Behaviour of Cantilever Slabs in Blast Environment and Strengthening Techniques

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Abstract: *Cantilever slabs are among the most vulnerable structural elements at blast loading. As they are indispensable to most structures, it is important to investigate the behaviour of cantilever slabs in a blast environment and possibilities of improving their blast resistant abilities. In this paper we are proposing simplified design envelopes drawn for steel to concrete ratio and effective depth of slabs against blast parameters for a common range of cantilever slabs. These design envelopes have been prepared using results of previous research. Using these envelopes, conclusions are made about the effect of slab thickness which is one of the major parameters for improving blast resistant ability. This paper also discusses the blast resistant ability of reinforced concrete cantilevers designed by using the code BS8110 and ways to improve such conventional designs to make them better resistant in a blast loading environment in an economical way.*

Keywords: *Blast resistance, cantilever slabs, structural designs, design envelopes, reinforced concrete, safety.*

1. INTRODUCTION

Even though blast resistant structural designs are becoming important due to the rise in blast risks throughout the world, high explosive blast loading has not yet been included directly in commonly used codes (High explosive blast design strategies are given in the codes UFC-04-10-01, UFC-03-340-02 etc., by the Department of Defence, USA). As the available codes are limited and the theories are complicated, it is worth preparing design guidelines for use by ordinary designers for application in their designs.

Considering the safety of structures and occupants, the EN 1990 and EN1991-1-7 Codes provide strategies for accidental design situations. However, for most common structures, the provisions of these codes are not applied. As the possibility of any structure facing blast loading cannot be predicted, it is important to know the blast resistant ability of vulnerable structural elements such as cantilevered slabs. Therefore, in this research, blast resistant design envelopes for cantilever slabs were developed by using results of previous research and current deign Codes. Using these envelopes, a detailed analysis on the strengthening techniques of cantilever slab by changing its effective depth and steel area is presented.

Strength (magnitude) of a blast depends on the weight of explosives and the effect of a blast on a structure depends on the distance from the blast to the structure. As the weight of explosives that can be brought close to a structure and the location (distance) of a possible explosion near a structure are controllable (i.e. by using appropriate site layouts, vehicle access control and restrictions, car parking away from the main structure, positioning waste bins away from critical structural elements, providing proper security fence (wall) etc.), attention must be drawn to such provisions during a design.

2. GENERATION OF PRESSURE AND ESTIMATION OF IT'S MAGNITUDE

As a result of the experiments done by various scientists since 1940s, there are theories developed mostly using empirical methods about the pressure generation due to a blast, the way this pressure acts on structures and acceptable methods to calculate blast wave parameters. Blast loading on a considered point on a structure is shown in figure 1.

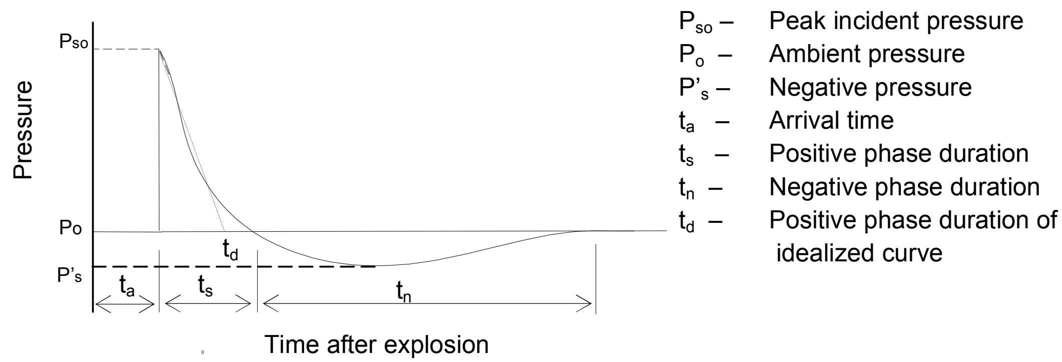

Figure 1 Variation of Pressure after a blast at a considered point

Specific energy of explosives is different from one explosive to another. Using TNT (tri nitro toluene) as the base material, equivalency factors have been estimated for the other explosives. Using the charge weight of TNT (W, measured in kg) and the distance from the centre of the blast to a considered point on the structure (R, also called the standoff distance, measured in m), the term scaled distance (Z) is defined which is;

