Dichotomy of Legacy Explosive Cubicle Designs and DoD 6055.09 Personnel Protection Requirements from an Accidental Detonation

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Abstract: This paper provides an overview of the 12-inch Substantial Dividing Wall (SDW) design, summarizing its development and its widespread use in explosives cubicles constructed during and after World War II. It next examines the damage by these cubicle walls in accidental detonations and tests. It then reviews the development of new personnel protection requirements from higher risk explosives operations, their introduction in DESR 6055.09, and their impacts on the siting of legacy cubicles for new explosives operations.

Introduction

The 12-inch SDW design was developed in response to the unexpectedly severe damage and debris hazards observed in accidental detonations of small quantities of Ammunition and Explosives (AE) in brick and masonry cubicles/buildings in the early years of WWII. Initially, 12-inch SDWs were only used to separate Hazard Division 1.1 (mass detonating) ammunition and explosives (AE). In the event of an accidental detonation of AE on either one side of a 12-inch SDW, it was believed that this wall would prevent the sympathetic detonation of AE on the other side of the wall.

As time passed, 12-inch SDWs were incorporated in cubicles designed to provide greater levels of protection, including the protection of personnel. In 1960, DDESB and the Services funded the first series of detonation tests inside a cubicle. In these tests, varying HD 1.l NEWs were detonated inside open, 3-wall cubicles. These tests made us aware of shock wave reflections within cubicles and their contribution to the much larger shock loads on interior cubicle's walls. We also became aware of premature failure mechanisms and their effect on the size and masses of pieces of debris from a donor cubicle's walls. The data from these and subsequent detonation tests were subsequently used to define blast design requirements to prevent these failure mechanisms. Similar to ACI 318, the initial, 1969 version of "Structures to Resist the Effects of Accidental Explosions," Army TM 5-1300/NAVFAC P-397/AFR 88-33, these requirements were developed to ensure the ductile response of continuously supported reinforced concrete elements, allowing them to develop their full moment capacities and undergo large deflections/support rotations before failure.

In 1984, new, objective protection requirements were introduced in "DoD Ammunition and Explosives Safety Standards" for explosives operations which presented an unacceptably high risk too personnel. When applicable, these requirements have substantially limited permissible uses of legacy cubicles for new explosives operations.

Great Expectations

"Ordnance Safety Manual" O. O. Form 7224, 1 Dec 1941

The dividing wall concept was introduced in the 1941 "Ordnance Safety Manual.: The manual defined the design requirements for a 12-inch thick dividing wall as follows: "A substantial dividing wall must extend to the roof and the side walls of the building or room which it divides into separate rooms. It must consist of concrete at least 12 inches thick, reinforced on both sides by rods [reinforcing bars or rebars] at least ½ inch in diameter, located at maximum centers of 12 inches both vertically and horizontally."

The only permitted use of a 12-inch SDW in this manual was to subdivide AE. If two rooms were subdivided and separated by a 12-inch SDW, it was believed that this wall would prevent an accidental detonation in one room from producing a sympathetic detonation in the other room.

The 1941 manual did not define a permissible HD 1.1 NEW limit in rooms separated by a 12-inch SDW. Instead, this NEW limit varied. Office of Ordnance guidance issued in June and October 1942 recommended a limit of 20,000-lbs while the Feld Director of Ammunition Plants during World War II allowed up to 65,000-lbs.

"Ordnance Safety Manual," O. O. Form 7224, 3 May 1945

The 1945 revision provided the following, more concise definition of a SDW: "An interior wall in a building designed to prevent simultaneous detonation of quantities of explosives on opposite sides of the wall." The 1945 manual also expanded the design requirements for a 12-inch SDW, stating that rebars must be interlocked with footing bars, SDWs must be secured to prevent overturning, and the rebars in one face must be staggered with regard to the rebars on the opposite face. As with the 1941 manual, the 1945 revision did not define a HD 1.1 non-prompt propagation limit in cubicles separated by a 12-inch SDW.

