



Probabilistic Analysis of Reinforced Concrete Slab Subjected to Blast Loading

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ABSTRACT

It is established in the literature that the effect of blast load on reinforced concrete structures depends on the distance between the point of the blast explosion and the affected structure; this is known as standoff distance. The usual approach to the study of the response of the structures under the blast loading assumed deterministic design variables. However, design variable that generally defined the applied loading as well as the structural resistance are random and therefore uncertain. The best approach to accommodate uncertainties is to use probabilistic method. Probabilistic analytical methods are available for assessment of the response of structures under static and dynamic loading that is usually accomplished with the aid of computer programs. In this paper, reinforced concrete slabs are considered for analysis being them commonly uses as blast shields for military personnel at warfare. Probabilistic analysis of the response of reinforced concrete slabs subjected to TNT explosion was carried out using the First Order Reliability Method (FORM) through a developed computer program based on MATLAB. The reliability analysis was implemented based on two pre-defined target reliabilities of 2 and 5, which accommodated the recommended target reliability of the Eurocode 0 (Pren EN 1990, 2004). The results confirmed the fact that, so long as the charge weight of the slab does not exceed 500kg TNT, the standoff distance not less than 7m should be used to achieve a target safety index of 2 and not less than 8m to achieve target safety index of 5.

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INTRODUCTION

In today's uncertain world, terrorism is a big concern. More and more attention has been drawn to design and retrofitting of critical military or civil infrastructures against explosive attack. Dynamic response of critical structural elements and overall structures under high-rate blast or shock load from the close-in explosion is of particular interest. Since

concrete is the fundamental construction material used worldwide, it is important to understand the material behaviour and structural response of concrete members under extreme loading. It is also well established in the literature that the design variables that defined the resistance and load effect models for structural members are random (uncertain) in nature and the best approach accommodate such effects in

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design is to use probabilistic method (Ang and Tang, 1984; Melchers, 1999; Afolayan and Abubakar, 2003; Ditlevsen and Madsen, 2005; Holicky, 2009). This paper is aimed at the accommodation of uncertainties in the probabilistic analysis of reinforced concrete under explosive loading. In this paper, the effect of uncertainties on the safety of reinforced concrete members, with specific reference to reinforced concrete slab subjected to blast at various standup distances is presented.

The specific objectives of the research include the following:

- i. Formulation of the performance functions for various failure modes of reinforced concrete slabs under explosive loading.
- ii. Establish the stochastic models of the basic design variables for each mode of failure.
- iii. Develop MATLAB based computer program for First Order Reliability Method (FORM) to evaluate the performance functions.
- iv. Perform sensitivity analysis to investigate the effect of uncertainties on reinforced concrete slabs under blast loading.

LITERATURE REVIEW

The renewed trends on the activities of terrorists lead to renewed interest on the effect of explosive loading on specially reinforced concrete structures. This is because, the bulk of structures today, especially in a developing country like Nigeria are made of reinforced concrete. The effect of explosive loading on structures could be aggravated by the effects of uncertainties in material properties and loading.

Many studies were previously conducted to investigate the response of reinforced concrete member to blast loading, such as Luccioni and Luege (2006); Tai, et al, (2011); Hosseinipoor, et al. (2014); Cheng et al, (2014); Abdel-Mooty et al (2014); Jose et al. (2016); Ibrahim et al., (2017); Shukla et al, (2017); Maazoun, et al, (2017); Alqedra et al. (2018). All these were based on deterministic design approach in which unique values of the basic design variables were used. However, some researchers attempted the consideration of the influence of uncertainties in the performance analysis of reinforced concrete structures:

Eamon (2007), investigated the reliability of masonry unit walls subjected to explosive loading. In this paper, reliability analysis was presented for a structural member that is fully reinforced. As most concrete structures designed to support both static and dynamic actions are fully reinforced.

Hao (2014) investigated the reliability of reinforced concrete slabs with and without CFRP (Carbon Fibre Reinforced Polymer) strengthening. In this research, all the design parameters were considered as normally distributed random variables. The results would have been better if the actual distribution of design parameters are used rather than considering normal distribution for all parameters. In this paper, RackwitzFiessler Transformation algorithm was used to transform non-normal variables to equivalent normal variables as required by the First Order Reliability Method (FORM), employed in the study. In this way, the actual probability distribution for each of the considered random variable was fully accommodated.