$$Z = R/W^{1/3} \text{ (units: } m/kg^{1/3}\text{)}$$

Other important terms are; ground zero distance (R_g) which is the horizontal projection of R, and the angle of incidence (α) which is the angle between the vector from the point of blast to the point of concern and its horizontal projection. Pressure due to air blasts (i.e. blasts happened in the air) differs in some ways from that of surface blasts (i.e. blasts happened on the ground). The area of interest of this paper is the pressure on cantilever slabs due to surface blasts.

Blast loading parameters such as Incident Pressure (P_s), Reflected Pressure (P_r), Incident Velocity (U_s), Reflected Velocity (U_r), Incident Impulse (I_s), Reflected Impulse (I_r) and Positive phase duration (t_s) etc., are estimated with respect to Z. In order to estimate these parameters, the well known Kingery & Bulmash's empirical solutions are used.

3. BLAST RESISTANT DESIGN

The blast resistant design was done using the procedure introduced by Cormie *et al* (2009). This procedure has been prepared following the codes UFC-3-340-02, EN 1990, BSEN 1992 and BS 8110, Part 1 (1997), Part 2 (1985) etc.

3.1. Structural resistance

The structural resistance is determined using the link between the duration of loading of blast pressure on a structure and the natural frequency of the structure. Structural resistance can be divided into three regimes according the response of the structure when it is loaded by blast waves. These 3 response regimes are quasi-static, impulsive and dynamic. The response of the structure is quasi-static when $10T<t_d$ and $tm<0.3t_d$, impulsive when $t_d<0.1T$ and $3t_d<t_m$, dynamic when $0.1T<t_d<10T$ and $0.3t_d<t_m<3t_d$ where T is the natural period of vibration of the element (structure) and t_m is the time the element needs to reach its maximum deflection. For designs, quasi-static and dynamic regimes are combined to form one regime and impulsive regime is the other. The designs are done for ultimate limit state and for one occurrence of blast. Refer the illustration given in Figure 2.

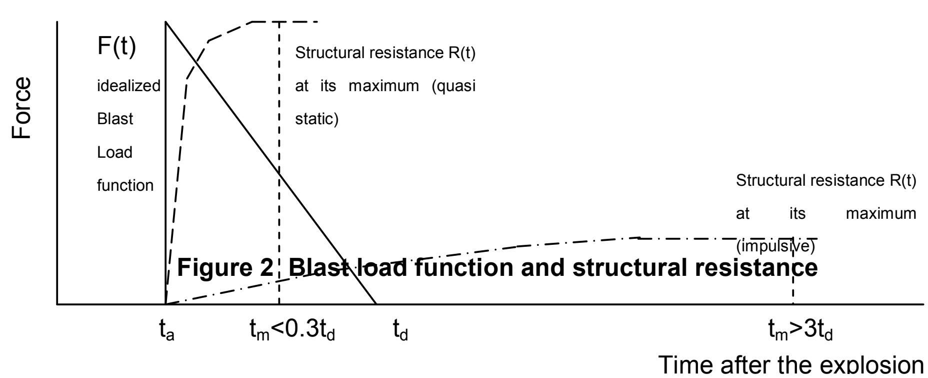

Figure 2 Blast load function and structural resistance

3.2. Protection categories

As described by Cromie *et al* (2009), two protection categories can be introduced for blast designs based on limits of deformation or deflection of the elements [support rotation (θ) and/or ductility ratio (μ) which is the ratio; total deflection (χ_m) / deflection at elastic limit (χ_e)]. Support rotation, $\theta \leq 2°$ comes under protection category 1 which protects structural elements as well as occupants from blast loads. For $\theta \leq 2°$, concrete cover at tensile side may be cracked but the cover on both tensile and compressive sides of the element is effective in resisting moments. Support rotation $\theta > 2°$ comes under protection category 2 in which structural elements are protected from collapse (protection from collapse can be expected till $\theta = 4°$). In this deformation region, concrete cracks at the tensile side and crushes at the compressive side. For $\theta > 2°$, deformation limits imply plastic deformations of the element.

