Design Envelopes for Cantilever Slabs to Resist Blast Loads

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Abstract

Blast resistant structural designs are becoming essential because of the upsurge in terrorist attacks throughout the world in recent years. A lot of research has been done since 1940s to develop design philosophies against blast forces. As a result, a number of methods have been introduced to estimate design parameters and procedures have been developed to carry out blast resistant designs.

Conventional designs codes consider risks such as excessive wind, floods, water waves, earthquakes, crashing of vehicles or aircraft on to buildings, collapse of masses, explosions (gas pipes, gas containers, pressured water lines etc) and consequences of human error. However, designs for explosions using explosives (bombs) are not included in commonly used conventional design codes. Therefore, developing design guidelines which can be easily used for designing blast resistant structures is important.

Using results of previous research works and numerical methods, design envelopes can be developed by means of which, the position of conventional structural elements in a blast loading environment can be identified.

Design envelopes for cantilever slabs were developed using Kingery and Bulmash's (1984) empirical method (for estimations of blast parameters) and the procedures described by Cormie D et al. (2009), for blast resistant reinforced concrete design, which have been prepared following the codes UFC-3-340-02, EN 1990, BSEN 1992 and BS 8110, Part 1, 1997 and Part 2, 1985 etc. Research was done for impulsive regime (protection category 2) and quasi static & dynamic regime (protection category 1) for a range of cantilever slabs.

The relationship between the scaled distance (Z) and steel to concrete ratio (As/[bd]) for different effective depths (d) were plotted graphically. The position of the conventional design was also plotted on these graphs.

Analyzing the envelopes developed, it can be observed that pushing a conventional design towards quasi-static & dynamic regime needs a greater amount of tensile and shear reinforcement. However conventional designs can be pushed towards impulsive regime with minor improvements. It can be observed that increasing effective depth (slab thickness) is more effective than increasing reinforcement for blast resistance. It can also be seen that there is a maximum limit to the amount of steel needed for an element to be in the impulsive regime and therefore the design must be done with great care.

Keywords: Explosions, Blast resistance, Cantilever slab, Design envelopes, Reinforced concrete.

1. Introduction

In order to improve conventional reinforced concrete structural elements, knowing the ability of a conventional design to bear blast loads (i.e. magnitude of a blast load) is important. In this research, blast resistant design envelopes were developed for cantilever slabs by using results of previous research and assessment calculations. These design envelopes can be used as tools to check and verify blast resistant abilities of conventionally designed cantilever slabs.

2. Explosions, generation of pressure and estimation of blast magnitude

An explosion generates a lot of pressure on air. These pressured air waves travel outwards from the point of explosion as an expanding pressure bulb which grows in size at a very high velocity. The pressure bulb can be approximated to a sphere if the explosion is in the air and a hemisphere if the explosion is on the ground. Because the waves move as a sphere or a hemisphere, when they pass a structure, different parts of the structure get loaded at different times with varying magnitudes. When the pressure wave arrives at a point on the structure, the pressure reaches its maximum value and then gets reduced with time. Figure 1 shows the pressure – time curve at a considered point after a blast.

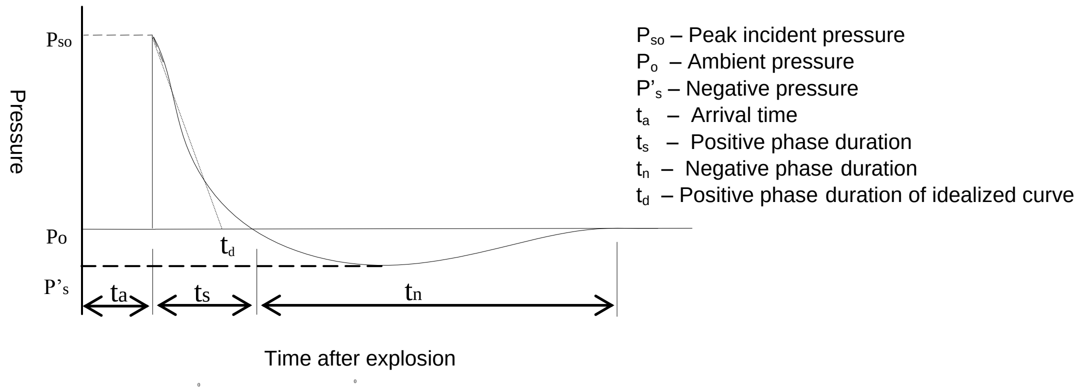

Figure 1: Pressure time curve, pressure at a considered point

Other important and commonly used terms in relation to blast load estimations are; standoff distance (R) which is the distance from the point of explosion to a point considered on the structure, 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 (if the point of concern is on a vertical plane) or the angle between the vector from the point of blast to the point of concern and the normal line (if the point of concern is on a horizontal plane, i.e. in an air blast).

