Airblast Variability and Reliability-Based Design for Protective Structures

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ABSTRACT: An understanding of airblast uncertainty allows reliability-based load factors to be calculated. Reliability-based load factors are influenced by the variability of model error, explosive mass and range distance, and are estimated for reliability levels of 0.05 to 0.99 for military, civilian and terrorist munitions. Structural reliabilities are then calculated for reinforced concrete columns, and compared to target values. It was found that RC columns designed to existing standards have a significant margin of safety conditional on successful detonation of the explosive and assuming a relatively low variability of range or explosive mass.

1. INTRODUCTION

A hazard of increasing interest is airblast loading from the accidental or malevolent detonation of explosives. For example, the manufacture, storage and handling of explosive ordnance (EO) poses risks to nearby infrastructure, and there is a need to ensure that damage and fatality risks are kept to acceptable levels. The variability of airblast pressure can be considerable (e.g., Netherton and Stewart 2010).

The limit state requirement is: $\phi R_u \geq \Sigma\lambda_i S_i$ where ϕ is a capacity reduction factor, R_u is the design ultimate strength of the section, S_i is the design load effect for load i, and λ_i is a load factor. UFC 3-340-02 (2008) recommends that ϕ=1.0 and λ=1.0 be used for structural design, and this appears to be the basis for the design of protective structures in many countries. However, as noted by Razaqpur et al. (2012), "*the prevailing practice of using load factors equal to 1.0 in blast resistance design .. seems inconsistent with the design practice for other loads.*"

Current design practice as adopted by UFC 3-340-02 (2008) recommends that the explosive mass be increased by a factor of 1.2 if accidental blast-loads are to be used for structural design (i.e., seems to apply to terrorism and EO situations). There seems to be little to no evidence to support the 20% "factor of safety".

The reliability-based load factor is represented herein as λ, which is consistent with terminology and nomenclature used in UFC 3-340-01 (2002) where λ is defined as a "*reliability-based design load factor (RBDF)*". In accordance with UFC 3-340-02 (2008), reliability-based load factors are calculated herein where the nominal load (i.e. 20% mass increase 'safety factor' is not considered) is multiplied by the load factor (λ) to ensure that the actual load is equal to the reliability level.

Stewart and Netherton (2015) and Stewart (2018a) used Monte-Carlo simulation to develop reliability-based design load factors where model error, range and explosive mass were random variables. The present paper extends this work by showing the effect that RBDFs have on structural reliability for RC columns designed for EO and terrorism blast scenarios. The blast scenarios cover a broad spectrum of explosive mass and range variabilities, thus showing how these variabilities effect RBDFs and structural reliabilities. This allows for reliability-based design to ensure that structures designed for explosive blast loading have an acceptable level of safety.

2. RELIABILITY OF RC COLUMNS

The probability of failure conditional on a hazard H (e.g., explosive blast loading) is:

$$\Pr\left(failure \middle| H\right) = \Pr\left(G(\mathbf{X}) \le 0\right) \qquad (1)$$

where G(**X**) is the limit state function, in the present case this is equal to resistance minus load, the n-dimensional vector $\mathbf{X} = \{X_1,....,X_n\}$ are random variables representing a resistance or a loading random variable acting on the system. Failure occurs if G(**X**) ≤ 0.

Shi et al. (2008) developed Pressure-Impulse (P-I) curves for three damage levels for RC columns subject to explosive blast loading, see Figure 1 for RC column details. The damage index is defined as

$$DI = 1 - \frac{N_{residual}}{N_0} \qquad (2)$$

where N_0 is the axial load carrying capacity of the undamaged column, and $N_{residual}$ is the axial load carrying capacity of the column due to blast damage. Numerical modelling considered shear and flexural damage in the estimation of N_0. The damage levels considered were DI=0.2, 0.5, and 0.8 representing low/medium, medium/high, and high/collapse degrees of damage.

