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LA-UR -89-1834

Received by OSTI

JUN 07 1989

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LA-UR--89-1834

DE89 012631

TITLE: ASPECTS OF BLAST RESISTANT MASONRY DESIGN

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SUBMITTED TO ASTM, Orlando, FL, December 5, 1989

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ASPECTS OF BLAST RESISTANT MASONRY DESIGN

REFERENCE: Volkman, D. E., "Aspects of Blast Resistant Masonry Design," Masonry - Components to Assemblages, ASTM STP 1063, John H. Mattys, Editor, American Society for Testing and Materials, Philadelphia, 1990.

ABSTRACT: Blast resistant design should be examined for building code incorporation, due to the potential of explosions occurring in an industrial society. Specifically, public and commercial structures of concrete masonry construction need additional building code criteria, since these buildings have high density populations to protect. Presently, blast resistant design is accomplished by using government published manuals, but these do not address industry standard construction. A design air blast load of 4.54 kg (10 lbs) of TNT, located 0.91 m (3 ft) above ground surface and 30.48 m (100 ft) from a structure should be considered standard criteria. This loading would be sufficient to protect against blast, resist progressive failure, and yet not be an economic impediment. Design details and adequate inspection must be observed to ensure blast resistant integrity.

KEYWORDS: blast resistant design, building code, detonation, reflected pressure, modelling, ultimate strength

Blast resistant design is a customary method of structural design for certain experimental and storage facilities at Department of Defense and Department of Energy installations throughout the United States. Comprehensive design and analysis manuals are available through the Government which allow engineering personnel, with a reasonable knowledge of structural mechanics, to determine the structural effects resulting from the dynamics of high explosive detonations. These manuals have been developed through extensive military testing to provide good correlation of yield in steel and reinforced concrete structures from blast loads. One of the most thorough and recent publications available is the six-volume set of engineering manuals, Structures to Resist the Effects of Accidental Explosives [1]. Through well referenced examples, the information contained in the separate volumes is woven together to serve as a guide in solving problems. Properties of blast loading from either

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internal or external explosions, structural dynamics, reinforced concrete design, and structural steel design are the four main topics that comprise the essence of this publication. Although the last volume in this series of manuals introduces blast resistant design of masonry and prestressed concrete, the design emphasis as a whole is placed on reinforced concrete and structural steel.

Most buildings in the United States are designed in accordance with the specifications of one of the major building codes. Due to the importance placed on seismic loading, the Uniform Building Code is probably the most conservative building code addressing lateral loads in masonry structures. However, only a small section of one chapter in this code mentions the structural requirements necessary to sustain blast loading, other than venting a structure to relieve internal pressures. This provision specifies that building components subject to blast exposure be designed to resist a minimum internal pressure of 4.79 kPa (100 psf)[2]. Curiously though, no mention is made of the exposure effects from external explosions.

Industrial complexes, mining operations, construction and demolition activities all employ explosives to varying degrees. Furthermore, many of these operations have close proximity to communities. An accidental explosion occurring within the confines of an industrial complex has the potential to exert significant shock loads through the ground or air to affect the environment beyond the plant perimeter. Development of new sites requires mining companies to handle and use explosive material. Over estimating of the charge necessary to loosen rock obstructions at the mine site can have the same effect as an industrial accident. In supplying the needs of these legitimate consumers with explosive materials, shipment either by truck or train necessitates trafficking hazardous materials through rural and urban areas. Any collision involving one of these vehicles containing a cargo of explosives can present serious destructive consequences, especially if the accident occurs within an urban setting. The blast load possibilities presented so far are derived from unplanned occurrences. Deliberate, planned bombings are the forte of terrorists. Fortunately in the United States, the probability of terrorist activity is remote, but cannot be categorically ignored.

BUILDING CODE CONSIDERATIONS

A building code standard for strengthening concrete masonry structures to withstand blast loads needs to focus on applicability. Public and commercial buildings are of prime concern because of the concentration of people in these facilities. An additional benefit derived from a blast load standard is increased resistance of total structural failure. By sustaining localized failures, prevention of major tragedies, resulting from progressive type yielding, can be averted.

