Structural Safety 71 (2018) 13–23

Contents lists available at ScienceDirect

Structural Safety

journal homepage: www.elsevier.com/locate/strusafe

# Reliability-based load factor design model for explosive blast loading

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ARTICLE INFO

*Article history:*
Received 21 May 2017
Received in revised form 29 August 2017
Accepted 28 October 2017

ABSTRACT

The risk of damage to infrastructure and people is affected by airblast variability. Reliability-based design allows the decision-maker to select the level of reliability for a specific blast loading scenario. Reliability-based load factors are calculated where the nominal load is multiplied by the load factor to ensure that the actual load is equal to the reliability level. A design model for predicting reliability-based load factors is developed where model error, explosive mass and stand-off distance are random variables, and calculated reliability-based design load factors (RBDF) are independent of explosive mass, net equivalent quantity, angle of incidence, temperature or pressure. Hence, a design model describing reliability-based load factors are presented for reliability levels of 0.05 to 0.99, and for coefficients of variation of explosive mass and range each varying from 0.0 to 0.3. The paper then shows the significant effect that range and explosive mass variability have on RBDFs, and how this affects structural design and damage predictions for reinforced concrete columns and glazing.



## 1. Introduction

The risk of damage to infrastructure and people is affected by variability and uncertainty with imposed loads, and the associated structural and human response to these loads. If the hazard is explosive blast loading, either accidental or malevolent, then stochastic and structural reliability methods have been developed to assess blast load variability, and predict the likelihood and extent of damage to infrastructure (e.g., [26,48,19,11,15,25,14,39,29]). This information can then be used in cost-benefit analyses to assess the cost-effectiveness of protective measures for infrastructure (e.g., [18,42,43,22,23,45]).

Blast loads predicted by Kingery and Bulmash [17] and codified into [7,50] are used by many personnel when assessing vulnerability of infrastructure and people to explosive blast loading. In addition, physics-based Finite Element Methods or Computational Fluid Dynamics models such as Air3D [1], ProSAir [33], LS-DYNA [20] and AUTODYN [2] improve the accuracy of predictions, particularly for complex blast environments. However, these deterministic approaches do not take into account the actual variability and uncertainty associated with the predictive model (i.e. model error), the input parameters (i.e. explosive mass, stand-off distance), and any inherent - or aleatory – variability, which relates to the natural (intrinsic, irreducible or fundamental) random uncertainty of a situation.

The U.S. Department of Defense Explosive Safety Board Safety Assessment for Explosives Risk [37] software estimates the quantity (or safety) distances for siting of explosive ordnance (EO). While SAFER considers some parameters to be random variables, such as exposure and infrastructure response, the blast load pressures are calculated deterministically. Similarly, current weaponeering techniques used by the Australian Defence Force, the U.S. Department of Defense and many other armed forces consider the variability of weapon-platform integration, weapon-launch and a weapon's delivery to a desired point of impact. No consideration is given to the variability of post-detonation blast-loads.

The U.S. Department of Defense manual [49] describes the benefits of performance-based or reliability-based design, which helps to "understand airblast uncertainty, intelligently select design loads, and conduct cost-survivability tradeoff studies". Twisdale et al. [48] developed reliability-based design load factors (RBDF) to be applied to nominal loads to give 5th to 99th percentiles of loads for general purpose (GP) bomb detonations. However, the statistics of pressure variability were obtained from a very limited database – only one detonation of a GP 500 lb bomb, and three detonations of GP 1000 lb bombs – and for a limited range of scaled distances (Z) of 0.5–2.6 $kg/m^{1/3}$ ($Z = R/W^{1/3}$ where R is stand-off distance and W is explosive mass). Moreover, it ignored the important variability W and R (i.e., Z is deterministic). The RBDFs were then incorporated into [49].

Very few studies describe the observed variability of explosive blast loads. Some derive statistics based on data obtained from tests aggregated from various scaled distances e.g., [19,3]. Hence, the observed statistics represent the variability of scaled distance (range, explosive mass) as well as of the blast itself. However,

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https://doi.org/10.1016/j.strusafe.2017.10.010
0167-4730/

Bogosian and Heidenreich [4] found that test data compares well to the Kingery-Bulmash model for peak reflected pressure, with a model error close to unity. However, for more complex blast environments variabilities increase and model accuracy reduces. Campidelli et al. [5] calculated model errors in the range of 0.62–0.95, with COV (coefficient of variation) of up to 0.5. Olmati et al. [30] considered the effect that variability of explosive mass and range have on reliability-based safety factors for Reinforced Concrete RC) panels. Others have also considered the variability of blast loads (e.g., [40,35,36]); see [28] for a full literature review of this work. Netherton and Stewart [26] and Stewart and Netherton [44] have desegregated model error and other sources of variability, incorporated uncertainty of explosive mass and range, and have conducted repetitive explosive field trials with 32 detonations and over 224 recorded time-pressure histories to better characterise model error. This allowed the development of a probabilistic blast load model called P-Blast that predicts the variability of the blast load itself [32]. This new probabilistic blast load model considered variability of explosive mass, net equivalent quantity (NEQ), range, angle of incidence, air temperature and pressure, inherent variability, and model error.