The 1945 manual also introduced the concept of an operational shield, defining it as "[A] barrier within an operating building constructed to protect personnel, materiel, or equipment from the effects of a fire or explosion occurring at a particular location." No design guidance or HD 1.1 NEW limits are provided for an operational shield.

On 28 Nov 1949, the US Attorney General granted authority to the Armed Services Explosives Safety Board (ASESB) - now Department of War Explosives Safety Board - to issue mandatory explosive safety requirements which deviated from and/or expanded upon the requirements instituted by Congress in 1928. ASESB and the Services subsequently applied data from a 1944-45 series of Army external detonation tests to establish a 5,000-lb HD 1.1 NEW limit to prevent prompt propagation to acceptor AE protected by a 12-inch SDW.

"Ordnance Safety Manual" Office of Ordnance Manual (ORDM) 7-224. 1951

ORDM 7-224 retained the 1945 definition – and by extension, permissible use - of a SDW. It added two recommendations to a 12-inch SDW's design requirements: (1) reinforcing bars should be approximately 2-inches from each face and (2) concrete should have a design compressive strength of 2,500 psi. ORDM 7-224 also introduced two alternate SDW configurations: (1) "…five-foot thickness of packed earth or sand, held between concrete, masonry or wooden retaining walls…" and (2) "six-foot thickness of sandbags (least desirable except for strictly temporary operations."

ORDM 7-224 retained the 1945 definition of an operational shield. With that said, subsequent changes to ORDM 7-224 introduced uses of substantial dividing walls to protect personnel and property. Unfortunately, these changes typically did not state HD 1.1 NEW limits for the new applications and did not define the protection to be afforded personnel and property by a substantial dividing wall. Examples:

Section 2003 – Temporary Storage in Shipping and Receiving Rooms – "Special rooms shall be provided for the temporary storage of ammunition and explosives awaiting shipment, and for their preparation for shipment before assembling, crating, marking, etc. The rooms shall be separated from each other by ***substantial dividing walls*** and shall be separated from offices and rooms in which inert operations such as the preparation of stencils, packing, and crating are performed, by ***substantial dividing walls*** so constructed that they comply with the requirements for fire walls also." *[emphasis added] – Change 3 (1954)*

Section 2619 – Concurrent Operations in Loading Plants – "*e.* Some explosives operations are inherently more hazardous than others. The ***personnel exposure*** in locations where concurrent operations must be performed should be controlled by installation of ***dividing*** **walls** so that the number exposed is no greater than if a single type of ammunition were worked on." *[emphasis added] – Change 4 (1955)*

Section 2511 – Sand or Shot Blast Operations within a Building in an Operating Line *[Changes 4 and 7]* – "*a.* The actual sand or blast operating must be separated from the preceding and/or succeeding operations by means of a ***substantial dividing wall to protect all other personnel*** in an unusual incident occurring at this location. Openings in the dividing wall shall be limited to the minimum size requirements to facilitate the handling of items to and from the operation…" *[emphasis added] – Change 4 (1955) and Change 7 (1958)*

Section 1621 – Maintenance and Repairs to Equipment and Buildings – "*i.* Maintenance and tool rooms in an operating line should be separated from explosives by intraline distance. When ***intraline distance*** cannot be provided, protection equivalent to that afforded by a ***substantial dividing wall*** must be provided*." [emphasis added] – Change 7 (1958)*

Section 2804 – Loading and Assembly Building - "*a.* The building or buildings used for the assembly and loading of ammunition shall be designed and constructed in accordance with established explosives safety principles. ***Personnel and explosives or ammunition*** shall be kept at the minimum consistent with safe and efficient operations. ***Substantial dividing walls*** shall be used to **limit exposures** and to separation operations involving dissimilar hazards…" *[emphasis added] – Change 9 (circa 1959)*

Section 2504 - Operational Shields for Disassembly
"*a.* ***A 12-inch reinforced concrete wall constitutes adequate protection for disassembly operations*** involving an item containing 15 pounds or less when the nearest part of the item is at least 3 feet from the wall and the item is 2 feet from the floor…"
"*d.* Each disassembly operation shall be separated from adjacent similar or dissimilar operations by ***operational shields designed to protect the operator at any location from the blast and*** **missiles** arising from a possible explosion at any other adjacent operation." *[emphasis added] – Change 9 (circa 1959)*

Interestingly, section 2504 does not define any reinforcing or support requirements for "a 12-inch reinforced concrete wall" Section 2504 also allows the use of 30-inch and 36-inch reinforced concrete walls as operational shields, applying HD 1.1 NEWs limits of 50-lbs and 70-lbs, respectively. Consequently, the only reinforcing in these walls may be the minimum temperature reinforcing required when the walls were constructed.

