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BLAST RESISTANT DESIGN OF REINFORCED CONCRETE WALL

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Abstract - *The study of blast effects on structure has been area of formal technical investigation for over many years. There are numerous texts guides and manuals on the subject with continuing research and technical reporting occurring at a brisk pace. However there is limited guidance available in the literature on the direct application of established blast effects principals to structural design. Numerous efforts are under way to develop comprehensive guides and standard to fill these voids. This study presents a general overview of key design concepts for reinforced concrete structure and same has been applied in the design of RCC walls for various percentage of steel and wall thickness.*

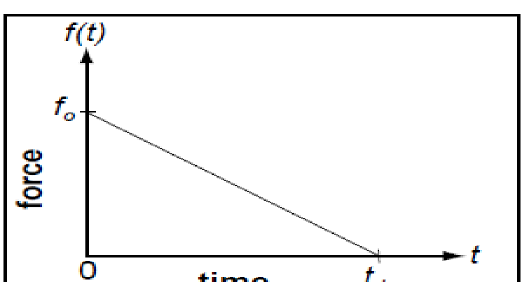
Key words- *Blast resistant design, Ductility ratio, Peak load, Peak reflected pressure, Positive phase duration,*

"I. INTRODUCTION"

The term blast refers to release of enormous amount of energy from the blast source that lasts for few milli-seconds. General buildings are not designed for blast loads, as blast loads because of explosion are quite high, this article specifically addresses the affects of shock loading from air blast are applied to the perimeter structural elements of a building due to a high explosive blast event external to the building. The pressure wave applied to the building is characterized by short duration and high intensity as shown in Figure 1. The blast wave duration (t_d) is typically in the range of 0.1 – .001 seconds. This is often much shorter than, or at most on the order of, the natural period (t_n) of typical structural elements. For situations where $t_d < 0.4t_n$, the blast wave effectively imparts an initial velocity to a structural element and the element then continues to respond at its natural frequency. The magnitude of that initial velocity, for a single-degree-of-freedom (SDOF) model is $v = f_0 t_d/2m$, where f_0 and t_d are shown in Figure 1 and m is the mass of structural element. The extreme nature of blast loading necessitates the acceptance that members will have some degree of inelastic response in most cases. This allows for reasonable economy in the structural design and provides an efficient mechanism for energy dissipation. This also requires the designer to understand how much inelastic response is appropriate. Greater inelastic response will provide greater dissipation of the blast energy and allow for the sizing of smaller structural elements, but it will also be accompanied by greater damage and, at some point, increased potential for failure of the element. The U.S. Army Corps of Engineers Protective Design Center (PDC) has developed response criteria for many typical structural elements in terms of maximum allowable support rotation, θ_{max}, or ductility ratio, μ_{max}, as shown in Table 1 and 2 [3].The requirements for the building are greatly influenced by the factors of distance from blast source, criticality of the function, and expected occupancy.

Explosive loads and impact loads are transients, or loads that are applied dynamically as one-half cycle of high amplitude, short duration air blast or contact and energy transfer related pulse. This transient load is applied only for a specific and typically short period of time in the case of blast loads, typically less than one-tenth of a second. Design to resist blast, impact and other extraordinary loads must be thought of in the context of life safety, not in terms of serviceability or life-cycle performance. Performance criteria for other critical facilities (nuclear reactors, explosive and impact test facilities, etc.) may require serviceability and reuse, but most commercial office and industrial facilities will not have to perform to these levels.
For blast resistant design of buildings, the principal parameter of the blast wave required to define the blast loading for a building's components are:

1. Peak side-on positive overpressure (P_{so}), positive phase duration (t_d), the corresponding positive impulse, I_o.
2. Peak side-on negative pressure (suction), negative phase duration, t_i, and the associated negative impulse, I_o



"Figure 1. Idealized blast pulse with a peak Intensity (f_0) and duration (t_d)

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"Table 1. Maximum allowable support rotation"