These P-I curves include the effect column width, column depth and column height, concrete compressive strength and reinforcing yield strength, longitudinal reinforcement ratio, and the transverse reinforcement ratio (Shi et al. 2008). Added to these are model errors ME_{Po} and ME_{Io} for peak reflected pressure and impulse, respectively.

The limit state function for a RC column subject to explosive blast loading is described in full by Hao et al. (2016).

The annual probability of failure (collapse) is

$$p_f = \Pr(H)\Pr\left(failure \middle| H\right) \qquad (3)$$

where Pr(H) is the annual probability of the hazard. For this paper, this is the annual probability that explosive loading will occur - e.g., that a terrorist attack is successful, or explosives accidentally detonate. The term Pr(failure|H) is obtained from Eqn (1).

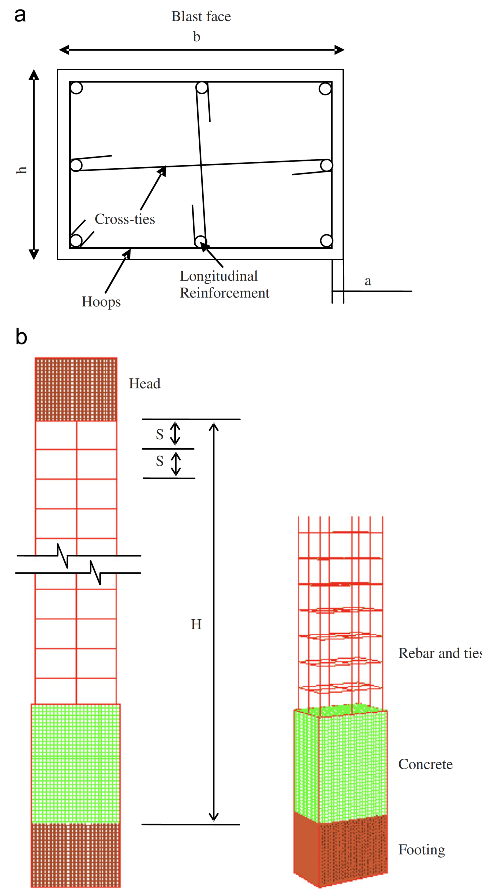

Figure 1: Details of RC column (Shi et al. 2008).

The statistical parameters for a RC column are shown in Table 1. Note that the statistics for cross-sectional area of reinforcing steel include the important effect of discretisation of rebar sizes where the installed (constructed) steel reinforcement is likely to be higher than the nominal (design) values (Mirza and McGregor 1979).

The P-I curves are a best fit to numerical results (Shi et al. 2008). The fits are very good, however, it is reasonable to estimate that they are accurate to something like ±10%. In this case, if this uncertainty represents 95% of all values then the COV of model error for the P-I curves (ME_{Po}, ME_{Io}) is approximately 0.05.

Table 1: Statistical parameters for properties and dimensions of RC column.

	Bias Factor	COV	Dist.
Column width and breadth	1.005	0.04	Normal
Column height	1.0	0.03	Normal
Longitudinal reinforcement	1.02	0.05	Modified Logn.
Transverse reinforcement	1.03	0.06	Modified Logn.
Concrete strength	1.06	0.15	Normal
Yield Stress	1.15	0.05	Normal
Model Errors (ME_{Po}, ME_{Io})	1.0	0.05	Normal

3. AIRBLAST VARIABILITY

The simplest case to analyse blast loads is that of a free-field detonation (i.e., in an open field). However, even in this "simple" case there are many sources of airblast variability and uncertainty, including:

- mass of explosive
- type of explosive
- energetic properties of explosive
- manufacture of explosives
- detonator type
- placement of detonator in explosive
- detonation location (range)
- temperature
- atmospheric pressure
- model errors
- height of detonation
- charge shape
- charge orientation
- casing effects
- topography of ground surface