3.3. Factors for material strengths

Mechanical properties of steel and concrete change at rapid loading. Therefore static strengths of materials are converted to dynamic strengths by applying appropriate factors called dynamic increase factors (DIF). Further, according to EN 1992-1-1 (2004), accidental material factors (AMF) are applied on design strengths of materials to withstand accidental loads. Accordingly, nominal material strengths are modified using both DIF and AMF in blast designs. The values of DIF and AMF used in this research are mentioned at relevant chapters in this paper.

3.4. Loading diagram for a cantilever slab

As the cantilevered slabs are generally positioned at floors above the ground level and the blasts considered are surface blasts, the blast pressure should act at the underside of cantilevers whereas the dead and imposed loads act from the top of the cantilevers as shown in figure 3. Therefore there is a necessity of providing tensile reinforcement for dead and imposed loads at the top fibers and tensile reinforcement for blast loading at the bottom fibers.

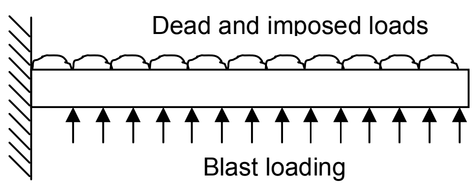

Figure 3 Loading diagram for a cantilever

3.5. Assumptions

As mentioned in the previous paragraphs, the important assumptions used are; idealized blast loading function (triangular pressure time function), idealized resistance deflection function, uniformly distributed loading, for quasi-static/dynamic regime t_d is longer compared to t_m ($t_m/t_d < 3$) and hence loading represents pressure (P) and for impulsive regime, t_d is shorter compared to t_m ($t_m/t_d \geq 3$) and hence loading represents impulse (I). Cantilevers are subjected to two loads from top and bottom sides at a blast as explained in chapter 3.4. The reduction of bending moment and shear forces due to dead and imposed loads (which are acting opposite to blast pressure) was not taken in to account depending on their magnitude compared with that of blast load.

3.6. Design for impulsive regime

The Impulsive regime is considered under protection category 2 which allows support rotations greater than 2° (up to 4°). The design resistant moment M_{Rd} (with dynamic design strengths) is given by;

$$M_{Rd} = [A_s f_{yd \cdot dyn}(z)]/b$$

where, A_s is the tensile reinforcement area, b is the width of the section, $f_{yd.dyn}$ (dynamic design strength of steel) is given by $1.2f_{yk}$ (static yield strength of steel) , z is the lever arm (distance between the tensile & compressive reinforcement). Ultimate resistance of the element R_m can be derived as a function of M_{Rd} and length (L) of the element and can be solved using:

$$I^2A^2/(2K_{LM}M) = (R_m\chi_e)/2 + R_m/(\chi_m-\chi_e)$$

where, I is the blast impulse, A is the loaded area, K_{LM} is the load mass factor, M is the mass of the element, χ_e is the elastic deflection and χ_m is the total deflection.

The relation between t_m/t_d vs t_d/T for triangular blast loading and the relation between the coefficient (f) for second moment of area for cracked section with equal reinforcement in opposite faces vs $A_s/(bd)$ are obtained from the charts of UFC-3-340-02. As the concrete in the compressive side of the element crushed due to allowed larger deflections in the impulsive regime, compression reinforcement is required. For cantilever slabs, the advantage is that tensile reinforcement provided at the top fibers to take dead and imposed loads can be improved to act as the compression reinforcement for blast loading.

3.7. Design for quasi-static/dynamic regime

Quasi-static/dynamic regime is the regime for protection category 1 designs where support rotation θ must be less than 2º. Simplified form of M_{Rd} (with dynamic design strengths) is found using;

$$M_{Rd} = [A_s f_{yd.dyn}(d-0.4x)]/b$$

where; d is the effective depth, x is given by $A_s f_{yk}/(0.59\ b\ f_{ck})$ and $f_{yd.dyn}$ is found using $1.2f_{yk}$.