Ajimitohu, et al., (2018) investigated the effect of uncertainties on the shear possibility reinforced concrete CFRP laminated shear walls under blast loading. The research considered 108.9kg of

Ammonium Nitrate Fuel Oil (ANFO) explosive. In a dynamic analysis of structures under blast loading, the explosive is established concerning standard TNT (Trinitrotoluene) explosive. Since TNT is the standard, it will be wise to consider it in all analysis rather than other explosive types.

ANALYTICAL TECHNIQUE

Structural Configuration and Specification of the Structure under Study

The study involved the detonation of a multistory building at a distance R , with a charge weight W kg TNT, affecting the

reinforced concrete floor slab at a height of 3.0 m. The slab is a reinforced concrete wall with a cross-section as shown in Figure 1.0. The slab is supported on reinforced concrete beams at a distance of 5m from each other. It is designed as a simply supported reinforced concrete slab supported by the beams at its ends. The slab has been designed to resist normal gravity loading by the requirements of the Eurocode 2 (2004). The amount of reinforcement is the same in both directions. The concrete has compressive strength on 25N/mm^2 and the yield strength is 500N/mm^2 .

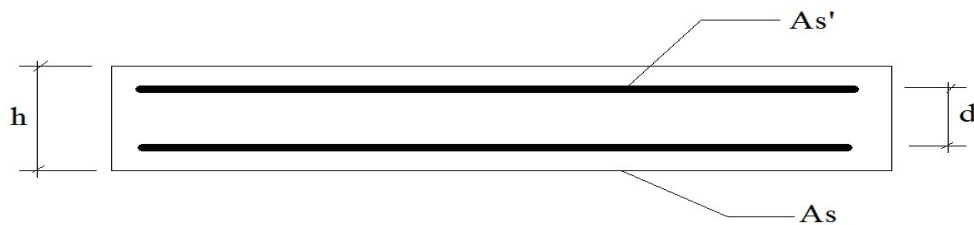


Figure 1.0: Rectangular cross-section of the studied reinforced concrete slab section

The reinforced concrete slab is simplified to an equivalent Single-degree-of-freedom (SDOF) system. Peak dynamic response of the SDOF system to blast load was solved dynamically. Structural reliability analysis was then carried out with the view to investigate the effects of uncertainties on the dynamic response of the slab under blast loading. The implementation was made through a developed MATLAB based computer program.

$$\dot{i}_r = \frac{1}{2} P_r t_d \quad (\text{Ns/m}^2)$$

The Impulsive Loading

When analyzing and designing a structure affected by a blast wave, the acting pressure load could be idealized as an equivalent triangular pulse with maximum peak pressure P_p and the duration, t_d . The impulse per surface area i_r is calculated as in Equation 2.0 due to a triangular shape of the acting impulse and is illustrated in Figure 2.0.

(1.0)

