p_{LD}) + C_{ST} + C_I \quad (6)$$

where C_I is the initial construction cost, LD means local damage state, C_{ST} is the cost for structural strengthening (APM method), and the possible system failure states are $SSTA$={damage arrested, beam bending collapse ($n_{r,c}$), column crushing collapse ($n_{r,c}$), pancake collapse (n_c)}, which were evaluated for increasing values of $n_{r,c} = \{n^0_{r,c}, \cdots, n_c\}$. Beck et al. [4–6] varied p_{LD} from very small (unlikely threat and initial damage state) to $p_{LD} = 1$ (sure damage state), obtaining what they called the "threshold" (or break-even) local damage probability, p^{th}_{LD}. For threats (terrorist attack or other) leading to $p_{LD} > p^{th}_{LD}$, strengthening the frame to support the local damage is cost-effective, i.e., the cost of strengthening is compensated by the reduction in risk (or expected cost of failure). For threats such that $p_{LD} < p^{th}_{LD}$, strengthening (APM method) is not cost-effective. Note that p_{LD} in Eq. (5) combines the threat, the hazard and the initial damage state $p(\mathbf{C}_l|EX_k)$.

Beck et al. [4–6] explored the problem considering different initial damage states, different extents of the strengthening measure (affecting single or multiple floors), different failure cost multipliers (k), and frames of different aspect ratio. They showed how the threshold local damage probability p^{th}_{LD} changes as a function of these problem parameters. A summary of their findings is presented in Fig. 7, together with common threat probabilities. In short, APM strengthening for robustness

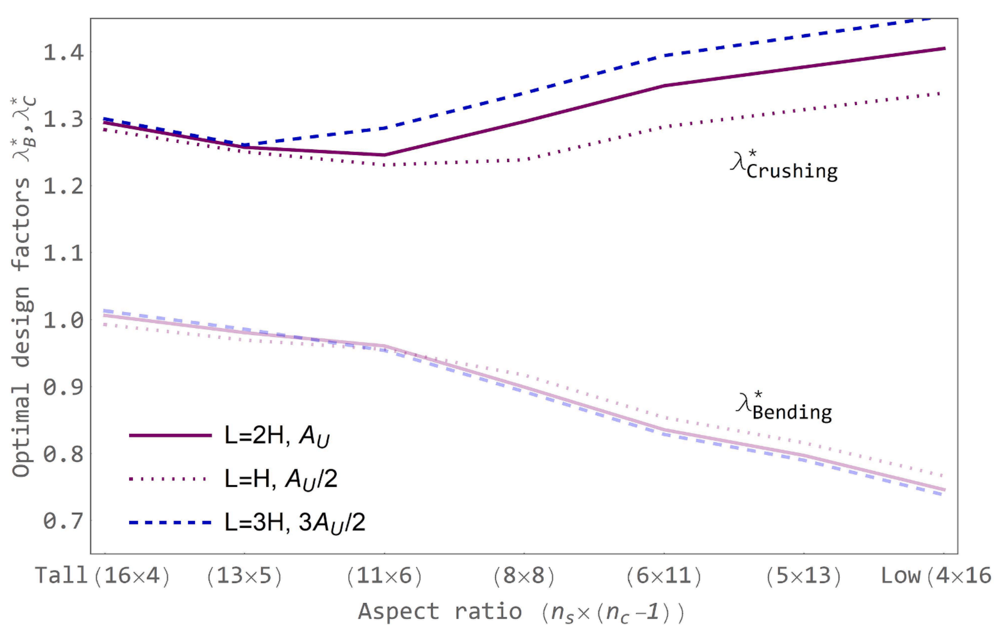

Fig. 8. Competition between failure modes in risk-based optimization of regular frame buildings subject to initial damage (based on [5]), A_U = floor area, the reference value $\lambda = 1$ corresponds to the usual design factor for beam bending in ASCE 7 (ASCE 2016).

against initial damage is justified for small initial damage in tall buildings with large failure consequences. Also, the strengthening measure must be targeted and precise, to minimize additional cost while maximizing benefits, in order to be cost-effective.

The progressive collapse risk optimization study by Beck et al. [4–6] also shows how the different failure mechanisms compete for the limited strengthening budget. In risk optimization, all expenditure in strengthening must produce a reduction in expected costs of failure. The points of compromise between strengthening costs and expected costs of failure for each failure mode change as the building's aspect ratio is varied. Take the 11 floors by 7 bays ($n_s \times (n_c - 1) = 11 \times 6$) regular building in Fig. 8 as the initial reference. For shorter and wider buildings (low aspect ratio, right in Fig. 8), the optimal design factor for bending ($\lambda^*_{\text{Bending}}$) decreases, whereas the design factor for column crushing ($\lambda^*_{\text{Crushing}}$) increases. This occurs because column crushing propagates horizontally, affecting a larger part of the building, and bending failure propagates upwards, affecting less and less floors as the building becomes shorter. Clearly, a structural fuse (not considered in Fig. 8) is a solution to limit horizontal propagation of damage in this case. For taller and narrower buildings (left in Fig. 8), the increase in $\lambda^*_{\text{Bending}}$ is accompanied by an increase in $\lambda^*_{\text{Crushing}}$. Clearly, $\lambda^*_{\text{Bending}}$ should increase because the taller the building, the greater the extent of vertical propagation of damage. Yet, for very tall buildings with few bays (and small number of columns) the increase in $\lambda^*_{\text{Bending}}$ must be accompanied by an increase in $\lambda^*_{\text{Crushing}}$ to avoid pancake collapse failures. Hence, what we observe in Fig. 8 is the competition between the different failure modes for the limited strengthening budget. Surely, specific results shown in this section are valid only for the structures considered, but the general trends are valid for any similar structure.

8. Conclusions

Terrorist explosive threats to bridges, buildings and other infrastructure need rational and careful assessment of the risks, costs and benefits of protective and risk reducing measures. The present paper described a probabilistic risk assessment for the protection of infrastructure from explosive attacks. This included a description of terrorist threats and hazards, vulnerability assessment including progressive or disproportionate collapse, and consequences assessment. The decision analysis of risk reduction strategies will result in the quantification of risk reduction cognizant of the strategy costs. Risk reduction strategies can be assessed in term of their cost-efficiency while also satisfying life safety and risk acceptance requirements. An illustrative example of a large iconic bridge found that surveillance information and bridge closure was more cost-efficient than structural protection. Another case study examined the progressive collapse of buildings estimating the threshold (or break even) damage probability, where the Alternate Path Method is justified for small initial damage in tall buildings with large failure consequences. However, it was noted that strengthening must be targeted and precise, to minimize additional cost, while maximizing risk-reduction benefits. To be sure, the examples are illustrative only; however, they provide a rational and quantitative decision analysis that may be adopted for other risk reduction strategies, time horizons, threats and consequences.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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