Acoustics need to be addressed for architectural treatment of blast resistant building designs. Walls and roofs should be designed to lower sound transmissions. Exterior finish should be a dense, close grain type surface to enhance reflectance of sound[3].

Fragmentation loads are capable of causing considerable damage. These result from unsecured objects within the vicinity of an explosion, which become launched projectiles by the sudden overpressures of the explosion. In depth examination of blast resistant design must ascertain the effect of fragmentation loading on a structure.

Successful construction of concrete masonry depends on attention to details. Explicit design in conjunction with proper inspection is necessary for a good end product. The following criteria should be considered for inclusion in a building code standard to ensure a better blast resistant structure:

1. Reinforcing steel bars need to have sufficient development length to deliver full tensile strength. Use splices of at least 40 bar diameters.
2. Wall anchorage to both the foundation and roof should be adequate to transfer loads.
3. Interior masonry walls should be connected to intersecting walls with S-type steel hooks wrapped around vertical reinforcement. Hooks should be located on alternate joints.
4. Specified grouting of vertical cells and bond beams must be completed with skill and be of high quality in order to develop bond strengths.
5. Joint mortar should cover the full horizontal projected surface and not just the exposed face of the masonry.
6. Horizontal wire reinforcement on alternate joints is required to provide a mechanism for load distribution.
7. Vertical steel reinforcement should be located at all building corners and wall openings.

BLAST LOAD CHARACTERISTICS

Explosive materials are classified as solid, liquid, or gas. Solid explosives are primarily high explosives and are the subject of this article.

Data on blast effects are available for many high explosives. For simplification, all explosive materials are related to the measured effects of a bare, spherical trinitrotoluene (TNT) charge. This is accomplished by determining the equivalent weight of TNT for the explosive in question. The equivalent charge weight is achieved by proportioning the heat of detonation of the explosive to the heat of detonation of TNT and multiplying the proportion by the weight of the charge.

Detonation of an explosive material is what causes a blast to occur. The result of this process is a very rapid and stable chemical reaction in the substance, which reduces the explosive to a hot, dense, high pressure gas. The volume expansion resulting from the detonation

is immense and results in source pressures somewhere between 53,090 kPa (7,700 ksi) and 33,784 kPa (4,900 ksi)[4].

An atmospheric explosion creates a very intense spherical shock wave expanding equilaterally from the origin of the explosion. Reflection from ground surface or building walls occurs as the wave moves along its propagation path. The effect of the interaction of this rebounding wave with the initial blast air current causes a strengthening of the shock. The shock wave completely engulfs any obstruction encountered and exerts pressure on all exposed surfaces throughout the duration of the blast effect.

Confined explosions occur within structures. Examples of facilities where confined explosions can occur are magazines storing explosive materials, chemical laboratories, grain elevators, any building in which natural gas leaks, gasoline tanks, as well as many other situations where the potential exists for an explosion to occur from within. A confined explosion is synonymous with an internal explosion. This type loading is presently acknowledged in building codes, though coverage is incomplete.

Unconfined explosions occur externally to structures. The three types of unconfined explosions are free air burst, air burst, and surface burst. Of these three, the air burst represents the external explosive loading most applicable to building code incorporation as structural design criteria. An air burst explosion is characterized by an explosive detonated slightly above the ground surface (Fig. 1). The consequence of ground separation decouples the explosive from the ground, eliminating immediate reflection which reduces total pressure magnification. After reflection does occur from the ground, the rebounding pressure wave combines with the air propagated wave producing an increase in pressure at the front. However, the pressure magnification is still less than would be observed from a surface blast, in which the blast occurs at ground surface.

FIG. 1 -- Air burst explosion.

Components of the pressure wave consist of two distinct impulses (Fig. 2). The initial impulse consists of high positive pressure, often referred to as overpressure or pressure exceeding normal atmospheric pressure. The positive impulse decays very rapidly and is followed by a negative pressure impulse, or vacuum, of significantly lower magnitude. The wall of a structure, undergoing such an explosion load, would sustain peak, side-on, positive pressure, which decays quickly over time followed subsequently by a stress reversal resulting from the suction of the negative pressure, but lasting over a longer period of time. Structural members are designed to withstand the stress and deflection incurred for the positive phase of blast loads, as well as the consequential response from the negative phase.