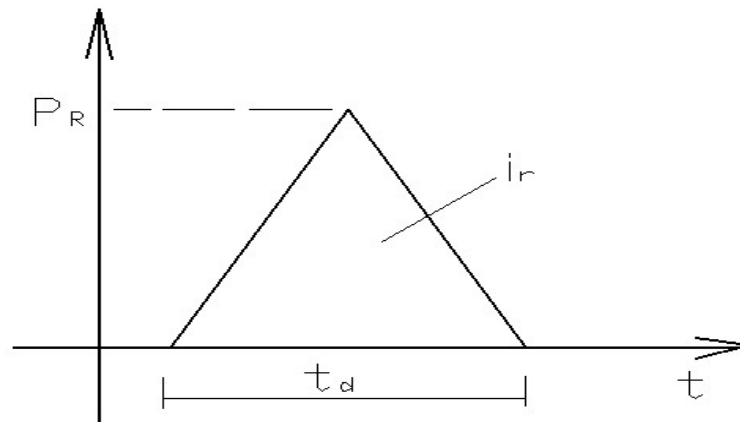


Figure 2.0: Idealised Triangular Impulse

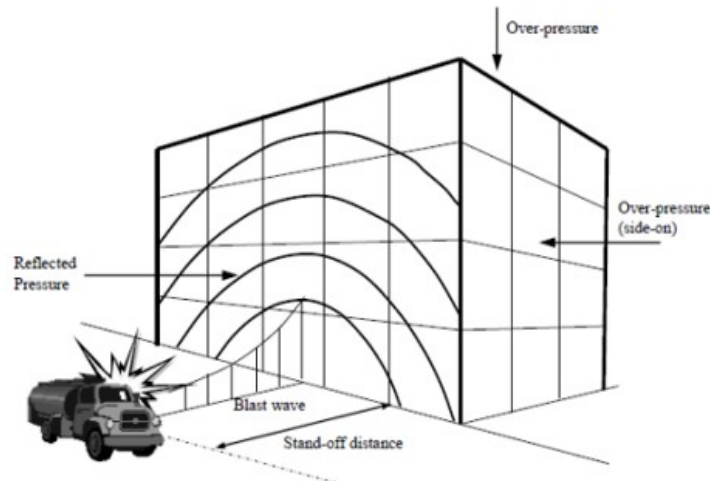


Figure 3.0: How a Blast Wave affects a building from Ngo et al (2007)

Stand-off Distance and Charge Weight

The two most relevant variables that are crucial when mentioning threats from a conventional bomb are the charge weight W , and the stand-off distance R , between the detonation and the target, as seen in Figure 3.0. As Ngo et al. (2007) mentioned.

The Failure Cases of the Structure of the Slab

Three failure cases of the reinforced concrete slab were considered as follows:

- i. Failure Case one: Uncracked Reinforced Concrete Slab Section
- ii. Failure case two: Cracked Reinforced Concrete Slab Section
- iii. Failure case three: Ideal Plastic Section

Likewise, the following assumption and simplification are considered in the analysis.

- i. The load is triangular and uniformly distributed over the entire slab.
- ii. There are no windows or other irregularities in the slab.
- iii. The connections between slab/beam are free.

iv. The supports are rigid.

Formulation of the Structural Reliability Analysis

Generally, a structural reliability problem can be formulated in the following form (Cheng, 2007):

$$\text{Minimise: } \beta = \|\mu\|^2 = \mu^T \cdot \mu$$

$$\text{Subject to: } g(\mu) = 0 \tag{2.0}$$

Where μ is the vector of standard normal variates; $g(\mu)$ is the limit state function; β is the reliability index.

The problem in equation 2.0, is a constrained nonlinear optimization problem. In this paper, the First Order Reliability Method (FORM) was utilized in the evaluation of the performance function for the various failure cases.

$$Z_i = \frac{X_i - \mu_{x_i}}{\sigma_{x_i}} \tag{3.0}$$

The Hasofer-Lind Reliability Index is defined as the shortest distance from the origin of the reduced variable space to the limit state function $g=0$ (Hasofer and Lind, 1974). An iteration is required to find the

The First Order Reliability Method

Considering a performance function $g(X_1, X_2, \dots, X_n)$ where the random variables X_i are all uncorrelated, the limit state function is rewritten in terms of the standard form of the variables using equation 3.0.

design point $\{Z_1^*, Z_2^*, \dots, Z_n^*\}$ in reduced variable space such that β still corresponds to the shortest distance (shown in Figure 3.0).

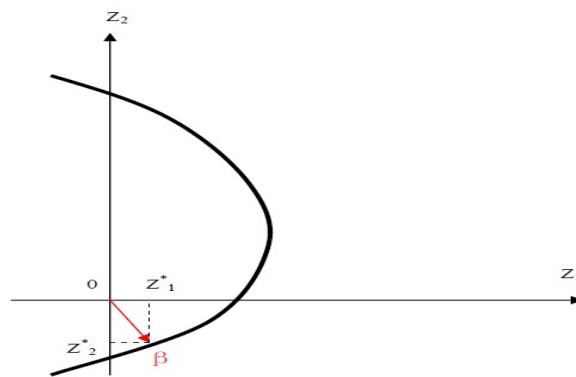


Figure 4.0: Definition of Hasofer Lind Reliability Index

The iterative procedure requires the solution of a set of $(2n+1)$ simultaneous equations with $(2n+1)$ unknowns:



$$\beta, \alpha_1, \alpha_2, \dots, \alpha_n, Z_1^*, Z_2^*, \dots, Z_n^* \quad (4.0)$$

$$\text{Where } \alpha_i = \frac{-\frac{\partial g}{\partial Z_i} \text{ evaluated_at_design_point}}{\sqrt{\sum_{k=1}^n \left(\frac{\partial g}{\partial Z_k} \text{ evaluated_at_design_point} \right)^2}} \quad (5.0)$$

