Protective Construction Design Roadmap

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Abstract

Department of Defense (DoD) Manual 6055.09-M, "DoD Ammunition and Explosives Safety Standards," provides governing explosives safety standards to manage risks with DoD-titled ammunitions and explosives (AE) by providing protection criteria to minimize serious injury, loss of life, and damage to property. When these requirements cannot be satisfied by meeting default separation distances between AE and exposed personnel and assets, protective construction may be designed to provide equivalent protection.

Protective construction must be designed in accordance with Unified Facilities Criteria (UFC) 3-340-02, "Structures to Resist the Effects of Accidental Explosions." This paper is intended to provide designers with high level guidance on the state of practice of protective construction for explosives safety. It shall discuss available design criteria and analysis tools with an emphasis on their developmental bases to provide a better understanding of their appropriate use cases and limitations. The ultimate goal is to improve the likelihood of successful completion of protective construction design projects.

Introduction

Department of Defense (DoD) Manual 6055.09-M, "DoD Ammunition and Explosives Safety Standards" [1], provides governing explosives safety standards to manage risks with DoD-titled ammunitions and explosives (AE) by providing protection criteria to minimize serious injury, loss of life, and damage to property. This paper presents a summary of explosives safety siting criteria in order to contextualize the explosives hazards and effects protective construction must provide protection from. For accidental explosions, governing protective construction design criteria is provided by Unified Facilities Criteria (UFC) 3-340-02, "Structures to Resist the Effects of Accidental Explosions" [2]. This paper discusses available criteria provided by UFC 3-340-02 with an emphasis on their developmental bases to provide a better understanding of their appropriate use cases and limitations. The goal of this paper is to present high level guidance to improve the likelihood of successful completion of protective construction design projects.

Summary of Explosive Safety Siting Criteria

Explosion Effects

Within the DoD hazard classification system, Class 1 applies to AE where the explosive hazard predominates. There are six Class 1 divisions and three 1.2 subdivisions. AE is assigned to the class that represents the item's predominant hazard characteristic. DoD 6055.09-M uses the term 'HD' followed by numerical designator to indicate the hazard class and division of AE. Three of the most prevalent hazard class/divisions defined for DoD AE are HD 1.1, HD 1.2, and HD 1.3. Their predominant hazards are as follows:

- HD 1.1: Mass explosion, blast overpressure and fragment hazard
- HD 1.2: Non-mass exploding, fragment and blast overpressure hazard
- HD 1.3: Combustible AE, primarily mass fire and thermal hazard

Permissible Exposures and Basic QD Principles

The potential for injury and damage to personnel and assets is normally determined by the separation distance between a Potential Explosion Site (PES) and an Exposed Site (ES). DoD 6055.09-M defines permissible exposures for both accidental and intentional detonations.

It also establishes explosives safety siting criteria for PESs and ESs based on explosion effects (blast, fragment, firebrand, thermal, and ground shock effects).This is known as Explosives Safety Quantity-Distance (ESQD) criteria, referred to as QD. QD defines the required standoff distance necessary to achieve a level of protection consistent with permissible exposures from a given quantity of AE. QD is determined by the effect requiring the greatest separation distance.

There are four predominant exposures within QD:

- Inhabited Building Distance (IBD)
- Public Traffic Route Distance (PTRD)
- Intraline Distance (ILD)
- Intermagazine Distance (IMD)

To narrow the focus and simplify this discussion, IBD exposure will be considered as an example. IBD exposure is required to provide protection to personnel. Permissible hazards at IBD are as follows:

- Overpressure: peak pressure limited to 1.2 to 0.9 psi
- Debris/Fragments: Hazardous fragment density must be less than 1 per 600 ft^2. A hazardous fragment is defined as having an impact kinetic energy of 58 ft-lbs or greater.
- Thermal: Prevent onset of 2nd degree burns