In complex urban environments there are additional sources of airblast variability and uncertainty:

- obstacles in path of airblast
- building locations and geometries
- building porosity
- type of building facades
- reflection of airblast from buildings, etc.
- accuracy of CFD models

Explosive mass is estimated as $W=W_{user}\times W_{NEQ}\times W_{mass}$ where W_{user} is the user factor, W_{NEQ} is the NEQ (net equivalent quantity) factor, and W_{mass} is the desired mass treated as deterministic in this analysis. The user factor refers to the variability (due to weighing tolerances, human error) in the mass selected or used. The NEQ factor recognises that the NEQ of an explosive can vary due to variations in the explosive's volume and/or density during manufacture, variations in mix proportions during manufacture, and other variables associated with storage and use of explosives. Variability of explosive mass may also arise from variability of charge shape, placement and type of detonators, height of blast, etc.

The variability of range is highly dependent on the placement of the explosives, how it is placed there, and for weapons, the type of guidance system used. Range variability for explosive ordnance storage is close to a COV=0 as the location of the explosives is known with considerable certainty. The location of a terrorist improvised explosive device (IED) or VBIED is less certain, but if the target is known, then minimum stand-off from a facility is obtained from knowledge of the site, access control and perimeter security.

The magnitude of airblast is often normalised to be a function of scaled distance ($Z=R/W^{1/3}$) where R is stand-off distance (m) and W is explosive mass (kg). For more details of the variability of explosive mass (W), range (R) and scaled distance (Z) see Stewart (2018a).

The probabilistic blast load model developed by Netherton and Stewart (2010) uses Monte-Carlo simulation to consider the variability of:

(a) User factor for mass of explosive (W_{user}),
(b) NEQ of an explosive in terms of a mass of TNT (W_{NEQ}),
(c) The range (R) and Angle of Incidence,
(d) Air temperature and pressure, and
(e) Model error (including Inherent variability) of predictive load models.

Probabilistic models for model error and inherent variability were obtained from field data of repeatable tests for reflected pressures and impulses (for more details see Stewart and Netherton 2015). The Kingery-Bulmash model has been incorporated into widely used and well respected blast load design models, such as ConWep, UFC 3-340-02 (2008) and LS-DYNA, and is used herein as the predictive model airblast. Note that once instrument error is removed from the analysis, inherent variability is less than 0.01. Hence, this source of variability is included in model error statistics. Model error statistics for airblast are shown in Table 2.

Table 2: Statistical parameters (Lognormal) for model error if $Z<4.7\ m/kg^{1/3}$.

	Mean	COV
Pressure: ME_P	1.03	0.087
Impulse: ME_I	0.905+0.0203Z	0.198-0.024Z

The results to follow assume that the explosive detonates on or very near to the ground. It is thus considered a hemispherical charge detonating against a reflecting surface. The blast load is from a single uninterrupted emanation of the shock-wave, and that reflections from other structures or surfaces are not considered. All detonations are assumed to occur within air that is at 15^o C and 1013.25 hPa. These assumptions provides the basis for the design of many protective structures.

The utility of the probabilistic approach is shown by a weaponeering scenario. The air force may be concerned about collateral damage to a civilian building 50 m from the military target. If the desired point of impact is the military target, Figure 2 shows the peak reflected pressure on the civilian building if a 500 lb Mark-82 GPS guided bomb is used (Netherton and Stewart 2010). Figure 2 shows that there is 43% chance that the design (anticipated) load will be exceeded. Thus, there is increased likelihood of damage and casualties to civilians. Whereas a fully deterministic analysis would say that as long as the civilian building can withstand a pressure of 24.5 kPa then no damage or casualties would occur. This ignores the high chance that in reality such loads can be exceeded.