$$\frac{\partial g}{\partial Z_i} = \frac{\partial g}{\partial X_i} \frac{\partial X_i}{\partial Z_i} = \frac{\partial g}{\partial X_i} \sigma_{X_i} \quad (6.0)$$

$$\sum_{i=1}^n (\alpha_i)^2 = 1 \quad (7.0)$$

$$Z_i^* = \beta \alpha_i \quad (8.0)$$

$$g(Z_1^*, Z_2^*, \dots, Z_n^*) = 0 \quad (9.0)$$

The Performance Functions of the Reinforced Concrete Slab

Three performance functions of the reinforced concrete slab, corresponding to each mode of failure were formulated based on the following:

- i. Maximum allowable deflection for the uncracked section.
- ii. Maximum allowable deflection for the cracked section.

$$G(x) = \frac{\theta k_\lambda}{2} - \frac{I}{\sqrt{m_I} K_I} \quad (10.0)$$

Where u_{rd} is the displacement capacity of the wall is u_i is induced displacement of the uncracked section, ϑ is the plastic rotation capacity of the section, k_λ is the modification factor for the plastic rotation capacity, I is the impulsive load, m_I is the transformed mass of the uncracked

$$G(x) = \frac{\theta k_\lambda}{2} - \frac{I}{\sqrt{m_{II}} K_{II}} \quad (11.0)$$

Where, u_{rd} is the displacement capacity of the wall, u_{ii} is induced displacement of the cracked section, θ is the plastic rotation capacity of the section,

- iii. Maximum allowable deflection for the plastic section

The details of the performance functions are as follows

1. Performance Function for the Uncracked Wall section

The performance function for the uncracked slab section is given by equation 10.0:

section, K_I is the stiffness of the uncracked section

2. Performance Function for the Cracked Wall section

The performance function for the uncracked wall section is given by equation 11.0:

k_λ is the modification factor for the plastic rotation capacity, I is the impulsive load, m_{II} is the transformed mass of the cracked



section, K_{ij} is the stiffness of the cracked section.

$$G(x) = \frac{\theta k_{\lambda}}{2} - \frac{I^2}{2Rm_{III}} \quad (12.0)$$

Where, u_{rd} is the displacement capacity of the slab, u_{III} is induced displacement of the plastic section, θ is the plastic rotation capacity of the section, k_{λ} is the modification factor for the plastic rotation capacity, I is the impulsive load, m_{III} is the transformed mass of the cracked section, R is the internal resistance of the cracked section

3. Performance Function for the Plastic Wall section

The performance function for the uncracked slab section is given by equation 12.0:

Stochastic Models of Basic Design Variables

Structural reliability analysis requires the stochastic (statistical) models of the random variables considering all the failure modes. The random variables in the three considered modes of failure are Plastic Rotation Capacity, Impulsive load, Transformed mass, Internal Resistance of the cracked section. The stochastic models are presented in Table 1.0.

Table 1.0: Stochastic Models of the Basic Design Variables (Source: Hao, 2014)

S/No	Basic Variable	Symbol	Distribution Type	Dimension	Coefficient of Variation
1	Plastic Rotation Capacity	ϑ	Normal	rad	0.15
2	Modification factor	k_{λ}	Constant	-	Nil
3	Impulsive load	I	Gumbel	Ns	0.11
4	Transformed mass	m_i, m_{II}, m_{III}	Normal	kg	0.05
5	stiffness	k_i, k_{II}, k_{III}	Normal	mm ⁴	0.05
6	Internal Resistance of the cracked section	R	Normal	kN	0.05

Numerical Experimentation Framework

The Hasofer and Lind First Order Reliability Method (FORM) algorithm presented on 3.3.1 is numerically

implemented using developed MATLAB program. The program flowchart modified from Sherif and Ayman, (2001) is presented in Figure 5.0.