Damages Sustained by 12-inch SDWs in Accidental Detonations

This section provides photos from four explosives mishaps in legacy explosives cubicles, illustrating the damages sustained by a donor cubicle's walls and surrounding cubicles and hallways. In each mishap, the reinforced concrete walls in the donor cubicle were 12-inch SDWs. The asphalt roof in each accident was supported on a tongue-in-groove wood decks on a wood framework. The exterior walls in accidents 1, 2, and 4 were constructed of 4-1/2-in deep hollow tiles while the exterior wall in accident 3 appears to be plywood on a wood frame.

Accident 1

Figure 1 – Damages sustained by a typical, WWII-era explosives operating building in an accidental detonation.

Figure 2 – Damages sustained by donor and acceptor cubicles when the dividing walls which separate them do not extend to the exterior wall.

Figure 3 – Direct shear cracks along the vertical side/rear wall joints of the donor cubicle.

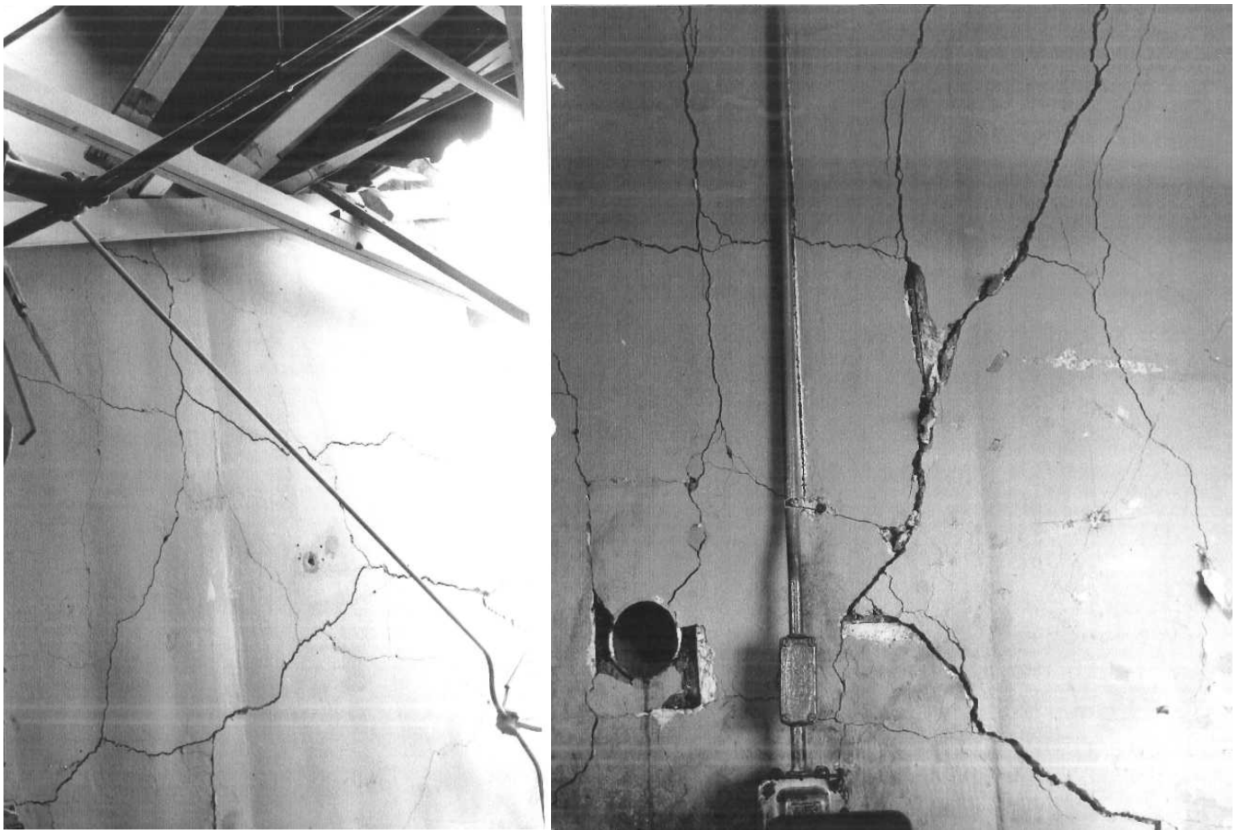

Figure 4 – Concrete cracking on the outside (acceptor) faces of the donor cubicle.

Accident 2

Figure 5 – Similar to accident 1, the 12-inch SDWs separating the donor and acceptor cubicles did not extend to the exterior wall, increasing the damage to the acceptor cubicle.

Figures 6 – The photo on the left depicts the diagonal tension and direct shear cracks in a donor cubicle's wall. The photo on the right shows a severe direct shear crack along the vertical, side/rear wall joint.

Accident 3

Figure 7 – Enhanced damage and debris hazards when donor and acceptor cubicles share a common roof.

Accident 4 – This accident which was used to define the personnel protection guidance in DDESB's 12-inch SDW policy memos. Although the HD 1.1 NEW in this accident was considerably less than the HD 1.1 NEWs in Accidents 1 and 2, the damage sustained by the donor cubicle's 12-inch SDWs, as shown on figure 8 and 9, was particularly severe.

Figure 8 – In this photo of the donor cubicle, deformations of the side walls are particularly apparent.

Figure 9 – Severe direct shear cracking along a side/rear wall joint in the donor cubicle

Internal Detonation Tests

"Work Group to Determine the Effectiveness of Dividing Walls in the Prevention of Propagation of Explosions"