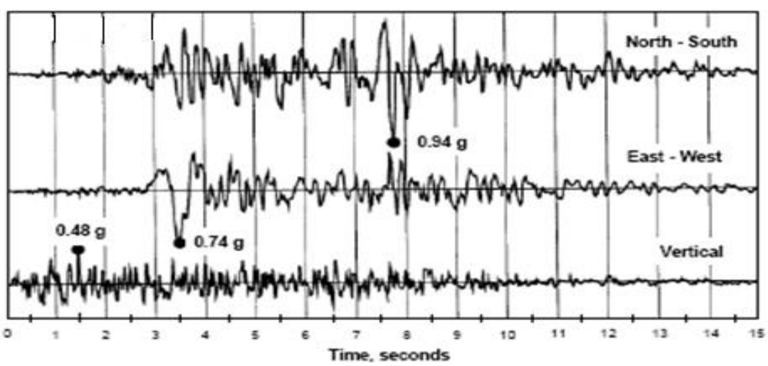
Type of stress	Type of reinforcement	Maximum support rotation (Degree)	Dynamic design stress (F_{ds})
Bending	Tension and Compression	$0<\theta\leq 2$ $2<\theta\leq 5$ $5<\theta\leq 12$	F_{dy} $F_{dy}+(F_{du}-F_{dy})/4$ $(F_{dy}+F_{du})/2$
Diagonal tension	Stirrups	-	F_{dy}
Direct Shear	Diagonal bars	$0<\theta\leq 2$ $2<\theta\leq 5$ $5<\theta\leq 12$	F_{dy} $F_{dy}+(F_{du}-F_{dy})/4$ $(F_{dy}+F_{du})/2$
Compression	Column	all	F_{dy}

"Table 2. Maximum allowable Ductility ratio"

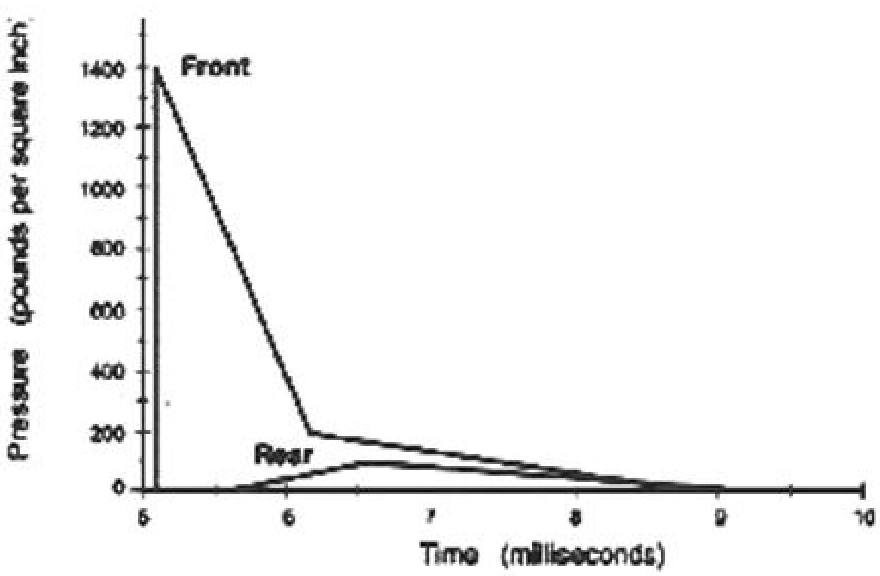
Type of stress	Maximum Ductility ratio	Dynamic Design stress
all	$\mu<10$	F_{dy}
all	$\mu>10$	$F_{dy}+(F_{du}-F_{dy})/4$

A. Blast loads versus seismic loads.

Blast loads are applied over a significantly shorter period of time (orders-of-magnitude shorter) than seismic loads. Thus, material strain rate effects become critical and must be accounted for in predicting connection performance for short duration loadings such as blast. Figure 2. Shows the comparison between seismic load and the blast load. Blast loads generally will be applied to a structure non-uniformly, i.e., there will be a variation of load amplitude across the face of the building, and dramatically reduced blast loads on the sides and rear of the building away from the blast.



"Figure 2a. Response of seismic loading on structure [5]"



"Figure 2b. Response of blast loading on structure. [5]"
"Figure 2. Comparison between seismic load and the blast load"

"II. LITERATURE REVIEW"

The methods available for prediction of blast effects on buildings structures are: Empirical methods, Semi-empirical methods and Numerical methods. Empirical methods are essentially correlations with experimental data. Most of these approaches are limited by the extent of the underlying experimental database. The accuracy of all empirical equations diminishes as the explosive event becomes increasingly near field. Semi-empirical methods are based on simplified models of physical phenomena. The attempt is to model the underlying important physical processes in a simplified way. These methods are dependent on extensive data and case study. Numerical (or first-principle) methods are based on mathematical equations that describe the basic laws of physics governing a problem. These principles include conservation of mass, momentum, and energy. In addition, the physical behavior of materials is described by constitutive relationships. These models are commonly termed computational fluid dynamics (CFD) models.