Given an equal amount of energetic material, HD 1.1 results in the most hazardous effects of all hazard divisions. For a given quantity of AE, QD is dictated by the explosion effect requiring the greatest separation distance. Hazards to persons from HD 1.1 at an ES are as follows:

- Primary fragments: Munitions casing (small, high velocity)
- Secondary fragments: Debris generated from the PES structure and contents (larger, slow-to-medium velocity)
- Building/window damage of the ES: hazardous debris generated by the blast
- Lesser effects
    - Direct blast wave effects: audial, pulmonary, and GI tract
    - Ground motion: can be significant for underground storage
    - Thermal/fireball effects

For overpressure, QD is calculated by using the formula $D\text{ (ft)} = K \cdot W^{1/3}$, where “D” is the distance in feet, “K” is a factor (also called K-factor) that is dependent on the risk assumed or permitted, and “W” is the Net Explosive Weight (NEW) in pounds.

Continuing consideration of IBD exposure, QD for HD 1.1 for PES’s of type “Other” is as follows:

- For quantities of HD 1.1 greater than 250,000 lbs, K is 50 (results in 0.9 psi)
- For quantities of HD 1.1 less than 100,000 lbs, K is 40 (results in 1.2 psi)
- For quantities of HD 1.1 less than 30,000 lbs, QD is controlled by debris

As an example, for an NEW of 50,000 lbs HD 1.1, and for a PES of type "Other", the applicable K-factor for IBD exposure (ex., administrative or recreation building) is 40. QD is calculated as D (ft) = $40 \cdot 50{,}000^{1/3}$ = 1474 ft (conservatively rounded up to the nearest whole foot). At this distance, expected overpressure is 1.2 psi. This is the minimum distance that must separate the ES from the PES to to limit exposure in a manner consistent with IBD protection.

Per 6055.09-M, the effects that can be expected at minimum IBD separation distance are as follows:

- Unstrengthened buildings can be expected to sustain damage that approximates five percent of their replacement cost.
- Personnel in buildings are provided a high degree of protection from death or serious injury; however, glass breakage and building debris may still cause some injuries.
- Personnel in the open are not expected to be injured seriously by blast effects. Fragments and debris may cause some injuries. The extent of injuries will depend upon the PES structure and the NEW and fragmentation characteristics of the AE involved.

Equivalent Protection through Protective Construction

When required separation distances per QD criteria cannot be provided, protective construction may be used to provide equivalent protection to personnel and assets. Protective construction falls into one of three categories: 1) existing, approved protective construction 2) a modification of an existing, previously approved protective construction design, and 3) new protective construction. This paper focuses on the last category as it is usually customized in nature and requires the most detailed application of protective construction design procedures.

For explosives safety, protective construction requirements are defined in Unified Facilities Criteria 3-340-02, "Structures to Resist the Effects of Accidental Explosions" [2]. UFC 3-340-02 presents design procedures for protective construction intended to prevent propagation of explosions and to provide protection for personnel and valuable assets from explosion effects.

UFC 3-340-02's protective construction design procedures assist in achieving the following technical objectives:

- Establish blast load parameters required of protective structures.
- Provide methods for calculating the dynamic response of structural elements including reinforced concrete, and structural steel.
- Establish construction details and procedures necessary to afford the required strength to resist the applied blast loads.
- Establish guidelines to prevent damage to interior portions of structures because of structural motion, shock, and fragment penetration.

This paper presents a discussion of available criteria with an emphasis on its appropriate uses and limitations. An attempt is made to address the most common design scenarios and sources of confusion.

Protective Construction Type

UFC 3-340-02 classifies protective structures into three categories: shelters, barriers, and containment structures.

- Shelters protect personnel and property from an external detonation. They are usually sufficiently separated from potential explosion sites to satisfy DoD 6055.09-M's default separation distances for thermal hazards.

Accordingly, the exterior walls and roof of a shelter are typically designed to protect occupants and property from blast overpressures and fragmentation hazards.