In February 1959, Dr. Ralph Ilsely (ASESB) briefed Board members on his detailed evaluation of the responses of 12-inch SDWs in accidental detonations. Later that year, the Board established the subject work group to (hopefully) verify the 5,000-lb HD 1.1 limit then applied to cubicles which relied on a 12-inch SDWs to prevent a prompt propagation. Unlike the 1944-45 Army tests, the tests would evaluate the risk of propagation from a detonation inside a typical explosives cubicle.

Between 1960 and 1962, DDESB and the Servies funded 21 full-scale detonation tests in open, 3-wall cubicles (no roof or exterior wall). The peak shock overpressures and total impulses on the cubicle walls measured in these tests far exceeded expectation, making us aware of the enhancement of shock loads in an internal detonation. Subsequent tests in cubicles with exterior wall and roof surfaces measured further enhancements in shock loads along with long duration loads. The loads – commonly referred to gas pressures – varied with the total area and unit weights of these surfaces, underscoring the benefit of incorporating lightweight/frangible wall and roof surfaces in cubicles to expedite the venting of blast overpressures to the exterior.

Development of Blast Load Prediction, Analysis and Design Procedures

The foregoing tests alerted us to premature failure mechanisms – direct shear, diagonal tension, breaching, etc. - which may develop in a cubicle's reinforced concrete walls and may limit the protection afforded by these walls in an accidental detonation. Similar to ACI 318, the initial (1969) and subsequent revisions of "Structures to Resist the Effects of Accidental Explosions" (Army TM 5-1300/NAVFAC P-397/AFR22992 UFC 3-340-02 and its predecessors apply supplementary blast design requirements to prevent premature failures of wall and roof elements, ensuring that they fail in flexure (bending) after undergoing large deflections/support rotations. Unfortunately, the flexural reinforcing in 12-inch SDWs is minimal, limiting their ability to withstand the more severe blast loads from an internal detonation. In addition, 12-inch SDWs lack the reinforcing needed to prevent other failure modes, making them vulnerable to premature failures by other mechanisms (e.g., direct shear along supports, diagonal tension, breaching, etc.). Such premature failures have been observed in both detonation tests and accidents.