Scaled distance (Z) is defined as (equal to) R / $W^{1/3}$ where W is the Try Nitro Toluene (TNT) Equivalent Explosive Weight in kg. Unit of Z is m/$kg^{1/3}$.

When the pressure wave generated by the blast (incident wave) hits the ground it reflects (reflected wave) and starts moving outwards strengthening the incident wave. In a surface blast, reflected waves instantly merge with incident waves. In an air blast, the time it takes for the reflected wave to join the incident wave (travel time of the incident and reflected waves) depends on the height of the blast from the ground. Where the incident angle is greater than 40˚, (α < 40˚), the incident wave reflects on the reflected wave creating an equal pressure region called Mack region. Therefore the pressure due to air blasts differs in some ways from that of the surface blasts.

3. Estimation of blast parameters and design philosophy

In this research, 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) were estimated using Kingery & Bulmash’s empirical solutions. The blast resistant design was done using the procedure introduced by Cormie et al., which 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 Impulsive & quasi-static & dynamic regimes

Considering the link between the duration of loading of blast pressure on a structure and the natural frequency of the structure, the response of the structure to blast loading can be determined. According to these, three types of response regimes are identified; quasi-static, impulsive and dynamic as illustrated in Figure 2.

The response of 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 tm 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 to be done for ultimate limit state and for one occurrence of blast.

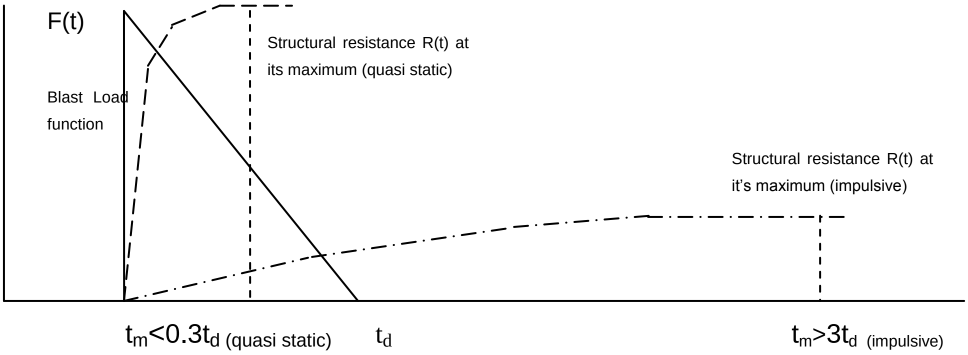

Figure 2: Blast load function and structural resistance function

3.2 Material strengths and protection categories

Mechanical properties of steel and concrete change at rapid loading. Therefore static strengths of materials have to be 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) should be applied on design strengths of materials to withstand accidental loads. Accordingly, nominal material strengths should be modified using both DIF and AMF in blast designs.

There are two protection categories 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, $\theta \leq 2^o$ comes under protection category 1 which protects structural elements as well as occupants from blast loads. For $\theta \leq 2^o$, 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 $\theta > 2^o$ comes under protection category 2 in which structural elements are protected from collapse (protection from collapse can be expected till $\theta = 4^o$). In this deformation region, concrete cracks at the tensile side and crushes at the compressive side. For $\theta > 2^o$, deformation limits imply plastic deformations of the element. For each protection category the factors used to estimate dynamic design strengths for concrete and reinforcement are different.

4. Methodology

In order to develop blast design envelopes for reinforced concrete cantilever slabs, a number of spans, effective depths and steel/concrete ratios were selected together with a number of scaled distances to execute around 5000 assessment calculations. Assessment calculations were carried out for both quasi-static & dynamic and impulsive regimes. Results of these assessment calculations were then plotted graphically for Z versus $A_s/(bd)$ (steel/effective concrete ratio) where A_s is tensile reinforcement area, b is the unit width of the section and d is the effective depth of the element] to develop envelopes. Further assessment calculations were done based on conventional design methods by using the code of practice BS 8110, Part 1, 1997 and plotted on the same envelopes to observe the position of conventional designs in the blast envelopes. Selected sizes (span and effective depth) and steel to concrete ratio for the research are common, practical sizes and up to the limit for which details of previous research results are available. The selected ranges for span, effective depth and steel/concrete ratio are described below in Table 1.