- Barriers are designed to prevent the propagation of an explosives detonation.

- Containment structures mitigate the blast effects from an internal detonation to acceptable levels. Containment rooms/cells may be designed to protect areas within the building in which an accidental detonation occurs or to protect other buildings sited within its applicable default separation distances. As a general guideline, UFC 3-340-02 recommends that the W/V ratio in a well vented cell be less than 0.15 where W is the effective explosives weight in pounds TNT and V is the interior room volume in cubic feet.

Blast Loads and Explosion Effects

UFC 3-340-02 provides procedures for determining explosive output from HD 1.1 AE and associated structural loadings, fragments, and structural motions associated with accidental explosions.

Unconfined explosions may occur in the air or on the ground, and produce blast waves that may be reflected and amplified off of the ground or other surfaces. Surface burst explosions typically result in blast loads of the greatest magnitude. Procedures to quantify external loads on structures in the form of pressure time-histories are provided, giving primary consideration to above-ground shelters.

The roof and external walls of a shelter provide resistance to blast pressures and fragments. Typically these pressures exert a “closing” effect on structures. However, where openings occur, external pressures will enter the shelter and impinge on its interior. Procedures to determine these pressures, including pressure buildup through small openings, should be followed as structures normally contain multiple openings for ventilation and utilities. These procedures may be used to optimize the number and size of openings into a structure.

Confined explosions result from internal detonations. These result in both short duration shock pressures that reflect off the containment structure’s interior and a buildup of long duration, quasi-static gas pressures. Procedures are provided to calculate the internal shock and gas pressures. These pressures exert an “opening” effect on containment structures, and requirements for connection details reflect this.

Gas pressures must be vented out of the structure. Vent paths are provided by structural openings and frangible panels. In general, elements that fail at loading no greater than 25 psf may be considered frangible. Increased venting provided to a containment structure decreases the duration of gas loads, allowing for structural sections that require less resistance.

The computer programs ConBlast [3] and BlastX [4] have been developed and approved for use in determining confined blast pressures in a manner consistent with the procedures and techniques of UFC 3-340-02. In general, these programs are meant to work for “small” explosions in “large” rooms, and so careful attention should be given to ensure that the loading density and vent ratios of the use case fall within accepted limits.

UFC 3-340-02 also provides procedures for determining the size, shape, and velocity of primary fragments resulting from AE casings. Procedures for secondary fragments such as building debris and equipment are also provided, but they require engineers to estimate expected conditions at the time of an accident.

Dynamic Structural Response

UFC 3-340-02 provides procedures for evaluating dynamic response of structural components to blast overpressures. Dynamic analysis is required because most blast-resistant components exhibit some degree of inelastic response, making static methods unsuitable. Dynamic analysis methods work by using the principles of energy balance and dynamic equilibrium.

Structural properties such as stiffness, yield and ultimate strength, mass, and structural damping affect the dynamic response of a component. Designers may optimize these properties to achieve desired response. Designers must account for the direction of applied loading and structural response relative to the direction of gravity. In general, the effects of damping on dynamic structural systems are minimal or even negligible in blast design applications while the effects of mass can be more significant.

Idealized resistance-deflection functions are developed for structural components. These are usually structurally equivalent single degree of freedom (SDOF) systems. Design response charts are available to determine structural response based on their resistance-deflection function coupled with idealized blast load curves. In lieu of response charts, dynamic response may be determined using numerical integration techniques.

The computer program SBEDS [5] is capable of performing numerical integration calculations using its “General SDOF” capability. It requires the user to input resistance and load functions, as well as dynamic system properties. When doing a UFC 3-340-02 blast response analysis, the capability of SBEDS to determine resistance functions should be ignored due to known, unconservative discrepancies that exist between the results obtained from SBEDS compared to those using UFC 3-340-02 procedures [6].