Khadid, [2007] studied the fully fixed stiffened plates under the effect of blast loads to determine the dynamic response of the plates with different stiffener configurations and considered the effect of mesh density, time duration and strain rate sensitivity. He used the finite element method and the central difference method for the time integration of the nonlinear equations of motion to obtain numerical solutions. Pandey studied the effects of an external explosion on the outer reinforced concrete shell of a typical nuclear containment structure. The analysis has been made using appropriate non-linear material models till the ultimate stages. An analytical procedure for nonlinear analysis by adopting the above model has been implemented into a finite element code. Remennikov and Alexander [2003] studied the methods for predicting bomb blast effects on buildings. Simplified analytical techniques used for obtaining conservative estimates of the blast effects on buildings. Numerical techniques including Lagrangian, Eulerian, and finite element modeling used for accurate prediction of blast loads on commercial and public buildings. Marchand, [2005] studied the dynamic response of a steel structure to the blast loading and shows the behavior of ductile steel column and steel connections for the blast loads.

"III. OBJECTIVE OF PRESENT WORK"

The primary objective of this report is to study the basic philosophy and general consideration involved in the design requirement for blast resistance in building. Accordingly the objectives of present study are as follow.

- To study the basic consideration principles and procedures involved in structural design and evaluation of buildings for blast overpressure effects.
- To design an RCC wall against the blast load.
- To study how the percentage of steel used and the thickness of RCC wall affect the blast resistant design.

"IV. BLAST RESISTANT DESIGN PROCESS"

The design procedure can be summarized into:
1) Blast load definition
2) Response limit selection
3) Trial member sizing and reinforcing
4) Nonlinear dynamic SDOF analysis of the member
5) Comparing the calculated SDOF response with the response limit and adjusting the trial member as necessary.

As noted above, some amount of inelastic response is generally anticipated when designing members for blast response. Economy of design is achieved by selecting smaller members and allowing greater inelasticity. Where greater protection is warranted, larger members are selected, potentially even such that the response to the design blast threat remains elastic. While member sizes can be scaled to match the desired level of protection, proper detailing of joints, connections and reinforcing should always be provided so that the members can achieve large, inelastic deformations even if the intent is for elastic response. This provides greater margins against an actual blast that is larger than the design blast.

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"V. DESIGN OF 200 mm THICK RCC WALL – AN EXAMPLE"

An exterior wall measuring 3.65m tall by 9.144m long, attached to the primary structural framing system at its top and bottom has been designed to resist the effects of a high explosive blast resulting peak reflected pressure of 0.0827N/mm^2,and a positive phase pulse duration ,t_d=50 milliseconds.

As the wall is attached at its top and bottom, the vertical reinforcement will provide the primary load path and blast resistance this example has been limited to design of the vertical reinforcement. As an initial trial, 12mm reinforcing bars spaced every 100 mm at each face has been considered. For each trial section, the bending and shear (yield) strength of a unit strip has been computed, applying Strength Increase Factors (SIF) to account for the actual (rather than code minimum) strength of materials and Dynamic Increase Factors (DIF) to account for the increased strength of materials exhibited under fast load application rates.

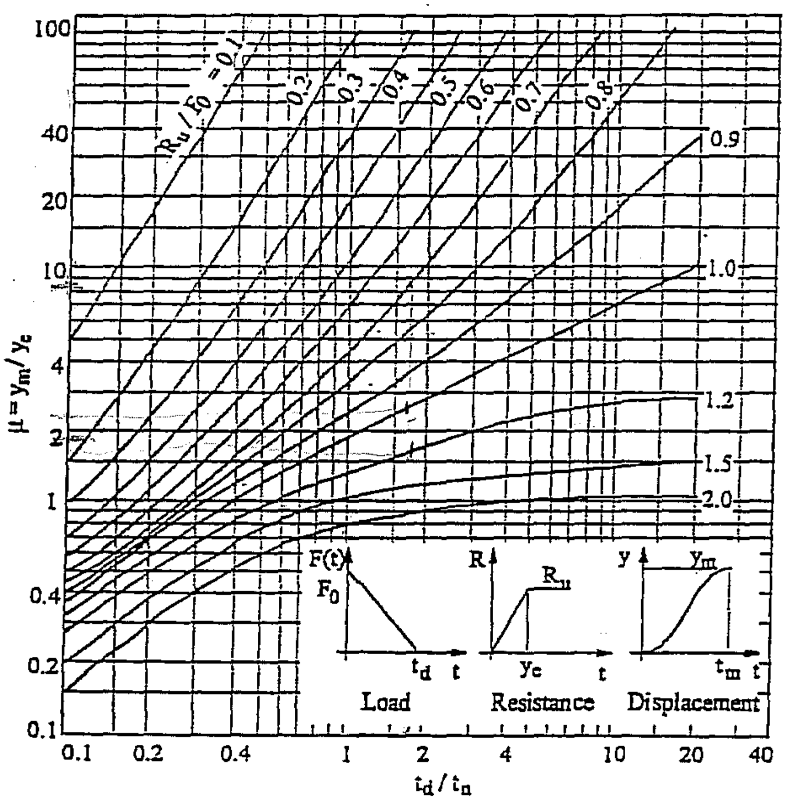
Using 200mm thick wall, the percentage of steel used is 0.75%.
Grade of steel used is Fe 415
Grade of concrete used is M_{30}