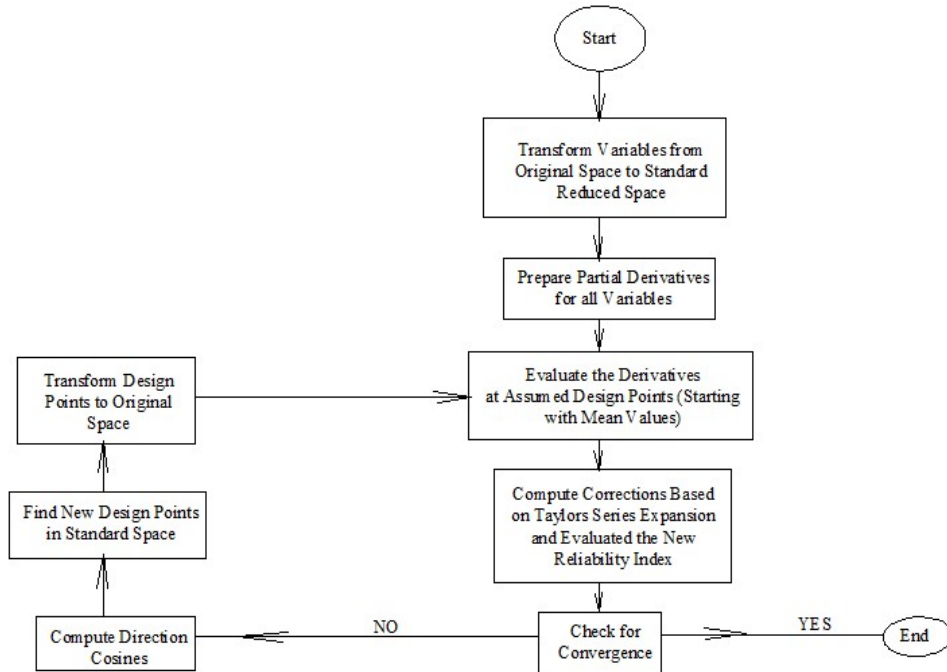


Figure 5.0: Flow chart for MATLAB implementation of FORM (Modified from Sherif and Ayman, 2001)

Setup of the Numerical Experiments

The Main Program 'blast.m'

The numerical experiments in this paper involved dynamic and structural reliability analysis of the considered reinforced concrete slabs subjected to blast explosions through developed MATLAB programs. The programs consist of one

main program and several sub-programs for various tasks. The main program 'blast.m' first requires the selection of the explosive types via the keyboard. The explosives are rated based on their TNT (Trinitrotoluene) equivalence. TNT (Trinitrotoluene) explosive is considered for the analysis.

The Sub-Programs (MATLAB Functions)

Eighteen (18) sub-programs were developed to perform specific tasks as follows:

1. **blast_input_mode1.m**: Keeps the preliminary input data for the probabilistic analysis considering failure case 1.
2. **blast_input_mode2.m**: Keeps the preliminary input data for the probabilistic analysis considering failure case 2.
3. **blast_input_mode3.m**: Keeps the preliminary input data for the probabilistic analysis considering failure case 3.
4. **covariance_mode1.m**: Keeps the coefficients of variation for the random variables for failure case 1.
5. **covariance_mode2.m**: Keeps the coefficients of variation for the random variables for failure case 2.
6. **covariance_mode3.m**: Keeps the coefficients of variation for the random variables for failure case 3.



7. **distribution_mode1.m**: Keeps the distribution model parameters for the random variables for failure case 1.
8. **distribution_mode2.m**: Keeps the distribution model parameters for the random variables for failure case 2.
9. **distribution_mode3.m**: Keeps the distribution model parameters for the random variables for failure case 3.
10. **frechet.m**: Transform frechet random variables to equivalent random variables.
11. **gamma.m**: Transform gamma random variables to equivalent random variables.
12. **gumbel.m**: Transform gumbel random variables to equivalent random variables.
13. **lognormal.m**: Transform lognormal random variables to equivalent random variables.
14. **weibull.m**: Transform weibull random variables to equivalent random variables.
15. **uncracked_section.m**: Compute the safety indices for failure case 1.
16. **cracked_section.m**: Compute the safety indices for failure case 2.
17. **plastic_section.m**: Compute the safety indices for failure case 3.
18. **probability_of_failure.m**: Compute the probabilities of failure for all failure cases.

RESULTS AND DISCUSSION

The study involved probabilistic analysis of the considered reinforced concrete slabs subjected to blast load. The results and discussion are presented in this section.