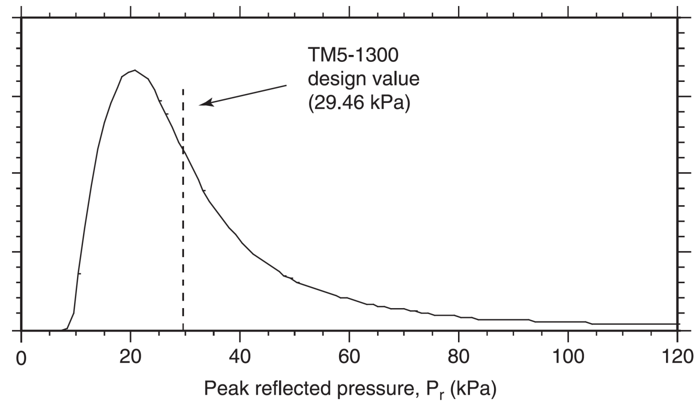

Figure 2: Blast Loads from a Collateral Damage Scenario.

4. CASE STUDIES

The US Department of Defense *Structures to Resist the Effects of Accidental Explosions* (UFC 3-340-02 2008) is typically used for the design of RC columns subject to explosive blast loading. The RC column is not permitted to attain large plastic deformation, hence, design is based on elastic or slightly plastic action. This leads to a design damage index of DI=0.2 (Stewart 2018b). In the following examples it is assumed that RC columns will be designed using the Shi et al. (2008) P-I curves for a damage index of 0.2.

Two blast scenarios are considered:

1. EO scenario - This hypothetical explosive case study assumes that W_{mass}=20,000 kg of bare exposed TNT explosive is stored outside, above ground and without bunker protection. The distance from this potential explosive site to the building of interest is R=80 m and the building is not protected by any barricade. The COV of charge mass is V_W=0.025 (Stewart 2018a). Because the location of the stored explosives is known with certainty, range is deterministic (V_R=0). Mean scaled distance is $Z=2.95\ m/kg^{1/3}$ and COV is $V_Z \approx 0.01$.
2. Terrorist scenario – This may involve a vehicle-borne improvised explosive device

(VBIED) containing W_{mass}=2,000 kg of home-made ANFO (ammonium nitrate fuel oil). The W_{NEQ} for ANFO is 0.82. The variability of home-made ANFO may be considerable with V_W=0.25, if the VBIED is located within a ±2 m tolerances then COV of R is V_R=0.05 for a range of R=25 m (e.g., Stewart 2018a). Mean Z=2.12 m/kg$^{1/3}$ and COV is V_Z=0.10.

For more scenarios see Stewart (2018b).

It is assumed that R, W and Z are lognormally distributed. Note that blast load variability (and hence, load factors) is expected to increase if a more realistic assessment of charge shape and orientation, impact orientation of bombs (e.g. half buried), casing effects, etc. are considered.

The RC columns are assumed to be exterior columns – i.e., those closest to the external blast loading (see Figure 3). The RC columns are designed assuming:

a) No load or safety factors,
b) Mass increase factor (MIF) of 20% is applied to charge mass in accordance with UFC 3-340-02 (2008), or
c) Reliability based load factors (RBDF) for 0.95 and 0.99 reliability estimated form the procedure described by Stewart (2018a).

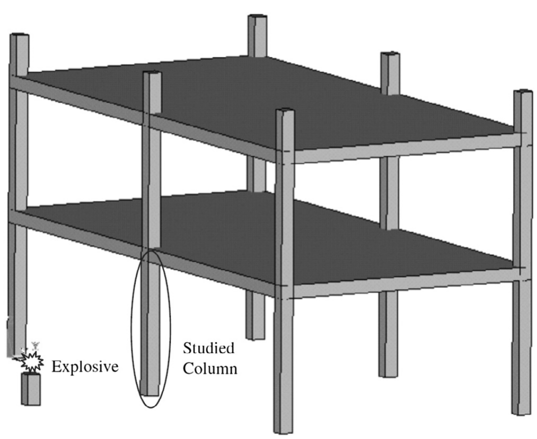

Figure 3: Schematic Position of Column (Shi et al. 2008).