R_m can be derived as a function of M_{Rd} and L using;

$$R_m = 2M_{Rd}/L$$

The natural frequency of vibration (T) is given by;

$$T = 2\pi\sqrt{(K_{LM}\ M/k_e)}$$

The relation between the coefficient (f) for second moment of area for cracked section with tension reinforcement vs $A_s/(bd)$, the relation between x_m/x_e and t_d/T and the relation between t_m/t_d vs t_d/T for triangular blast loading are obtained from the charts of UFC-3-340-02. Since concrete is effective in resisting moments at compression side, compressive reinforcement may be avoided in the quasi-static & dynamic regime.

4. METHODOLOGY

Use of the term $A_s/(bd)$ in reinforced concrete designs is common. When a design is done using BS8110 or similar codes, the ultimate result is the values for A_s and d. Z is the most convenience parameter in determining the effect of a blast. Therefore the requirement is to develop envelopes (design envelopes) for $A_s/(bd)$ vs Z covering all practical Z values, cantilever spans, effective depths and $A_s/(bd)$ values for both impulsive and quasi-static/dynamic regimes. Accordingly, in this research, the range of Z selected was $0.11\ m/kg^{1/3} \leq Z \leq 40.94\ m/kg^{1/3}$. The selected spans are 1.0m, 1.5m, 2.0m and 3.0m. Effective depths considered are within the rage 100mm ~ 350mm and $A_s/(bd)$ values are in the rage 0.05% ~ 2.00%. Using the method described in chapters 3.6 & 3.7, a series of numerical analyses were conducted using spreadsheets and the relationship between Z and $A_s/(bd)$ was obtained. The shear reinforcement was designed using BS8110, Part-1: 1997 with the use of DIF and DMF values which are described in chapter 3.3. The results were then plotted in 8 graphs (8 design envelopes), 4 of which contain 4 selected spans in the impulsive regime while the other 4 show the 4 spans in the quasi-static/dynamic regime. Cantilevers designed for BS8110 (conventional design) have also been plotted in these envelopes. The imposed load used for conventional design is 5.0kN/m2.

5. DESIGN ENVELOPES

Out of the 8 design envelops, 4 were selected for this paper. Figures 4 and 5 are the envelopes for spans 1.5m and 3.0m for impulsive regime. Figures 6 and 7 show the envelopes for spans 1.5m and 3.0m for quasi-static/dynamic regime.