Current design practice as adopted by [50] 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 evidence to support the 20% "factor of safety" other than "unknown factors can still cause an overestimation of a structure's capacity to resist the effects of an explosion. Unexpected shock wave reflections, construction methods, quality of construction materials, etc., vary for each facility. To compensate for such unknowns it is recommended that the TNT equivalent weight be increased by 20 percent." [50]. Whilst such an approach may provide an intuitive, and seemingly conservative, means of accommodating the uncertainty and variability associated with blast-loading, a 20% safety factor may not be the most appropriate means of dealing with such variability. Stewart and Netherton [44] have shown that the reliability level or the probability of non-exceedance of design blast loads varies from 0.72–0.95 and 0.86–0.99 for pressures and impulse, respectively. A reliability-based design requires information about the reliability level of blast loads, as this is a true measure of the degree of conservatism, or not, that the designer, owner or regulator is prepared to accept or tolerate. This is the basis for load and resistance factor design (LRFD) or limit states design incorporated in United States, Canadian, European, Australian and most international design codes and standards (e.g., [41]).

In accordance with [50], 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 ($\lambda$) to ensure that the actual load is equal to the reliability level, see Fig. 1. A load factor greater than one increases nominal loads resulting in more conservative structural designs. A risk-averse decision maker may prefer there to be 99% certainty (0.99 reliability level) that the actual blast is less than the nominal (predicted) value. Conversely, some decision-makers may be more interested in the 0.50 reliability (mean) blast load given that the threat scenario may already be a conservative (or worst-case) estimate of explosive mass or range. The military may be more interested in ensuring that there is 95% surety of damaging a military target, and so might be interested in a lower level of reliability (such as 0.05 or 5th percentile of blast load).

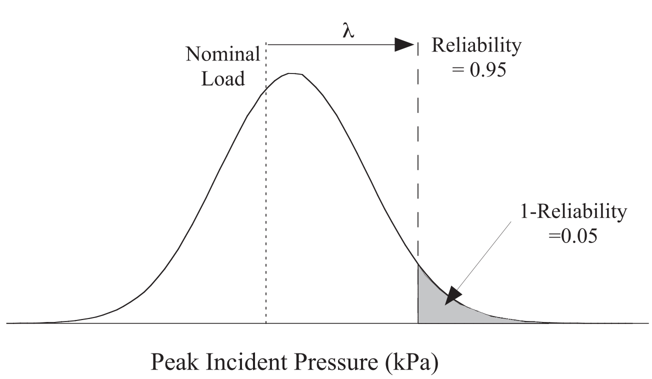


**Fig. 1.** Schematic of reliability-based load factor ($\lambda$) for a reliability level of 0.95.

Stewart and Netherton [44] used Monte-Carlo simulation to develop reliability-based design load factors for an EO scenario where range and explosive mass were deterministic, and the explosive considered was Tritonal. Hence, model error was the only source of airblast variability. The present paper extends this work considerably by developing an analytical design model showing the significant effect that range and explosive mass variability have on airblast variability and reliability-based design load factors, and how this affects performance-based structural design and damage predictions for RC columns and glazing. The calibration is conducted for military, commercial, and terrorist explosives where explosive mass (W) and stand-off distance (R) are random variables. Hence, a design model for reliability-based load factors is presented for reliability levels of 0.05 to 0.99, and for COV of W and R each varying from 0.0 to 0.3.

## 2. P-blast: Probabilistic blast-load model

The probabilistic blast load model (P-Blast) developed by Netherton and Stewart [26] and Netherton [24] used Monte-Carlo simulation to consider the variability of:

(a) User factor for mass of explosive ($W_{user}$),
(b) Net equivalent quantity (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,
(e) Accuracy (model error) of predictive load models, and
(f) Inherent variability.

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 [26]). The Kingery-Bulmash model [17] has been incorporated into widely used and well respected blast load design models, such as [7,50,47], and LS-DYNA, and is used as the predictive model for P-Blast.

A key variable is model error, defined as actual test) blast load divided by predicted load. Model error allows the accuracy and variability of the predictive model to be characterised, as well as inherent variability. In general, model error is obtained from repetitive tests where variability of other parameters is minimised, and a statistical comparison of test data with predicted values allows model error to be described probabilistically. The output from the Netherton and Stewart [26] P-Blast model is particularly sensitive to changes in model error. The model is also sensitive, but to a much lesser degree, to blast wave inherent variability and instrumentation error of the data capture system. Consequently, improved characterisation of model error is crucial to improving the accuracy of probabilistic blast load modelling.

Thus, it is desirable to conduct explosive field trials with the specific purpose of repeatability and the derivation of variability of model error. An explosives range owned by the Australian Defence Forces ADF) was used by The University of Newcastle in 2012 to conduct repeatable explosive field trials [27]. A total of 32 detonations were conducted for scaled distances of