Influence of standoff Distance of the Slab Safety

Figure 6.0 shows the relationship between the reliability index (Safety of the slab) and the blast standoff distance, considering the three failure cases of the uncracked section, cracked and plastic section and 100kg TNT equivalent explosive. As observed from the plot, the safety index increases with increasing standoff distance. For instance, at 5m standoff distance, the safety index of the slab is 14, before the development of crack. This implied that, if the material is of adequate strength and stiffness to prevent crack development, then the considered explosive will not result in slab damage, and structural failure would be averted. Likewise, the level of loss to

human and properties would be minimal. This is clear since such loss are usually due to failing structural component.

For the case of the cracked section, the slab deformation was high, resulting in a safety index of -18 for the cracked section and -10 for the plastic section. The advantage of the damage case three is that, although the results indicated that, the deformation limits were excessively exceeded, the excessive deformation may not result to the collapse of the slab, it will only result to excessive deformation that may render the slab unserviceable. As the standoff distance increased, the safety indices for both the cracked and the plastic section continue increasing. When the standoff distance of the blast is above 6m, the safety indices for both case two and case three moved to safe regions, gradually increasing toward the case one trend. The results confirmed the fact that the method of regulating the access distance to property in areas that are highly vulnerable to blast is a very effective strategy.

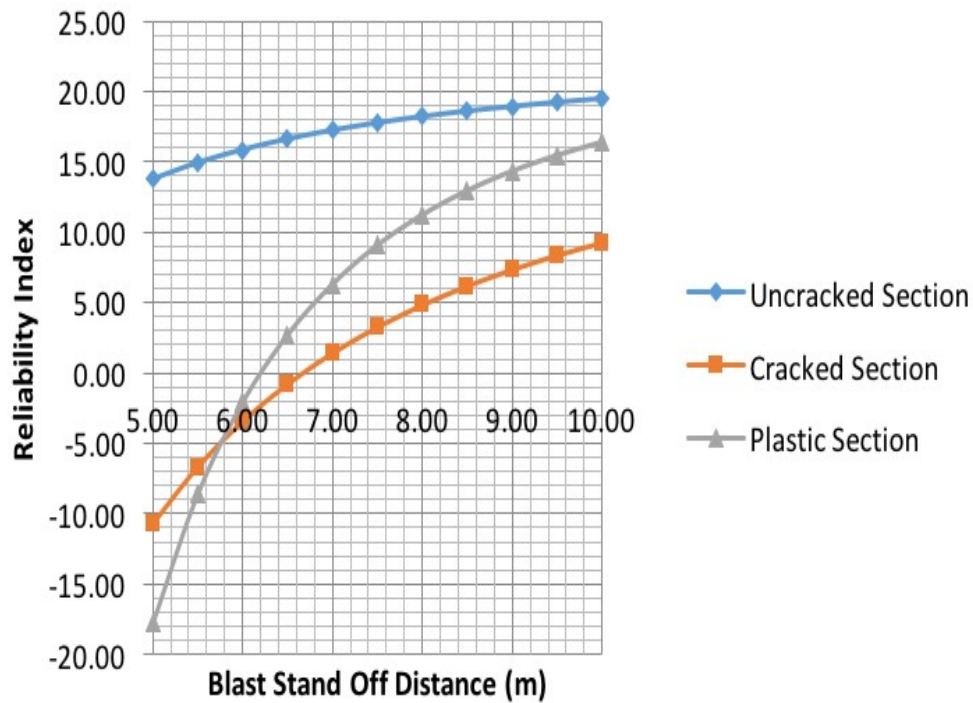


Figure 6.0: Reliability index against blast standoff distance for the three failure cases