Introduction of Personnel Protection Requirements

"DoD Ammunition and Explosives Safety Standards," DoD 6055.09-STD (1984) introduced a new chapter on personnel protection which required the performance of a hazard/risk assessment for all new or modified industrial operations and facilities involving ammunition and explosives. When this assessment indicates that the probability of an accidental explosion is above an acceptable risk level, personnel exposures in a MCE detonation must be limited to the following:

- Incident blast overpressure ≤ 2.3 psi [15.9 kPa].
- Fragment energy < 58 ft-lb [79 joules]
- Thermal flux ≤ 0.3 calorie per cm^2 [12.56 kW per m^2] (subsequently revised)

These personnel protection requirements remain in effect.

Clearly, neither 12-inch SDWs nor the legacy cubicles in which they were constructed were designed to satisfy the foregoing exposure limits. In addition to the vulnerability of 12-inch SDWs to the high intensity blast loads from an accidental detonation, the exterior wall and roof over adjacent areas of a building were not designed to withstand the wrap around overpressure from an accidental detonation and may create unacceptable debris to personnel below. In addition, legacy cubicles of ten incorporate openings – most typically for conveyors – which provide pathways for blast hazards into adjacent cubicles.

In light of the foregoing, DDESB funded an extensive review of Service accident reports to assess the protection afforded personnel by the 12-inch SDWs in legacy cubicles. This investigation led, in part, to the development of DDESB's initial policy memos for 12-inch SDWs in 2001. In 2020, DDESB issued a revised memo, incorporating knowledge gained since the previous revision in 2003 and adding detailed explanations of the memo's technical bases and permissible uses.

Status of the Services' High Priority Protective Construction Projects

Update of UFC 3-340-02's Gas Pressure model and Calculation Procedure/Software (FRANG code)

UFC 3-340-02's gas pressure model was developed from blast load measurements in small rooms ($V_{int} \leq 7\ ft^3$) with small vent areas ($A_V/V^{2/3} \leq 0.182$). This model proved to be very conservative for typical, well-vented cubicles, yielding long duration loads which greatly reducing calculated HD 1.1 NEW limits.

In 2018, DDESB funded a series of full-scale detonation tests in cubicles with one and two vent surfaces (wall/roof) to provide the data needed to resolve this knowledge gap. DDESB's proponent for these tests was Art Kaminski with technical support from Dr. Chuck Oswald. These tests confirmed the undue conservative of the UFC's gas pressure calculation model when applied to well-vented cubicles. Dr. Oswald then used the blast load measurements from these tests test to develop a new, more realistic gas pressure model, calculation procedure, and calculation spreadsheet. DDESB disseminated these deliverables for Service review in FY 22.

In FY 24, DDESB provided funding for Dr. Oswald to resolve Service comments on his draft model, procedure and spreadsheet; to incorporate the resulting revisions; and to prepare a documentation report and user's guidance for the revised spreadsheet. Final DDESB and Service reviews of Dr. Oswald's deliverables – for approval and dissemination - are in progress. *POC: Dr. Serdar Astarlioglu*

Investigation of Thermal Hazards behind Openings in a Donor Cubicle's Walls from an Accidental HD 1.3 (mass fire) Initiation

DDESB is funding an ERDC research program to measure the thermal hazards behind a donor cubicle's interior doors and penetrations in HD 1.3 initiations. If/when possible, a thermal prediction model/procedure will be developed from these data. ERDC POCs are Josh Payne and Denis Rickman.

In support of this effort, DDESB provided FY 25 funding to USACE-Huntsville, Structural Branch to design the test cubicle and to AVFAC EXWC to provide technical expertise on the cubicle's design and instrumentation. POCs are Michael Pickett (USACE-Huntsville) and Brad Durant (EXWC).

Construction of the test cubicle is underway at ERDC's Fort Polk, Louisiana test facility. Initial tests are planned for late 2026/early 2027.

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