Figure 4 shows a schematic of RBDFs. Blast loads are dependent on the mass of explosive, range, type of explosive, angle of incidence, and air temperature and pressure. However, the reliability-based load factor (RBDF or λ) is invariant to the design values of these parameters, as these affect the nominal load and probabilistic load equally. The effects of these design parameters hence cancel out in the calculation of λ, and so λ is only a function of scaled distance and the variability of these parameters. Note, that this finding holds if the deterministic (nominal) values used for predicting nominal loads are equal to the mean values as used in the probabilistic model of airblast variability. Note also that RBDFs are insensitive to the mean and COV of air temperature and pressure (Stewart 2018a). Hence, the RBDF (λ) is dependent only on:

- nominal scaled distance Z=R/W$^{1/3}$,
- COV of scaled distance (V_Z) for pressure,
- V_W and V_Z for impulse, and
- statistics of blast loading model error for pressure (ME_P) and impulse (ME_I).

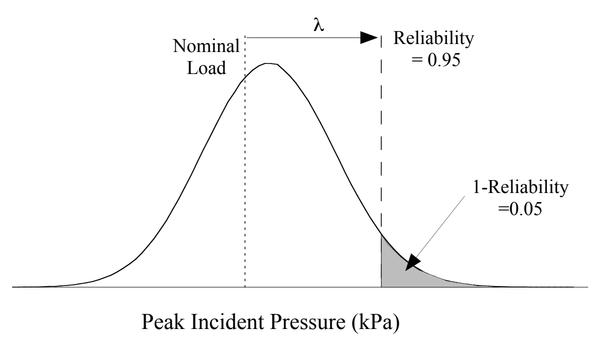

Figure 4: Schematic of Reliability-Based Load Factor for a Reliability Level of 0.95.

Note that RBDFs will increase as the variability of mass and range increase. Table 3 shows the RBDFs for the terrorism scenario as a function of scaled distance. It is observed that, as expected, the RBDF is approximately unity for a 50% reliability level. As the reliability level increases the RBDFs increase, sometimes substantially to more than twice the nominal blast loads.

Table 3: RBDFs for peak reflected pressure, for terrorism scenario with V_R=0.05 and V_W=0.25.

Reliability Level	Z=1 m/kg$^{1/3}$	Z=2 m/kg$^{1/3}$	Z=5 m/kg$^{1/3}$	Z=10 m/kg$^{1/3}$	Z=20 m/kg$^{1/3}$
0.05	0.66	0.63	0.73	0.79	0.81
0.10	0.73	0.71	0.79	0.84	0.85
0.50	1.03	1.04	1.04	1.04	1.03
0.90	1.46	1.54	1.37	1.28	1.25
0.95	1.61	1.72	1.48	1.36	1.32
0.99	1.93	2.11	1.71	1.52	1.47

5. RESULTS

5.1 EO Scenario

Table 4 shows the RBDFs and design loads, for the RC column designed for Scenario 1. As expected, the MIF has higher design loads and so requires a stronger column, and the size increases again as RBDFs are applied.

Table 4: RBDFs and design loads.

	EO Scenario			
	No Factor	20% MIF	0.95 Rel	0.99 Rel
RBDF (λ) - Pressure	1.0	-	1.2	1.25
RBDF (λ) - Impulse	1.0	-	1.2	1.3
Design Press. (kPa)	350	410	410	440
Design Imp. (kPa.sec)	6.21	7.06	7.45	8.01

The probability of failure conditional on the hazard is calculated using Monte-Carlo simulation, see Table 5. For extreme events loading some damage to structures is expected for the design event. However, there is expected to be considerable reserve capacity defined as the capacity above that predicted from design codes. Hence, as discussed in Section 4, UFC 3-340-02 (2008) design provisions are conservative and provide a reasonable margin of safety against collapse. Hence, the probability of collapse given a blast load Pr(failure|H) is expected to be a relatively low number, and Table 5 shows that Pr(failure|H) is about 1×10^{-3} if no safety factors are applied. This collapse probability reduces by about 25-fold if the 20% MIF is applied to charge mass W. These probabilities reduce four-fold again when the RC column is designed for a RBDF with a 0.99 level of reliability (i.e. 1% chance of load exceedance).