Blast Design Overview and General Recommendations

Detailing of Walls and Slabs of Reinforced Concrete Operating Rooms

Within the DoD, close-in exposures usually occur in explosives operating and storage rooms. These rooms typically have hardened reinforced concrete side and rear walls and a frangible exterior wall. Depending on protection requirements, roofs may be frangible (e.g., metal deck or tongue-in-groove wood deck) or hardened (e.g., blast resistant reinforced concrete). In UFC 3-340-02, the foregoing configurations are termed partial containment cells. This section shall discuss a few key items related to the detailing and construction of continuously supported walls/slabs in these cells.

Flexure

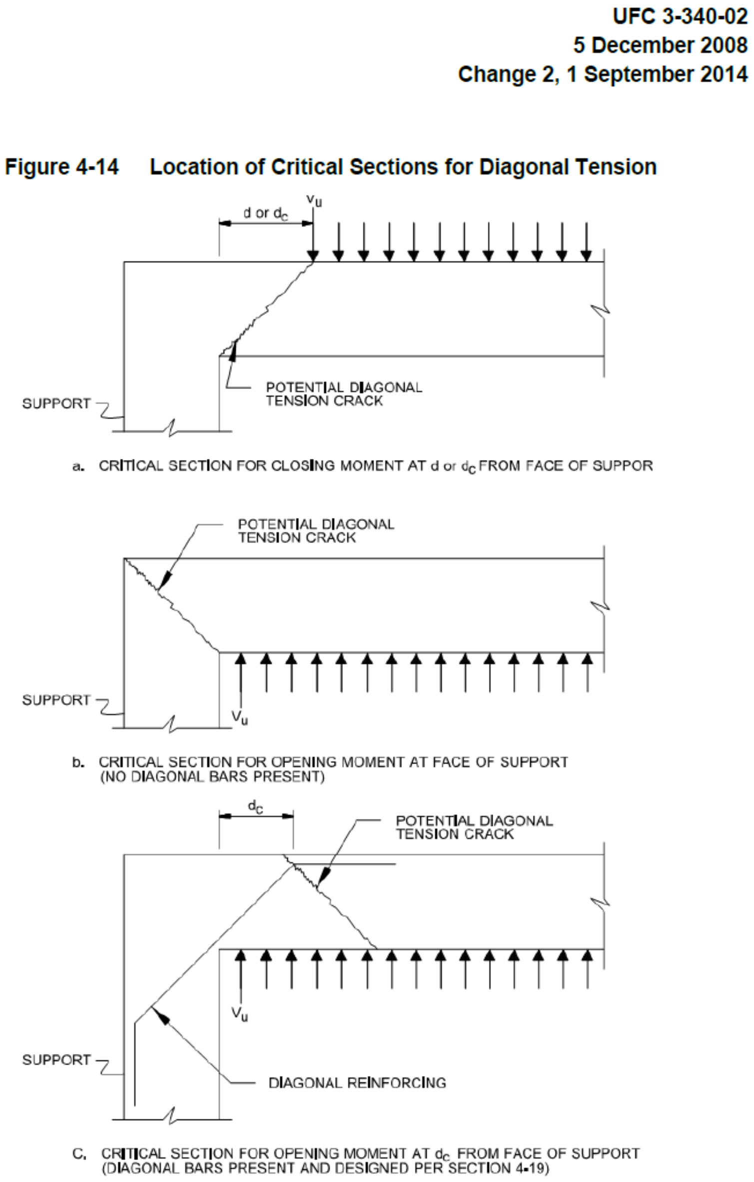
UFC 3-340-02 establishes four protection categories. These categories establish limits on the maximum support rotation an element may undergo under blast loading. For personnel protection, Protection Category 1 must be applied, which typically limits maximum support rotations for walls and slabs to two degrees. Greater support rotations are allowed for elements that protect assets or serve to delay propagation of explosion (Protection Categories two through four).