Effect of Standoff Distance and Charge Weight on the Safety of the Slab

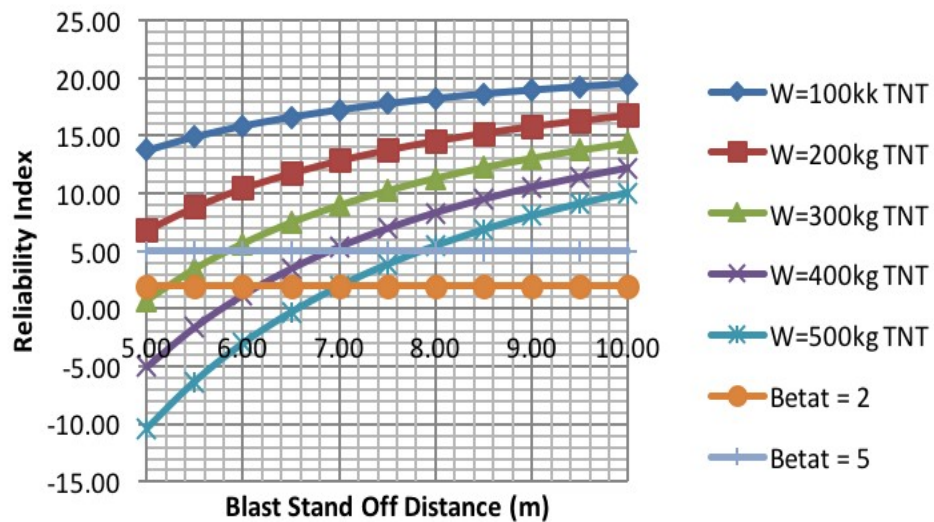


Figure 7.0: Reliability index against blast standoff distance for various charge weights

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Figure 7.0 displayed the relationship between safety index and blast standoff distance for five different explosive charge weights; 100kg TNT, 200kg TNT, 300kg TNT, 400kg TNT and 500kg TNT, considering failure case one (uncracked slab section).

For all the considered charge weights, the safety indices increase with increasing standoff distance. At the default 5m standoff distance, the safety of the slabs detonated with 100kg TNT and 200kg TNT are in safe regions with safety indices of 14 and 7 respectively. Under, 300kg TNT explosive, the slab is at the critical point (Limit State), with safety index equal to 0. For charge weights of 400kg TNT and 500kg TNT, the safety is on the failure side with safety indices of -5 and -10 respectively. However, at standoff distance above 5.8m, the safety of the slab detonated with 400kg TNT, moved to the safe region, and that of 500kg TNT explosive moved to safety region at standoff distance above 6.5m. The computed safety indices were compared with pre-assigned target safety indices of 2 and 5. These values were selected to accommodate the Eurocode 0 (2004) recommended safety indices for both serviceability limit states (1.5, 2.5) and that of ultimate limit states (3.8, 4.7). It is clear from the plot that the safety indices for both 100kg TNT and 200kg TNT are above the target safety indices at all standoff distances. For the 300kg TNT explosive, the target safety indices of 2 and 5 were only respectively satisfied at a standoff distance of 5.1m and 5.9m. While for the 400kg TNT, explosive, the target reliabilities are satisfied at standoff distances of 6m and 6.9m. Likewise, for the 500kg TNT explosives, the target safety indices of 2 and 5 were achieved at 7m and 8m respectively.

CONCLUSION

The random nature of the explosion load, associated with the random

nature of material properties, and geometric dimensional characteristics, implied the need to consider them into the reliability analysis to have a more correct estimation of the structural behaviour. Therefore, when the randomness of these parameters in the analysis is considered, the response of the structure assumes probabilistic nature, and this makes it necessary to look into the reliability measure. This paper presented results from the reliability of reinforced concrete (RC) slab subjected to blast load. The probabilistic responses of the maximum displacement for the reinforced concrete slab under blast loadings were evaluated by means First Order Reliability Method (FORM). Based on the results obtained, the following conclusion is made:

- i. Performance functions for the slab were developed for each of the trees considered a failure case. The performance functions defined the deformation limit states, with the deformation capacity obtained using the criteria recommended in Eurocode 2 (2004). The deformation of the slab for each failure case was established based on UFC 3-340-02 (2008).
- ii. The statistical models for the basic design variables defining the deformation limit states were generated based on data reported in the international literature. The statistical models include mean values, standard deviation, coefficients of variation and distribution models.
- iii. Robust computer programs were developed for the implementation of the reliability analysis. MATLAB compiler was developed for the programming. The developed programs consist of one main program 'blast.m' and several subroutines that perform specific



tasks. The subroutines include preliminary input data subroutines, coefficients of variation subroutines and distribution models subroutines, subroutines for rackwitzfiessler transformation, subroutines for computation of safety indices, subroutines for determination of the probability of failure.

- iv. Sensitivity analysis was performed with the view to determine the effects of uncertainties on the safety of the slab. The results established that, so long as the charge weight of the slab do not exceed 500kg TNT, the standoff distance not less than 7m should be used to achieve a target safety index of 2 and not less than 8m to achieve target safety index of 5.

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