FIG. 2 -- Pressure progression at fixed location.

The magnitude and distribution of a blast load on a structure is a function of three factors. First is the explosive properties, primarily consisting of material composition, energy output, and charge weight. Next is the location of the source detonation relative to the structure. Last is the magnitude and reinforcement of the pressure wave by its reflective interaction with the ground or structure itself.

Some of the measured characteristics of blast phenomenon are accomplished through scaled properties. Distance, wave length, time, and impulse are represented as scaled quantities, that is, the unit of measure divided by the cubed root of the charge weight.

LOAD AND STRUCTURE MODELLING

The primary function of current blast resistant design manuals is to predict structural adequacy in the advent of an accidental explosion. Much of the structural analysis and design techniques deal with the

elasto-plastic and plastic range of response. The presumption behind this approach is the need for precision in producing yield of structural materials for a certain quantity and arrangement of an explosive charge. Conversely, building codes establish design criteria and specify the use of standard methods of design to provide a level of structural quality for a material to function in the elastic range. Therefore, to manipulate the complexities of blast resistant design into a usable building code standard necessitates idealizing loads and structures, which can be readily adapted for the construction industry.

The time endured concept of dynamic load factor (DLF) equates the maximum deflection of a dynamic load to that deflection resulting from the static loading condition of an equal magnitude force[5]. Under idealized conditions of triangular or rectangular impulse load, the DLF correlates well within the elastic range of structures. Blast impulse load for the positive phase, which produces maximum structural response, can be idealized as a triangular dynamic load. The peak positive pressure makes initial contact at time equal to zero. This peak pressure reduces to zero through the time of duration of the loading in an approximately linear function, thus creating a triangular impulse.

Modelling of a structure is always the most difficult task associated with design because of the numerous degrees of freedom for movement. For simplification, a single degree of freedom system, consisting of a spring and mass is the usual model for structural components (Fig. 3). The single degree of freedom system is arranged to emulate the motion of significant response for the structural component. Since structural systems are more complicated than single degree of freedom models, adjustments must be made to the model parameters for true correlation with the actual structure. Three dynamic load factors are used to modify load, mass and structural resistance. Damping is considered negligible, since it has little effect on the maximum response of the structure which is the first cycle of motion. Traditional concrete masonry wall design can be made equivalent to the elastic response of a one degree of freedom idealized system by utilizing the appropriate dynamic load factors[6].

FIG. 3 -- Model of structural response.

MASONRY CONSIDERATIONS

The American Society of Civil Engineers published research stating that unreinforced masonry walls display inherent strength in resisting blast loads. The strength was greater than could be accounted for by

flexural considerations alone. By relating to other research, a theory was proposed to advance the understanding of this inherent strength. While undergoing the rapid straining associated with blast loads, the mortar failed in tension, thus causing a yielding from flexure. The extra strength of concrete masonry appeared after this mode of failure. Segmental in construction, the masonry wall produced a load induced deflection in the shape of an arch. Exhibiting strong compressive strength, the masonry wall transformed its bending response into arch action, which produced greater than anticipated resistance to blast loading before ultimate failure[7]. However, due to the inability of unreinforced masonry to elastically sustain blast load, and in the attempt to prevent progressive type failure, use of steel reinforced concrete masonry is the only acceptable means for providing a blast resistant masonry structure.

Depending on geographical location, the Uniform Building Code requires the use of vertical and horizontal reinforcing steel in concrete masonry unit wall construction to resist seismic lateral loads. Utilizing standard practice for seismic construction while incorporating the previously introduced blast analysis techniques, design criteria for blast loads can be established. Pursuant to these goals, single wythe, running bond, concrete masonry unit construction with both joint and vertical cell reinforcement is studied for suitability as a blast resistance standard.

For consistency with the blast analysis techniques, all design is based on ultimate strength to determine the yield of the structural member. Due to the impulse nature of blast loading, the concrete masonry undergoes rapid rates of straining, not unlike the behavior of other construction materials. Incorporating this response for the design allows the use of greater material strengths[8] than would be obtainable under static loading conditions (Table 1).