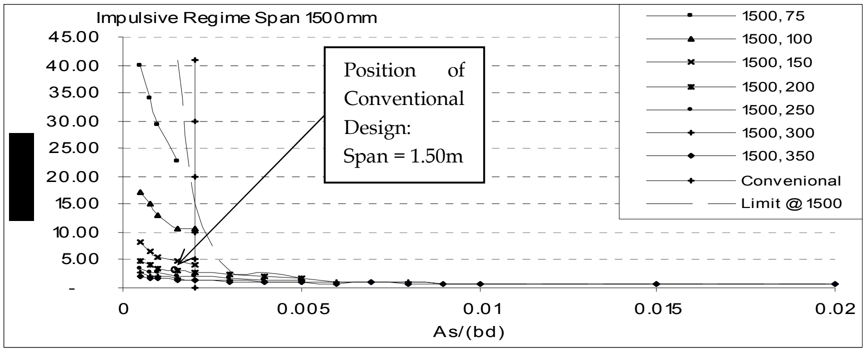

Figure 4 Z vs A_s/(bd) for span 1.5 m in the impulsive regime

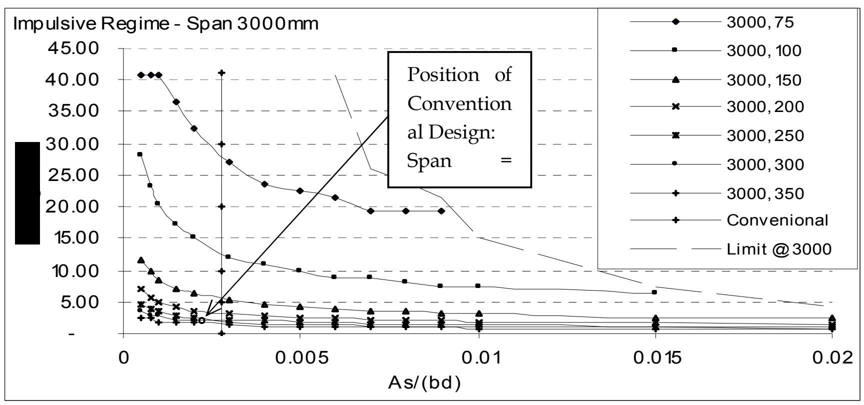

Figure 5 Z vs A_s/(bd) for span 3.0 m in the impulsive regime

The graphs for impulsive regime given in figure 4 and 5 show impulsive design limit which is one of the important observations in this research.

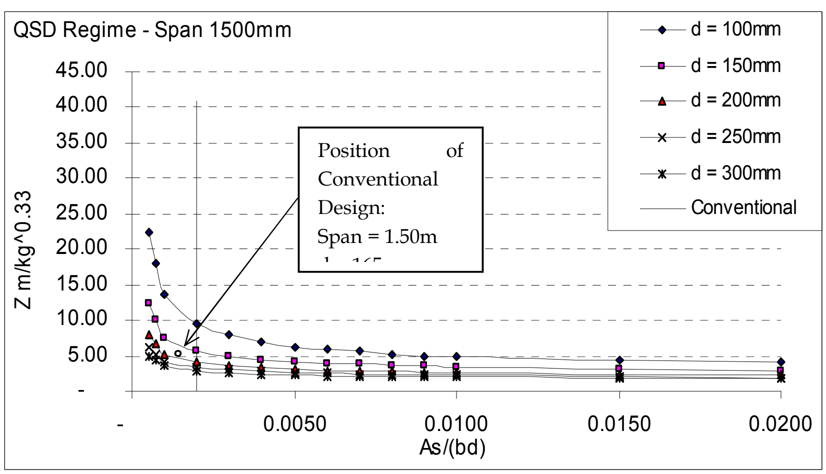

Figure 6 Z vs A_s/(bd) for span 1.5 m in the quasi-static / dynamic regime

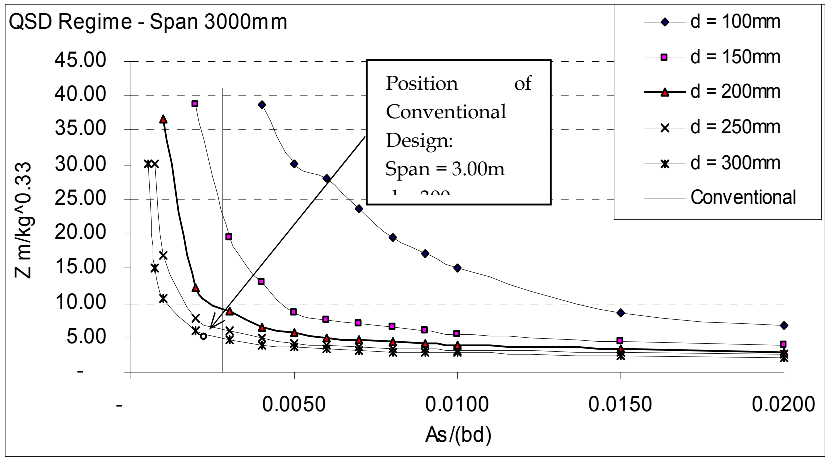

Figure 7 Z vs A_s/(bd) for span 3.0 m in the quasi-static / dynamic regime

Table 1 shows a comparison of shear reinforcement between impulsive and quasi-static / dynamic regimes for Z = 2.155 m/kg$^{1/3}$.