Table 1: Selected range of cantilever slabs for the analysis

<table>
<tr><td colspan="6">Blast Resistant Design</td></tr>
<tr><td colspan="3">Impulsive Regime</td><td colspan="3">Quasi-static & Dynamic Regime</td></tr>
<tr><td>Span (mm)</td><td>Steel/Concrete Ratio $A_s/(bd)$</td><td>Effective Depth d (mm)</td><td>Span (mm)</td><td>Effective Depth d (mm)</td><td>Steel/Concrete Ratio $A_s/(bd)$</td></tr>
<tr><td rowspan="5">1000</td><td rowspan="5">0.0005, 0.00075, 0.001, 0.0015, 0.002, 0.003, 0.004, 0.005, 0.006, 0.007, 0.008, 0.009, 0.01, 0.015, 0.02</td><td rowspan="20">To be calculated (selected range is 60mm<d<400mm)</td><td rowspan="5">1000</td><td>100</td><td rowspan="5">0.0005, 0.001, 0.002, 0.003, 0.004, 0.005, 0.006, 0.008, 0.01, 0.015, 0.02</td></tr>
<tr><td>150</td></tr>
<tr><td>200</td></tr>
<tr><td>250</td></tr>
<tr><td>300</td></tr>
<tr><td rowspan="5">1500</td><td rowspan="5">0.0005, 0.00075, 0.001, 0.0015, 0.002, 0.003, 0.004, 0.005, 0.006, 0.007, 0.008, 0.009, 0.01, 0.015, 0.02</td><td rowspan="5">1500</td><td>100</td><td rowspan="5">0.0005, 0.001, 0.002, 0.003, 0.004, 0.005, 0.006, 0.008, 0.01, 0.015, 0.02</td></tr>
<tr><td>150</td></tr>
<tr><td>200</td></tr>
<tr><td>250</td></tr>
<tr><td>300</td></tr>
<tr><td rowspan="5">2000</td><td rowspan="5">0.0005, 0.00075, 0.001, 0.0015, 0.002, 0.003, 0.004, 0.005, 0.006, 0.007, 0.008, 0.009, 0.01, 0.015, 0.02</td><td rowspan="5">2000</td><td>100</td><td rowspan="5">0.0005, 0.001, 0.002, 0.003, 0.004, 0.005, 0.006, 0.008, 0.01, 0.015, 0.02</td></tr>
<tr><td>150</td></tr>
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<tr><td>250</td></tr>
<tr><td>300</td></tr>
<tr><td rowspan="5">3000</td><td rowspan="5">0.0005, 0.00075, 0.001, 0.0015, 0.002, 0.003, 0.004, 0.005, 0.006, 0.007, 0.008, 0.009, 0.01, 0.015, 0.02</td><td rowspan="5">3000</td><td>100</td><td rowspan="5">0.0005, 0.001, 0.002, 0.003, 0.004, 0.005, 0.006, 0.008, 0.01, 0.015, 0.02</td></tr>
<tr><td>150</td></tr>
<tr><td>200</td></tr>
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<tr><td>300</td></tr>
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Cantilever spans selected for blast resistant designs are 1000mm to 3000mm. Steel to effective concrete ratios were taken from 0.0005 (0.05%) to 0.020 (2%) as shown in the Table 1.

Effective depths (d) of impulsive design are calculated figures in the design for all $A_s/(bd)$ values mentioned in the Table 1 above and from 60mm to 400mm were selected for the envelop. Range for d from 100mm to 300mm were selected for quasi-static & dynamic design calculations and trials were carried out for all $A_s/(bd)$ values mentioned in the Table 1. Further, 42 numbers of scaled distances from the range $0.11\ m/kg^{1/3} \leq Z \leq 40.94\ m/kg^{1/3}$ were used at each design calculation.

4.1 Basic assumptions

In this research idealized blast loading (triangular pressure time function) conditions and uniformly distributed loading on the element were assumed. For quasi-static & dynamic regime, t_d is longer compared to t_m ($t_m/t_d < 3$) and hence it was assumed that the loading represents pressure P. For impulsive regime, t_d is shorter compared to t_m ($t_m/t_d \geq 3$) and loading represents impulse I.

4.2 Blast resistant design

The Impulsive regime is considered under protection category 2 which allows support rotations greater than 2º (up to 4º). The design resistant moment (M_{Rd}) (with dynamic design strengths) is given by $[A_s f_{yd.dyn} z]/b$, where $f_{yd.dyn}$ (dynamic design strength of steel) is $1.2f_{yk}$ (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. Since concrete is not effective in resisting moments at compression side, compression reinforcement must be provided.

