Enhancing Constructability and Reducing Construction Costs of Reinforced Concrete Blast Cells

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Abstract

Within the US Department of Defense, "DoD Ammunition and Explosives Safety Standards" (DoD 6055.09-M) is applied to manage risks associated with DoD-titled ammunition and explosives (AE). These standards provide protection criteria to minimize serious injury, loss of life and damage to property from an accidental detonation.

Typically, DoD 6055.09-M protection requirements are satisfied by maintaining minimum default separation distances between AE and exposed personnel and property. If these distances aren't available, protective construction may be designed in accordance with "Structures to Resist the Effects of Accidental Explosions" (UFC 3-340-02) to provide equivalent protection.

UFC 3-340-02's blast analysis and design procedures were developed from detonation tests in typical Service explosives operating and storage rooms. While UFC 3-340-02's reinforced concrete design procedures are based on the ACI 318 Building Code, more rigorous requirements are applied, when needed, to ensure adequate performance under blast loading. These requirements may produce severe reinforcing bar congestion, particularly at element intersections.

In this paper, UFC 3-340-02's blast design requirements for continuously supported walls and slabs will be reviewed, focusing on applications to typical DoD explosives operating and storage rooms. Potential constructability impacts will be examined, and recommendations will be provided for mitigating them, thereby reducing construction costs.

Introduction

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 the default DoD 6055.09-M 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.

UFC 3-340-02 applies more stringent blast design requirements to structural elements that may be placed in tension under blast loading or that may be exposed to a close-in detonation. In UFC 3-340-02, a close-in detonation is defined by the distance from the center of the explosives charge to an element (in feet) divided by the charge's TNT equivalent weight (in pounds) raised to the one-third power. To illustrate, AE with an effective charge weight of 8-lbs TNT located 3-ft from a wall would be located at a scaled stand-off distance of 3-ft/(8-lbs)$^{1/3}$ or 1.5 from the wall. UFC 3-340-02 applies close-in requirements when the scaled stand-off distance is less than 3.0.

Within the US Department of Defense (DoD), close-in exposures often 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. The remainder of this paper focuses on the design, detailing and construction of continuously supported walls/slabs in these cells.

Blast Design Overview and Recommendations

General

UFC 3-340-02's blast analysis and design requirements for partial containment cells were developed from detonation tests of Hazard Division (HD) 1.1 AE in typical DoD explosives operating cell configurations. The UFC's procedures do not consider protection from multiple HD 1.2.1/HD 1.2.2 detonations or protection from HD 1.3 (mass fire) reactions.

Protective construction design requirements may be reduced and, in some cases, eliminated by careful consideration of a facility's siting and layout. Accordingly, it is strongly recommended the personnel with experience in explosives safety and protective construction design participate in planning and early design team meetings where definitive and conceptual facility layouts are developed and evaluated.

UFC 3-340-02's blast load prediction, analysis and design procedures were specifically developed to satisfy DoD 6055.09-M's explosives safety requirements. Consequently, when designing protective construction for explosives safety applications, it is not permissible to substitute less rigorous requirements from blast guidance documents developed for other applications.

In explanation, blast design manuals and procedures developed by other user communities typically consider different explosive threats (e.g., external attack), mitigate different hazards (e.g., glass breakage caused by blast overpressures but not primary fragment hazards) and/or are written to satisfy very different protection requirements (e.g., prevent mass casualties). In addition, many of UFC 3-340-02's design procedures are contingent upon the satisfaction of design requirements stated elsewhere in the manual. As an example, UFC 3-340-02's spall and breach prediction curves were developed, in part, from tests of reinforced concrete walls/slabs with specific stirrup configurations. A design that deviates from the UFC's stirrup requirements may also be outside the scope of the UFC's spall and breach prediction models.

Flexure

UFC 3-340-02's flexural design procedures limit the maximum support rotation an element may undergo under blast loading. For applications in which DoD 6055.09-M's personnel protection requirements apply, the maximum allowable support rotation of a wall/slab is typically 2-degrees. Greater support rotation limits apply to elements that are designed to protect equipment, supplies or stored explosives or to prevent or delay an explosives propagation.

UFC 3-340-02's design requirements for diagonal tension, direct shear and direct tension are calculated using the wall/slab's ultimate resistance. Thus, an overdesign in flexure will increase blast design requirements in diagonal tension, direct shear and direct tension. Do not overdesign!