The lesser of the computed bending or shear strengths is used as the maximum resistance (R_u) in the elasto-plastic resistance function. Hence R_u = 57.6 kN.

A 200 thick unit strip trial section has an equivalent stiffness (k_e) = 57.80 kN/cm and an equivalent mass, (m_e) = 0.4132kN-sec^2/m giving a natural period of vibration t_n= 0.052 sec. Peak load has been calculated as,
$F_o = 3.65m\ (span) x 0.305m\ (width) x 82.73\ kPa\ = 92.1\ kN$
$t_d / t_n = 0.05\ sec\ /\ 0.052 sec\ = 0.97$
$R_u\ /\ F_o = 57.6kN\ / 92.1\ kN\ = 0.63$

As per the chart for Elasto-Plastic SDOF System given in figure 3 ductility ratio has been calculated as
$ductility\ ratio\ \mu = 6$
$Yeild\ deflection, Y = Ru/k = 9.9mm$
$Maximum\ deflection, Y_m = \mu\ x\ Y = 6\ x\ 9.9 = 59.4mm$
$Support\ rotation$
$\theta = arctan\ (Y_m\ /\ 0.5L) = arctan\ [(59.4)\ /\ (0.5)(3.65m)(1000)] = 1.82\ degree$

Which is less than the response limits for flexural members of q_{max} =2.0 degree .Hence the section is safe in blast load.



"Figure 3.Typically graphical Solution Chart For Elasto-Plastic SDOF System (from Biggs 1964)"

The design has been repeated for the increased wall thickness. When the design is not safe for the given wall thickness, percentage of steel has been increased to make the design safe. Percentage of steel has been calculated as follow (Cross sectional area of steel bar x unit width of steel bar) / (spacing of main reinforcement bar).

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Accordingly safe design of 200mm, 250mm and 300mm thick wall has been carried out and has been tabulated in Table 3, Table 4 and Table 5.

"Table 3. Design of 200mm thick wal"

CASE STUDIED	Area of steel per unit width	Percentage of steel (%)	Remarks
CASE 1	230 mm^2	0.5	$\theta>2^o$.Hence Wall is not safe
CASE 2	345 mm^2	0.75	$\theta<2^o$.Hence Wall is safe

"Table 4. Design of 250mm thick wall"

CASE STUDIED	Area of steel per unit width	Percentage of steel (%)	Remarks
CASE 3	173 mm^2	0.28	$\theta>2^o$.Hence Wall is not safe
CASE 4	230 mm^2	0.40	$\theta<2^o$.Hence Wall is safe.

"Table 5 Design of 300mm thick wall"

CASE STUDIED	Area of steel per unit width	Percentage of steel (%)	Remarks
CASE 5	137.98 mm^2	0.19	$\theta>2^o$.Hence Wall is not safe
CASE 6	173 mm^2	0.25	$\theta<2^o$.Hence Wall is safe

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"Table 6. Minimum Percentage of steel reinforcement need for the Safe design"

Case	Area of steel (mm^2)	Thickness of RCC wall (mm)	Percentage of steel for safe design (%)
CASE 2	345	200	0.75
CASE 4	230	250	0.4
CASE 6	173	300	0.25

"V. RESULT AND CONCLUSION"

Safe design of RCC wall can be done by either increasing the thickness of wall or by increasing the percentage of steel. In case where there is restriction of space, such that the wall thickness has been restricted it is desirable to increase the percentage of steel as it leads to safer design from ductility point of view but should comply with the minimum percentage of steel as per table 6. This can lead to cost effectiveness of RCC wall .It has been found that for a 200mm thick RCC wall, minimum percentage of steel required to resist blast loading is 0.75%. For a 250mm thick RCC wall, percentage of steel required to resist blast loading is 0.40%. For a 300mm, thick RCC wall percentage of steel required to resist blast loading is 0.25%.

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