Quasi-static & dynamic regime is the regime for protection category 1 designs where support rotation θ must be less than 2º. M_{Rd} (with dynamic design strengths) is $[A_s f_{yd.dyn}(d-0.4x)]/b$, where; x is given by $A_s f_{yk}/(0.59\ b\ f_{ck})$ and $f_{yd.dyn}$ is $1.2f_{yk}$. R_m can be derived as a function of M_{Rd} and L. The natural frequency of vibration (T) is $2\pi\sqrt{(K_{LM}\ M/k_e)}$. Since concrete is effective in resisting moments at compression side, compressive reinforcement can be avoided depending on the requirements of the detailed design.

5. Design envelopes and position of conventional design

Figures 3 and 4 are the selected envelopes to explain the observations of impulsive design and Figures 5 and 6 are the selected envelopes for quasi-static and dynamic design. The values of $A_s/(bd)$ of conventional designs have been plotted in these envelopes for comparison purposes. The Table 2 shows the requirement of shear reinforcement for Z value of 2.155 m/kg$^{1/3}$ for both impulsive and quasi-static & dynamic regimes.

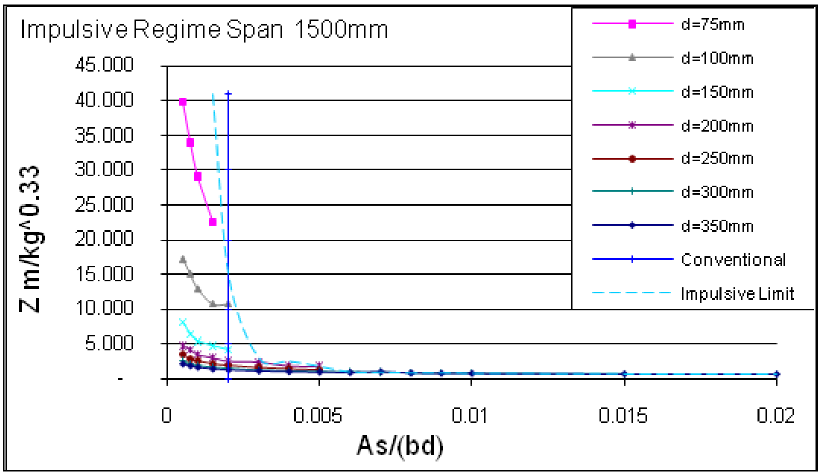

Figure 3: Impulsive envelope and conventional design for span 1.5m

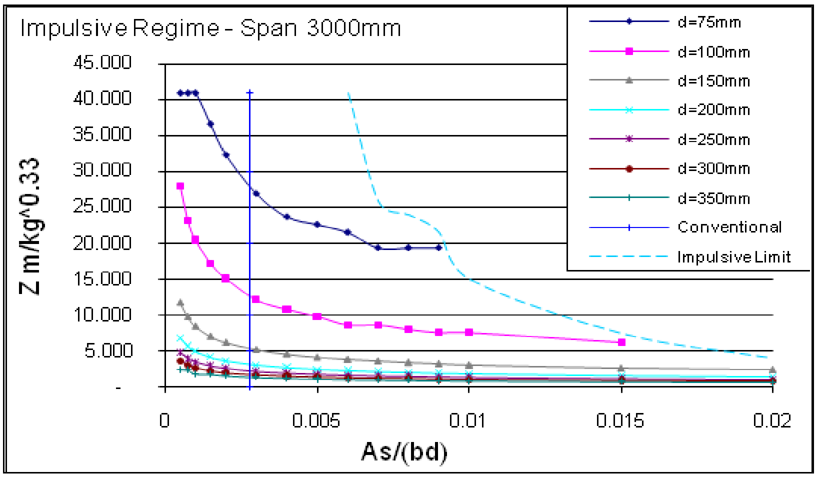

Figure 4: Impulsive envelope and conventional design for span 3.0m

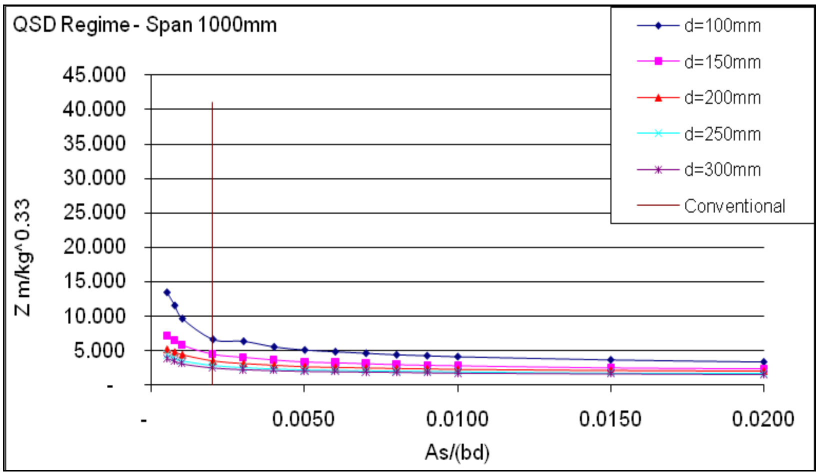

Figure 5: Quasi-static & dynamic envelope and conventional design for span 1.0m

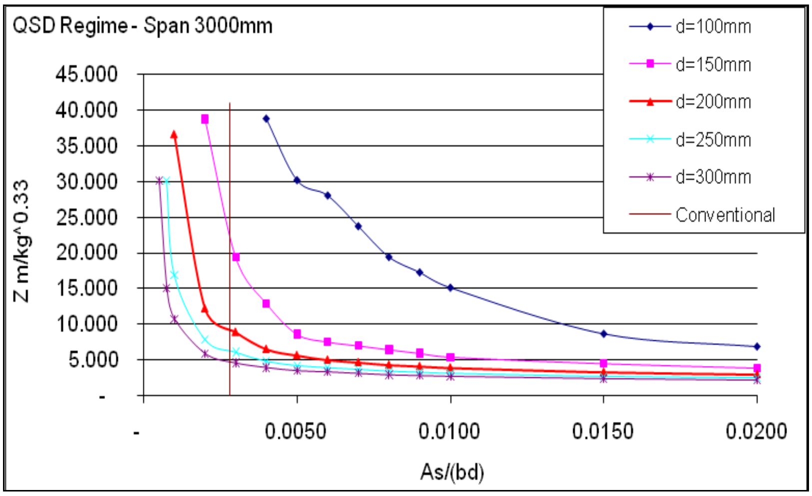

Figure 6: Quasi-static & dynamic envelope and conventional design for span 3.0m

Table 2: Shear Reinforcement Requirement 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*

6. Observations & analysis of results

From the graphical envelopes above, it can be observed that increasing effective depth causes a drastic reduction of Z while increasing of $A_s/(bd)$ results in a comparatively small reduction. This means that increasing of d is more effective than increasing of tensile or compressive reinforcement for blast resistance.

In the impulsive envelope, it can be observed that there is a maximum limit to $A_s/(bd)$ for an element to be in the impulsive regime and the element moves away from the impulsive regime when $A_s/(bd)$ goes beyond this maximum limit. In Figure 3, the conventional design is outside the impulsive limit at less d values and in Figure 4, the design is within the impulsive limit for all Z. 