Structural elements typically have negative reinforcement to resist rebound response. In addition, design requirements for diagonal tension, direct shear, and direct tension are based on an element’s ultimate resistance. Thus an overdesign in flexure will result in higher demands for diagonal tension, direct shear, and direct tension, result in significant reinforcement congestion. Therefore, it is strongly advised to avoid overdesigning in flexure. If additional capacity is required, it may be wiser to consider an increase in concrete thickness before increasing reinforcement.

Diagonal Tension

In UFC 3-340-02, the allowable diagonal tension (shear) stress in a concrete wall/slab is reduced if it may be placed in tension under blast loading. In addition, UFC 3-340-02 requires minimum diagonal tension reinforcement in walls/slabs that may be exposed to close-in blast loading. For beams, minimum diagonal tension requirements apply regardless of design range. If diagonal tension reinforcement is required, stirrups are preferable over lacing due to their better constructability.

Critical sections for diagonal tension design depend on the orientation of the blast overpressure relative to the structural element. Blast loads can induce opening or closing moments, as shown in Figure 1. Opening moments move the critical section at the face of the support, resulting in increased shear stresses.



UFC 3-340-02
5 December 2008
Change 2, 1 September 2014

Figure 4-14 Location of Critical Sections for Diagonal Tension

a. CRITICAL SECTION FOR CLOSING MOMENT AT d or d_c FROM FACE OF SUPPOR

b. CRITICAL SECTION FOR OPENING MOMENT AT FACE OF SUPPORT (NO DIAGONAL BARS PRESENT)

C. CRITICAL SECTION FOR OPENING MOMENT AT d_c FROM FACE OF SUPPORT (DIAGONAL BARS PRESENT AND DESIGNED PER SECTION 4-19)

Figure 1. UFC 3-340-02 Figure 4-14 Locations of Critical Sections for Diagonal Tension.

Direct Shear

If a wall/slab may be placed in tension under blast loading, the ultimate direct shear capacity of the concrete is zero, and diagonal bars must be designed to take all direct shear forces. This condition is likely to occur in containment structures. Depending on the location of frangible surfaces, walls/slabs may undergo tension in one direction or both directions. Diagonal bars are inclined at 45-degrees from the plane of the wall/slab and are designed to resist direct shear forces in tension or compression. The required configuration and permissible locations of these bars are provided in the UFC's "Construction Details and Procedures" sections.

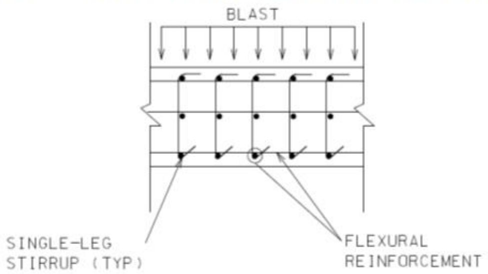
General Reinforced Concrete Design Overview

Minimum Diagonal Tension Reinforcement and Detailing

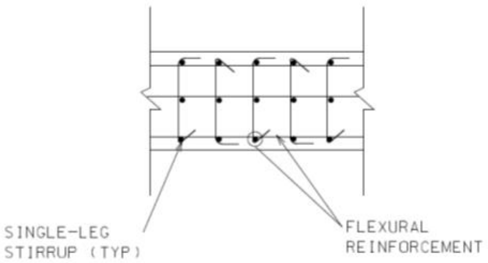
Minimum requirements for diagonal tension reinforcement do not apply walls/slabs with Type I cross sections in the far design range (scaled distance greater than or equal to 3) provided that concrete shear capacity exceeds demand. Minimum diagonal tension reinforcement requirements always apply to beams.

Hooked ends for single leg stirrups used in walls/slabs may be of Type A (90°-135°), B (135°-135°), or C (180°-180°). Designers may use each type provided they meet prescribed limitations on design range (scaled distance, Z) support rotation, and/or response type. For example, Type A stirrups are permitted when the scaled distance from the charge to the wall/slab is greater than 1 ft/lb$^{1/3}$, the design support rotation is 2-degrees or less, and concrete spalling is prevented. Given the asymmetric hooks of Type A stirrups, placement requirements for these stirrups are as shown in UFC 3-340-02 Figure 4-101 (Figure 2).

