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The effects of explosive blast load variability on safety hazard and damage risks for monolithic window glazing

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A R T I C L E I N F O

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A B S T R A C T

Although the modelling of built infrastructure subject to blast loading has been well developed, considerable uncertainty remains with respect to explosive loading parameters and structural response. This paper focuses on facade glazing – as this poses significant safety hazards when affected by explosive blast loads. A structural reliability analysis is used to calculate probabilities of glazing damage and safety hazards conditional on given threat scenarios. The analysis considers the variability of explosive blast loading; in particular, from variations in explosive weight, explosion effects in terms of pressure, stand-off distance, inherent blast load variability and model error. Uncertainties in structural response (including the variability in glazing stress limits, situational geometry, fragment drag coefficients and modelling error) are then considered in the analysis. This allows the prediction of likelihood and extent of damage and casualties. It was found that damage and safety hazard risks are very sensitive to the accuracy of the blast loading prediction model and the inherent variability of blast loading.

1. Introduction

A favoured method of attack to infrastructure is via Vehicle Borne Improvised Explosive Devices (VBIEDs) detonated within urban environments. The use of terrorist-style explosive blast loads within urban environments typically aims to maximise disruption, damage or destruction to infrastructure, public systems or people. Military planners, on the other hand, try to minimise collateral damage that may occur as a result of ordnance delivered into areas where civilian infrastructure and military targets are in close proximity, which tends to also occur in complex urban environs. Thus, for these and many other scenarios the quantification of infrastructure related safety hazards and damage risks will be of significant interest to decision makers in civil defence, the military and elsewhere.

With the exception of extraordinarily large blasts, experience in the United Kingdom [1] and elsewhere, shows that terrorist-style blast loadings cause little structural damage to moment resisting reinforced concrete or steel framed buildings designed to modern codes. Most damage occurs to building facades (see Fig. 1), particularly glazed areas, causing high casualties and significant damage to building interiors. For example, window damage and glass related injuries occurred up to 1.6 km from 'ground zero' of the 1995 Oklahoma city bombing [2]. Clearly, in urban environs, a very large number of buildings can be affected by a medium to large explosive charge. It follows that the effects of explosive blast loading on building facades are worthy of detailed analysis, and for glass facades in particular.

Nearly all current explosive blast modelling techniques are deterministic, for example, given an explosive weight and range, does a particular element of a building survive the shock wave or not? One tool that is often used in the deterministic prediction of glazing safety hazards is HazL [3]. This software and other design tools and specifications are also likely to be conservative (i.e. provide an upper bound value of damage or safety hazard). This may be appropriate for risk screening or preliminary hazard analyses, but they often fail to reflect degrees of uncertainty associated with many aspects of threats and vulnerabilities and the degree of conservatism in predictions is not known. For example, there may be considerable variability in the weight of explosive, the range to the intended target, the energetic output of the explosive (in terms of either peak pressure or impulse), the vulnerability of any element affected, trajectory path of debris, and so on. A favoured method for dealing with such uncertainties is probabilistic risk assessment where quantitative advice can be provided to decision makers in the form of probabilities of damage or safety hazard. Information derived using probability and structural reliability

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Fig. 1. Blast damage to glass facades on buildings adjacent to the Australian Embassy in Jakarta, Indonesia, 2004 (image used with permission of the Australian Federal Police).

theory has significant utility not available from deterministic methods. Moreover, society readily accepts the use of probabilistic techniques in risk-based decision-making and applies them to a range of potentially hazardous industries and situations [4].

The need for a decision-making framework that enables security and blast risks to be quantified in a rational and consistent manner has been widely recognized (e.g., Refs. [5,6]) and decision frameworks for security risk management developed (e.g., Refs. [7,8]). Although a number of decision frameworks exist, these are often developed for initial risk screening or ranking/prioritisation purposes, and so a key issue which is largely unresolved is the quantification of security risks and effectiveness of costs of mitigating measures. Notwithstanding, the quantification of security risks to assess existing risks and the effectiveness of protective measures have recently being addressed by some researchers (e.g., Refs. [9–13]). Information about damage, safety hazard, casualty and economic risks may be used:

- as a decision support tool to mitigate damage,
- by emergency services to predict the extent and likelihood of damage and hazard levels in contingency planning and emergency response simulations,
- in collateral damage estimation and weaponeering by military planners, or
- in post-blast forensics.