Table 1 Shear reinforcement for Z = 2.155 m/kg$^{1/3}$

Span (mm)	Z (m/kg$^{1/3}$)	Impulsive Regime		Quasi-static & dynamic regime	
		d / (mm)	Shear links (mm^2/m^2)	d / (mm)	Shear links (mm^2/m^2)
1000	2.155	169	0.00	215	3,934
1500	2.155	194	0.00	255	4,647
2000	2.155	215	0.00	280	3,203
3000	2.155	230	0.00	350	2,878

Figure 8 shows the shear reinforcement requirement for cantilevers 3.0m in span. It was observed that the effective depth d < 300mm cannot be designed for Z < 1.05 m/kg$^{1/3}$ and that shear reinforcement is not required for Z > 1.05 m/kg$^{1/3}$.

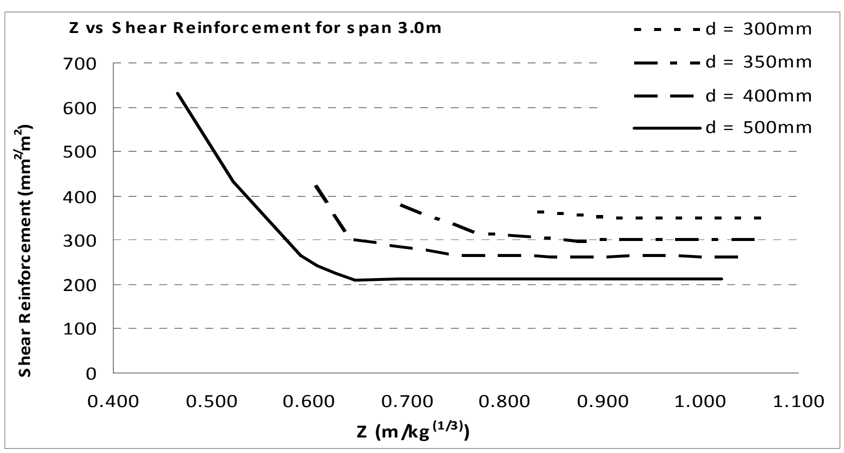

Figure 8 Shear reinforcement for span 3.0 m in the impulsive regime

6. ANALYSIS

Observing the graphical envelopes given in figures 4, 5, 6 & 7, for both impulsive and quasi-static/dynamic regimes, it can be seen that gradients of graphs get reduced with increasing $A_s/(bd)$. For a range of small $A_s/(bd)$ values, there is a faster reduction of Z values but with the increase of $A_s/(bd)$ the reduction of Z goes down. Therefore after a range of $A_s/(bd)$, increase of $A_s/(bd)$ has a minor influence in reducing Z. This means that, after a certain limit, the increase of A_s is not effective in improving blast resistant abilities. Studying the same graphs, it can be seen that by increasing effective depths d, Z can be reduced. The influence of d in reducing Z has spread along a wide range. The important observation is the effectiveness of increasing d for improving blast resistant abilities.

As mentioned in chapter 3.2 and 3.6, impulsive designs come under protection category 2 where no collapse is expected but not as safe as quasi-static/dynamic designs (chapter 3.7). As can be seen in table 2, there is a higher requirement of shear reinforcement for quasi-static/dynamic designs, but impulsive designs are possible without shear reinforcement up to a considerable limit of Z. Figure 8 shows impulsive shear requirement envelope for a cantilever slab (with a span of 3.0m) in which shear reinforcement is needed when $Z < 1.05\ m/kg^{1/3}$ but in minor quantities compared to quasi-static/dynamic designs. Therefore, selecting impulsive designs with possible other safety measures as mentioned in the introduction may prove economical.

One of the important observations is the influence of impulsive limits for a design. As shown in figures 4, 5, there are maximum limits to $A_s/(bd)$ for cantilever slabs to be in the impulsive regime and the slabs move away from the impulsive regime when $A_s/(bd)$ goes beyond these maximum limits. For example, in figure 4, the conventional design is outside the impulsive limit for small d values and in figure 5, the design is within the impulsive limit for all considered d values. One of the reasons for this difference is the mass of the element (i.e. when the mass of the element is high, blast resistant ability is high too). An effective way to increase the mass is increasing the value of d. Further, the effects of T and t_m too have an impact. Increasing A_s (which increase $A_s/(bd)$) reduces T & t_m which in turn reduces the impulsive properties pushing the element away from impulsive limits.