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 tm 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 is to be noted that the impulsive envelopes show only tensile reinforcements (A_s) but compressive reinforcement should also be provided to bear the compressive loads (i.e. compressive side concrete may be crushed at protection category 2). One of the important observations was that shear reinforcement is either not required or minimal (up to a considerable value of Z) in the impulsive regime designs. Therefore conventional cantilever slab designs can easily be improved towards impulsive regime.

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). In the quasi-static & dynamic regime, the lesser the span, the higher the ability of the element to bear blast loads. However, mass of the element plays a major role because of which the increasing value of d gives greater improvement to blast resistant properties. Further, the assessment calculations (i.e. Table 2) show that a greater amount of tensile and shear reinforcement is necessary for an element to be in the quasi-static and dynamic regime (shear reinforcement is not shown in these envelopes).

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 and dynamic regime and have less blast resistant abilities unless there are no greater improvements to the elements. Therefore the suggestion is that keeping conventional designs (for normal structures which are not at risk from a blast) within the impulsive regime limits is safe and economical.

7. Conclusion

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

Conventional designs can be improved towards blast resistance. 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 and dynamic regime gives the best protection from blast loading. However, pushing a conventional design towards quasi-static and dynamic regime needs greater improvements such as a larger quantity of tensile and shear reinforcement. Therefore it can be recommended that conventional designs (structures with less risk of blasts) should be kept within the limits of the impulsive regime.

Increasing slab thickness (effective depth) is more effective than increasing tensile and compressive reinforcement for blast resistance. 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 get reduced 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 must 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. This methodology can be used to develop envelopes for any structural element.

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