TABLE 1 -- Blast load material strength.

Material	Stress Component	Blast Increase Factor
Concrete Masonry Unit	Flexure	1.19
	Shear	1.00
	Compression	1.12
Steel Reinforcement	Flexure	1.17

DESIGN PROCEDURE

The cohesiveness of a methodical procedure is an attractive expedient to tie the concepts of blast design with commercial masonry construction. While using a building code as a forum, a blast design manual should be used for blast loading synthesis and dynamic analysis, with the entire process fused by the design procedure. This will enable engineering personnel, unfamiliar with this type of design to maintain confidence in the calculations they generate. Therefore, the following

design procedure, conforming to these guidelines, is recommended for flexural members:

1. Determine all known parameters of the design. This is accomplished by sketching the structure and component to be designed. Show supports, spans, known dimensions, openings, charge location, charge size, other loads, and so forth. Next, list the properties of the concrete masonry and reinforcing steel materials. This includes the thickness of the masonry block, assumed joint and vertical cell reinforcement size and spacing, mortar type, specified compressive strength of the masonry, the modulus of elasticity of the masonry, the tensile yield stress of the steel reinforcement, and the modulus of elasticity of the steel.

2. Calculate the ultimate strength design properties of the member. For flexural design, the equivalent rectangular compressive stress block needs to be determined, from which the ultimate moment capacity can be computed. The material strengths in these calculations need to be corrected for the blast increase factors (see Table 1), as well as adjusted for the standard reliability factors associated with ultimate strength design. In addition, the average of the gross and cracked section, moment of inertia needs to be established.

3. Determine the dynamic transformation equivalents of the structure. For elastic response of a simple span, the equivalent elastic stiffness, the load/mass equivalent factor, the equivalent mass, and the natural period of vibration has to be calculated[9].

4. Based on charge size and location, develop the blast load properties and scaled characteristics. For an air burst explosion, the scaled height of the charge, the scaled horizontal distance of the charge, the angle of incidence of the charge to the structure are primary computations. Assuming full ground reflection of the blast before striking the structure, both the ground reflected pressure and the scaled ground reflected impulse must be calculated to determine the reflected pressure acting on the structure and the accompanying scaled time of duration[10].

5. With the information generated, determine the ratio of the time of duration for the positive phase impulse to the natural period of vibration of the structure. From this ratio, the dynamic load factor is selected[5].

6. Multiply the dynamic load factor times the calculated reflected pressure on the structure to determine the equivalent static pressure. This result needs to be increased by the standard ultimate strength design load factors for infrequent live load in order to establish a design pressure.

7. Using the design pressure, calculate the design moment, and compare this result with the ultimate moment capacity of the structural member from step two. Sufficiency is attained if the latter moment exceeds the design moment.

For an appraisal of the order of magnitude involved in blast resistant masonry design, consider using the design procedure for a wall with

a 3.05 m (10 ft) vertical span. The wall consists of 20.32 cm (8 in.) thick concrete masonry, reinforced with 1.27 cm (0.5 in.) diameter steel bars at 1.22 m (4 ft) centers and wire reinforcing on alternate horizontal joints. This represents steel reinforcement consistent with building code requirements in seismically active geographic areas. The blast resistance of a wall of this dimension and strength is approximately a 4.54 kg (10 lb) charge of TNT located 0.91 m (3 ft) above ground and 30.48 m (100 ft) from the structure.

Flexural aspects of blast resistant masonry design is a major constituent to be examined for a building code standard. Surface spalling of the masonry requires additional analysis for closer, higher yield explosions. Satisfactory results should be obtained from the same order of magnitude deemed adequate for the flexural mode. Other issues requiring further investigation are deflection, shear requirements, anchorage, and support rotation. Expansion of the design procedure to incorporate these components is necessary for a comprehensive design.

ACKNOWLEDGEMENTS

The author acknowledges with appreciation the effort and assistance of Debra Archuleta-Lugo and M. Dean Keller, P.E., as well as the support extended by Rita Crohan Volkman, Edward Jennings Volkman, and the author's wife.

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