When sizing reinforced concrete walls and slabs, consider out-to-out reinforcing bar dimensions and hook diameters. The intersections of walls, roof slabs and floor slabs are often very congested. Joints that appear acceptable using nominal dimensions may not be constructible. Out-to-out dimensions are used to verify that reinforcing bars may be properly placed. Additional space should be provided to allow for irregularities in the bars and for movement of dowel bars during concrete placement.

To limit reinforcing bar congestion, always consider increasing the thickness of a concrete wall or slab before increasing its reinforcing ratio. Flexural bars should be spaced at no less than 6-inches (on center) in walls/slabs with no diagonal tension reinforcement and at no less than 8-inches (on center) in wall/slabs with stirrups for diagonal tension reinforcement. In general, flexural bars, stirrups, diagonal bars and direct tension bars should use the same spacing.

Diagonal Tension (Shear)

In UFC 3-340-02, the allowable diagonal tension (shear) stress in a concrete wall/slab is reduced in elements that 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.

Diagonal reinforcement may be single leg stirrups or lacing. The installation of reinforcing bars in laced elements is typically difficult and labor intensive. In some cases, construction contractors have defaulted on contracts due to their inability to install bars in laced walls. Designers are strongly encouraged to use stirrups wherever they're allowed.

When stirrups are used for diagonal tension reinforcement, their spacing is limited to d/2 in Type I cross-sections (concrete on compression face effective in resisting moment) and $d_c/2$ in Type II and Type III cross-sections (concrete on compression face not effective in resulting moment).

UFC 3-340-02 requires that stirrups hook around the outside flexural reinforcing bars in each face. Thus, the foregoing spacing limits typically apply to the flexural bars in these walls/slabs, as well. Applying these limits, the recommended minimum thicknesses of lightly reinforced, interior walls/slabs with stirrups are 14-inches for Type I cross-sections and 16-inches for Type II and Type III cross-sections. Given the greater cover requirement for concrete exposed to weather and for concrete cast against and permanently exposed to earth and the increased diameter of larger flexural bars, minimum thicknesses for these elements will be somewhat greater.

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. These 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 3-340-02's "Construction Details and Procedures" sections.

Direct Tension

UFC 3-340-02 requires the addition of tension bars in single-cell structures and in the end cells of multicubicle configurations. These bars are placed the mid-depth of the wall/slab and are designed to withstand the tension forces that develop in these elements under blast loading.

Spall and Breach

UFC 3-340-02 provides curves and equations for determining the minimum thicknesses of a concrete wall/slab to prevent concrete spall and breach. These thicknesses were developed from empirical data. For a given donor AE, the required thicknesses vary with the scaled stand-off distance. As the scaled stand-off distance decreases, minimum wall/slab thicknesses to prevent spall and breach increase**.**

Detailing and Construction Recommendations

UFC 3-340-02 provides extensive detailing guidance for reinforced concrete walls and slabs. Structural design drawings should include details depicting the reinforcing bars at all element intersections. If bundled bars are used, the detail should depict each bar. The drawings should also note and depict supplementary detailing requirements applied by the UFC (e.g., placement of splices in regions of low stress and staggering of adjacent splices).

Detailers may not be familiar with some of UFC 3-340-02's design details and thus, may understand them. To avoid such errors, contracts should require blast designer review of the reinforcing bar shop drawings to verify both their accuracy and constructability.

To facilitate construction, contractors should consider the placement of concrete working pads. These pads are normally 4-inches thick. They provided needed support to steel cages during assembly and protect capillary water and vapor barriers during construction.

The design team should hold an orientation meeting with the contractor during the preconstruction conference to review the UFC's unique design and detailing requirements and to coordinate with the contractor on recommended reinforcing bar installation and concrete placement methods. Very few contractors and reinforcing bar erectors have experience constructing laced walls or slabs. If a design includes laced elements, discussion of the UFC's recommended sequence of construction should prove beneficial.

Conclusions

UFC 3-340-02 is written to facilitate its use by structural designers with limited blast design experience. While this approach simplifies the design process, it may lead to reinforced concrete wall and slab designs that are very difficult to construct. By following the design, detailing and construction recommendations in this paper, designers may avoid such an unfortunate result.

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