Table 5: Reliabilities for RC columns.

	EO Scenario			
	No Factor	20% MIF	0.95 Rel	0.99 Rel
Pr(failure|H)	1.2×10^{-3}	4.9×10^{-5}	3.9×10^{-5}	1.4×10^{-5}
Pr(H)	8.1×10^{-3}	8.1×10^{-3}	8.1×10^{-3}	8.1×10^{-3}
Annual p_f	9.7×10^{-6}	4.0×10^{-7}	3.2×10^{-7}	1.1×10^{-7}

The annual probability of the hazard (i.e., explosive event) for the EO scenario is based on guidance from the U.S. Department of Defense and the Department of Defense Explosives Safety Board (DDESB). In this case, if the explosives (Compatibility Group D) are for disposal for "*Operations involving dangerously unserviceable items awaiting destruction*" then Pr(H)= 8.1×10^{-3} per year (DDESB 2009). The annual probabilities of failure p_f given by Eqn. (3) are also shown in Table 5. Note that ISO 2394 (2015) recommends β_T=4.7 for ultimate strength limit states design where consequences of failure are high (Class 4) and cost of safety measures are small. This is equivalent to an annual probability of failure of p_f=1.3×10^{-6}. Hence, designing a RC column with no safety or load factors fails to satisfy the target reliability for this scenario, and such a design would not comply to ISO 2394 (2015). However, all other RC designs satisfy the target reliability for the EO scenario.

Figures 5 and 6 show the conditional probability of failure Pr(failure|H) for this EO scenario when the RC column is not designed for any safety or load factors, as a function of range and explosive mass. The size of the RC column is based on the design pressure and impulse given in Table 4, hence, these figures show the effect of actual range or mass being higher or lower than the design values. Clearly, failure probabilities are sensitive to small changes in range, and less so for explosive mass. For example, if the range to the EO reduces from 80 m to 60 m, the failure probability is close to 100% if the RC column is only designed for an 80 m standoff (see Figure

5). On the other hand, explosive mass needs to increase by 150% for the failure probability to reach 100%, see Figure 6.

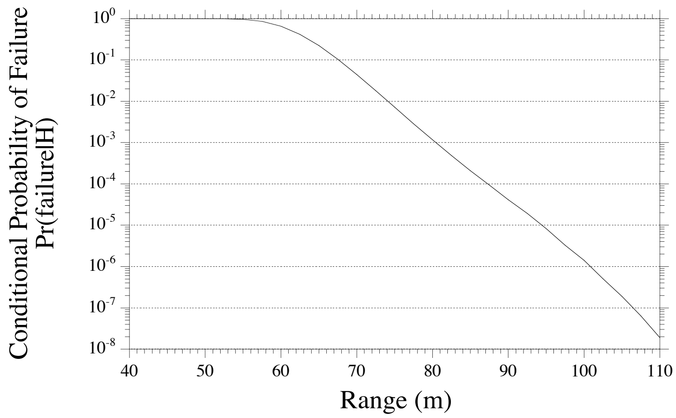

Figure 5: Effect of Range on the Conditional Failure Probability for a RC Column Designed for the EO Scenario with No Load or Safety Factors.