It can be observed that unlike in the impulsive regime, there are no maximum limits for $A_s/(bd)$ for quasi-static/dynamic regime (i.e. any element if not in the impulsive regime should be in the quasi-static/dynamic regime). However, similar to impulsive regime designs, mass of the element plays a major role in the quasi-static/dynamic regime too and therefore, by increasing the value of d, blast resistant abilities can be improved effectively. However, in the quasi-static/dynamic regime designs, the quantity of tensile steel requirement is higher than that in the impulsive regime for a given value of Z (i.e., compare the impulsive envelope with quasi-static/dynamic envelope for similar d and Z). The shear reinforcement requirement in quasi-static/dynamic designs has already been discussed above.

Keeping appropriate values for $A_s/(bd)$ and d, cantilever slabs can be kept within the impulsive limits. If the limits are exceeded, the elements will not resist blast loading efficiently. The elements will then be in the quasi-static/dynamic regime and have less blast resistant abilities unless there are greater improvements to the elements.

It is to be noted that the envelopes show only tensile reinforcements (A_s). Equal reinforcement has been recommended for both tension and compression in the impulsive design and this compression reinforcement will act as the usual tensile reinforcement for dead and imposed loads if appropriate. No compression reinforcement is necessary for quasi-static/dynamic designs as per the principals of the design. However, for cantilevers, the tensile reinforcement provided for dead and imposed loads will act as compressive reinforcement during blast loading.

The positions of conventional designs (approximate values) have been plotted on each design envelop according to their spans. These are given as vertical lines in relation to $A_s/(bd)$ and the arrow pointer shows the position with respect to the effective depth d (i.e., in figure 4, the conventional design for the span 1.50m and effective depth 165mm is sufficient for a Z value of $3.5m/kg^{1/3}$). For example, the obvious way to improve the blast resistant abilities of this conventional design in the impulsive regime is increasing d with $A_s/(bd)$ remaining unchanged and providing compressive reinforcement.

7. CONCLUSIONS

Any conventional design can withstand blast loads up to a certain magnitude. Knowing this limit is helpful in improving a conventional design and making it more blast resistant. In this research, the main aim was to develop design envelopes for reinforced concrete cantilever slabs in order to find out their position in a blast environment and then determine the improvements needed to make them blast resistant. The conclusions reached are as follows.

Conventional designs can be improved and made blast resistant. If the requirement is to protect the structure from collapse, the structure should at least satisfy the impulsive regime limits. The improvements needed to push a conventional design into the impulsive regime are minor and easily achievable. Quasi-static/dynamic regime gives the best protection from blast loading. However, pushing a conventional design towards quasi-static/dynamic regime needs greater improvements such as a larger quantity of tensile and shear reinforcement. Therefore, considering the cost impact, it can be recommended that conventional designs (structures with less blast risks) should be kept within the limits of the impulsive regime.

Increasing slab thickness (effective depth) is more effective in making structures blast resistant than increasing tensile and compressive reinforcement. There is a limit to the amount of tensile and compressive steel needed for an element to be in the impulsive regime and a requirement for sufficient mass (connected with effective depth). If steel is increased (without increasing the effective depth), the natural frequency and the time the element needs to reach its maximum deflection decrease due to which the element moves away from the impulsive regime (i.e. the element will enter into the quasi-static/dynamic regime where many modifications are necessary to resist blast loads). Therefore a design check for conventional designs should be introduced to see whether the element is within the impulsive regime.

Most practical sizes of conventional cantilever slab designs can be analyzed using the envelopes developed in this research. The authors are suggesting that, using this methodology, design envelopes can be developed for any other structural element to observe their behavior in a blast environment.

8. ACKNOWLEDGMENTS

Authors would like to acknowledge the contributions of the National Research Council of Sri Lanka (NRC / 11-106) and the assistance of Dr. U. I. Dissanayake, Senior Lecturer, Faculty of Engineering, University of Peradeniya.

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