Figure 4-101 **Placement Requirements for Type A Single-Leg Stirrups**



ELEMENT DESIGNED FOR BLAST
LOAD ON ONE FACE ONLY



ELEMENT DESIGNED FOR BLAST
LOAD ON EITHER FACE

Figure 2. UFC 3-340-02 Figure 4-14 Locations of Critical Sections for Diagonal Tension

Reinforcement Splicing

In general, reinforcement should be lap spliced in regions of low stress. Splices of parallel reinforcing bars must be staggered by at least the splice length. Mechanical splices that have been tested per the requirements of UFC 3-340-02 to perform adequately in high strain rate environments are permitted. Welding of reinforcement is strongly discouraged. The use of bundled reinforcement is not desirable, but where absolutely required, bundles should be limited to no more than three bars and must conform to ACI 318 requirements.

General Steel Design Overview

Close-in Design Range

For close-in high impulse design situations where containment structures are utilized, massive reinforced concrete structures are generally better than steel structures at limiting deflections and protecting against primary and secondary fragments.

In some cases, structural steel can be used in the design of containment cells. However, charge weights should be low so as to prevent brittle modes of failure due to high pressure intensity (fragment penetration).

Large Rebound Response

Damping in reinforced concrete due to cracking usually reduces rebound response significantly. However, steel elements do not tend to dampen to the same degree, and thus significant rebound response (up to 100 percent of inbound) can be obtained. As such, it may be necessary to account for extreme responses of comparable magnitudes in both directions.

Stress Interaction

Structural steel elements are susceptible to the effects of stress interaction much more so than reinforced concrete structures. In the case of containment structures, elements and connections are subject to simultaneous tensile and shear stresses, and the interaction of these stresses must be accounted for.

Fragment Resistance Controlling Design

If fragment hazards exist, care must be given to brittle modes of failure. For example, the penetration depth of a fragment may govern the thickness of a plate instead of its flexural capacity.

Dynamic Design of Connections

Dynamic design stresses must be considered for connections. The AISC Steel Design Manual provides allowable load tables for various connection types (bolts, welds, rivets) based on their static strength. UFC 3-340-02 recommends a dynamic strength increase of 1.7 times the applicable dynamic increase factor (DIF). Instead of recalculating the values from allowable load tables in the AISC specification, designers may find it advantageous to divide the forces being considered by 1.7(DIF).

Protective Construction Validation

Minimum Requirements to Validate Protective Construction

DDESB Memorandum dates 21 October 2008 defines the minimum requirements to validate protective construction. Fore new protective construction, validation requires a quality control review by a competent by a competent DoD blast design agency, such as the Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) or the US Army Engineering and Support Center, Huntsville (USAESCH).

Protective Construction Approval Authorities

It should be noted that the aforementioned DoD blast design agencies are not design approval authorities. Their role in the validation process is to provide quality control review. At the service level, approval authority exists within explosives safety activities such as the Naval Ordnance Safety and Security Activity (NOSSA) and the US Army Technical Center for Explosives Safety (USATCES). The Department of Defense Explosives Safety Board is the DoD level approval authority.

Stakeholder Coordination

A key to the successful completion of a protective construction design project is early and frequent coordination among the various stakeholders. Explosives safety protective construction design requirements must be carefully coordinated with other engineering design disciplines and operational requirements. Stakeholder coordination at all stages of design, particularly in the conceptual stage, is essential to ensure successful outcomes.

Conclusions

Successful completion of protective construction designs depends in large part on an accurate understanding of available criteria. By following the high level guidance on available criteria in UFC 3-340-02, designers should be able to increase the likelihood of successful outcomes for their protective construction design projects.

References

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