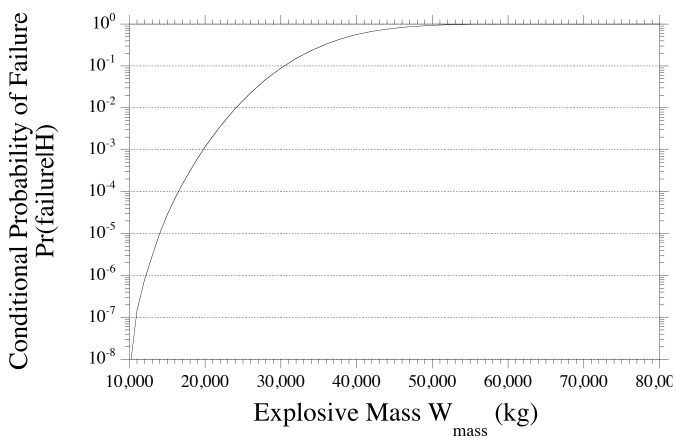

Figure 6: Effect of Explosive Mass on the Conditional Failure Probability for a RC Column Designed for the EO Scenario with No Load or Safety Factors.

5.2 Terrorism Scenario

Airblast variability is higher for the terrorist VBIED scenario when compared to the EO scenario because variability of range and mass are both higher. Hence, Table 6 shows that the RBDFs for the terrorist VBIED scenario are higher. As expected, the probability of failure conditional on the successful detonation of the VBIED Pr(failure|H) increase when the VBIED contains the more variable home-made ANFO (see Table 7).

Table 6: RBDFs and design loads.

	Terrorism Scenario			
	No Factor	20% MIF	0.95 Rel	0.99 Rel
RBDF (λ) - Pressure	1.0	-	1.64	1.98
RBDF (λ) - Impulse	1.0	-	1.39	1.63
Design Press. (kPa)	340	780	1,110	1,360
Design Imp. (kPa.sec)	1.90	3.62	4.45	5.24

Table 7: Reliabilities for RC columns.

	Terrorism Scenario			
	No Factor	20% MIF	0.95 Rel	0.99 Rel
Pr(failure|H)	1.2×10^{-3}	4.9×10^{-5}	1.5×10^{-12}	2.7×10^{-19}
Pr(H)	1×10^{-6}	1×10^{-6}	1×10^{-6}	1×10^{-6}
Annual p_f	1.2×10^{-9}	4.9×10^{-11}	1.5×10^{-18}	2.7×10^{-25}

The annual probability of a terrorist attack involving a VBIED will be low, and the odds are even lower that the attack is successful in detonating a large amount of home-made explosives such as ANFO. Stewart (2017) estimates that a VBIED threat probability is approximately 8×10^{-6} per building per year for attacks on large government and defence buildings in the United States. A statistical analysis of the Global Terrorism Database for IED attacks in the United States reveals that the probability that an IED will successfully detonate is around 15% (Grant and Stewart 2015, 2017). The likelihood that a large VBIED 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. Hence, the hazard likelihood Pr(H) is $8\times10^{-6} \times 15\% = 1\times10^{-6}$ per building per year.

The annual probabilities of failure then all fall below the target values recommended by ISO 2394 (2015). Moreover, the annual probabilities of failure are less than 10^{-18} for reliability-based design due in part to the high

RBDFs for this scenario. Ellingwood (2006) suggested that the threat probability be taken as 1×10^{-4} per building per year for key governmental and international institutions, monumental or iconic buildings or other critical facilities with a specific threat. Even with this higher threat likelihood the annual probabilities of failure still all fall below the target value.

6. CONCLUSIONS

Reliability-based load factors were calculated that considered the variability of model error, explosive mass and range. Reliability-based load factors were estimated for a reinforced concrete column, for explosive ordnance and terrorism blast scenarios. Structural reliabilities were then calculated, and compared to target values. It was found that RC columns designed to existing standards have a significant margin of safety conditional on successful detonation of the explosive and assuming a relatively low variability of scaled distance.

7. ACKNOWLEDGEMENTS

The support of the Australian Research Council through Discovery Project DP160100855 is gratefully acknowledged.

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