Stewart et al. [14–16] have described a risk-based framework that considers threat scenarios, attack probabilities and relative threat likelihoods to assess damage risks, safety hazard risks and life-cycle costs of protective measures with respect to annealed and toughened glazing. This work has evolved to now include the variability of blast loading, which is the main topic of the present paper. A new software research tool called "Blast-RF" (Blast Risks for Facades) [17] considers such variations in blast loading and has been used to undertake a probabilistic risk assessment procedure to predict damage and safety hazard risks of glazing. The structural reliability analysis uses stress limit states and the rating criteria of the UK Glazing Hazard Guide [18] to calculate probabilities of glazing damage and safety hazards conditional on a given blast scenario. In other words, Blast-RF can be used to predict the likelihood and extent of damage or safety hazard for a single window or an entire building facade. The reliability analysis considers the variability of explosive blast loads, in particular, from variations in explosive weight, explosive material energetic output (in terms of peak pressure), stand-off distance, inherent blast load variability and from errors within the model used to generate blast load parameters. The analysis then considers structural response whilst also considering the variability in glazing stress limits and geometry, fragment drag coefficients and solver modelling error. This means that both the load (in terms of blast) and response (in terms of glazing stress and post-break fragment trajectory) are variable, which then leads to estimates of risk.

The vulnerability of existing buildings to explosive blast loading is dominated by the large amounts of monolithic (particularly annealed) glazing in existing buildings. Hence, the present paper describes the risks of damage and safety hazards for monolithic glazing whilst considering the uncertainty and variability associated with blast loads from a commonly available high explosive, trinitrotoluene (TNT). The outcomes of the reliability analysis are probabilities of glazing damage and safety hazards which are calculated for all annealed or fully tempered glass windows in a typical 20 storey commercial building. Blast Reliability Curves (BRCs) are then developed to show the probability of damage and safety hazards (for different ranges) for a single window of annealed glazing. The influence on risk is assessed from consideration of a blast wave's inherent variability, the uncertainty and variability of input parameters for a blast-load model and model error. Note that the threat scenarios for the present paper are intentionally hypothetical and do not represent actual beliefs.

2. Probabilistic analysis of glazing damage and safety hazard risks

2.1. Calculation of risks using Blast-RF

There are many input parameters needed to predict glazing damage and safety hazard risks. Very few of these parameters are precisely known and so, as distinct from the single point estimates used in deterministic modelling, parameters are assumed to be random variables each described by a probability distribution. This variability extends beyond glazing systems to include all manner of construction materials, for example, concrete strength is known to have a coefficient of variation (COV = standard deviation divided by mean) of 0.1–0.2. An illustrative example with load effect (S) and resistance (R) distributions is shown in Fig. 2. In this example, failure occurs when load effect exceeds resistance and the probability of failure (p_f) = Pr ($R < S$). When R and S are random variables, even though nominal (or design) load (S_n) and resistance (R_n) values may be such that $R_n > S_n$, the probability of failure will not be zero but is calculated as:

$$p_f = \int_0^{\infty} F_R(x) f_S(x) \mathrm{d}x \quad (1)$$

where $F_R(x)$ is the cumulative distribution function of resistance (also referred to as a fragility curve) and $f_S(x)$ represents the probability distribution of loading considering inherent variability, model error and parameter uncertainties.

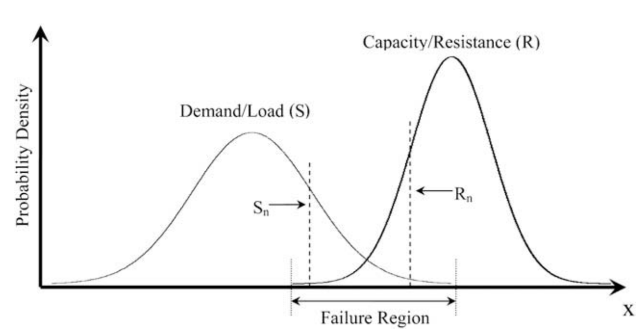

Fig. 2. Probabilistic modelling of load and resistance.