The Twenty-Eighth DoD Explosives Safety Seminar

Using 3-D Finite Element Method (FEM) Modeling For Designing Prefabricated Concrete Protective/Containment Structures

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I. Abstract

Numerous military projects now planned or under way will require constructing blast protection barriers, earth-covered magazines, hazardous materials containment vaults and the like. Most of these structures will be built with cast-in-place reinforced concrete walls and, in many cases, will use cast-in-place reinforced concrete arches. The Reinforced Earth Company (RECo) has developed an alternative to the Army's standard earth covered munitions magazine which combines the benefits of advanced three-dimensional Finite Element Method (FEM) modeling with the use of a prefabricated concrete arch.

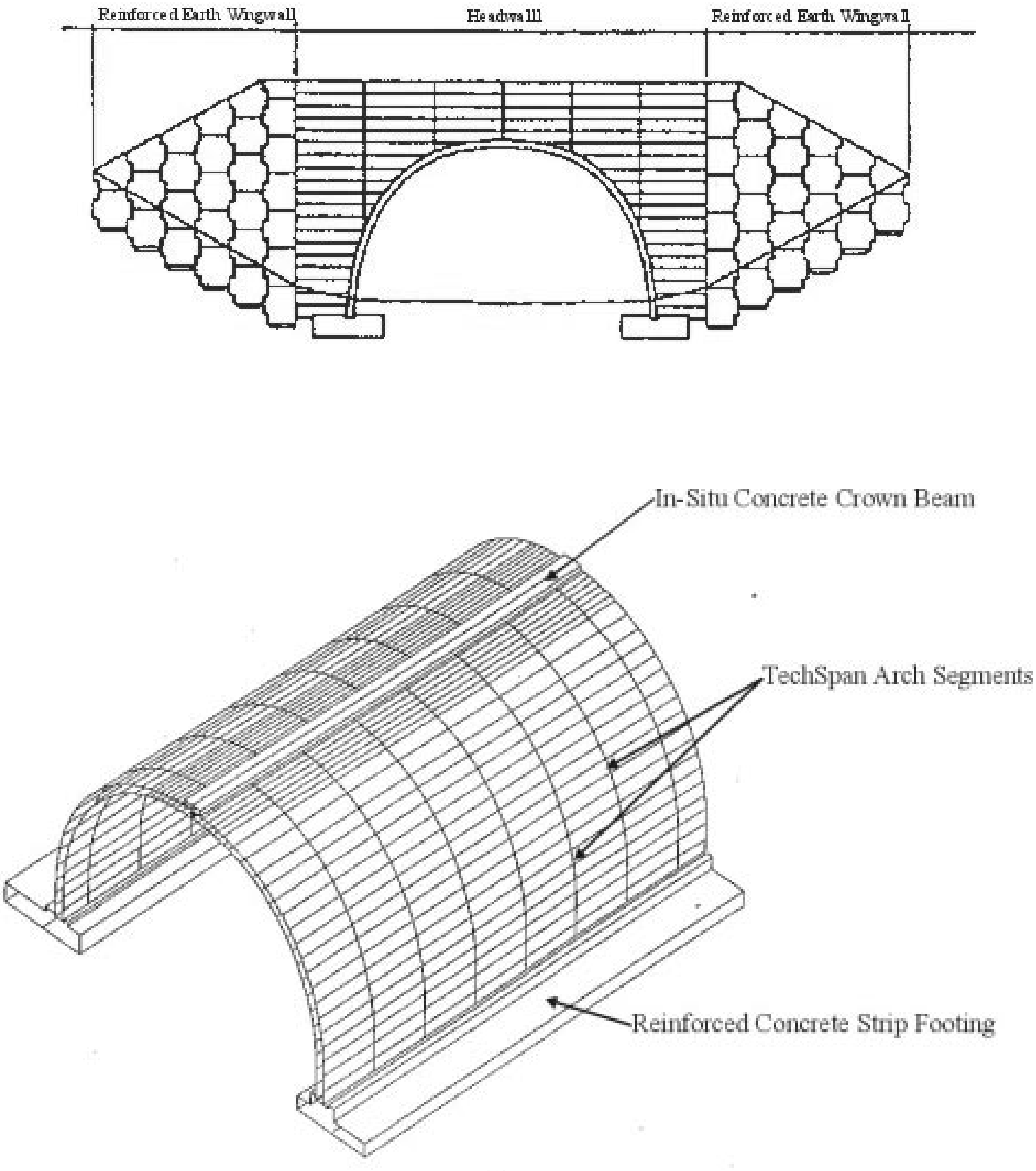
The advanced FEM design tool is capable of determining the optimum profile of the arches. The program considers the application-specific load requirements including live, static and handling loads, while the time-history analysis option permits accurate analysis of blast loads and the ensuing structural behavior. The result is thinner concrete elements which can withstand large blast loads with a maximum of 0.25 cm (0.1 in) displacement. The concrete arch manufacturing process utilizes precision-engineered forms which are both flexible and mobile, allowing numerous arch configurations to be made in a limited number of form types. Installation of the prefabricated components is rapid, simple and predictable, requiring neither specialty formwork nor highly skilled labor. This combination of FEM modeling, adjustable forming techniques and simple installation procedures ensures the accuracy and structural integrity of these vital structures.

II. Background

The Reinforced Earth Company (RECo) introduced Mechanically Stabilized Earth (MSE) retaining wall technology in the United States with its product called Reinforced Earth®. This system consists of alternating layers of granular (non-cohesive) backfill and linear metallic soil reinforcements to which are attached precast concrete facing panels. Reinforced Earth walls are efficient in their use of prefabricated construction materials, yet are able to support large dead, live and dynamic loads. The first U.S. use of this system was a landslide repair constructed in 1969 by the Federal Highway Administration and the California Department of Transportation. Currently over 700,000 m^2 of MSE walls are installed annually in the U.S., primarily for Federal and State governments. Cost savings of 20-40% (in some situations as much as 80%) as compared to conventional cast-in-place concrete construction are typical of MSE structures.

Military testing of this construction method by our European allies began in 1975 and continued to 1990, at which time the USAF conducted full-scale blast tests of munitions magazines constructed with Reinforced Earth components. These tests demonstrated that a MSE magazine offers significant performance advantages over those built of cast-in-place concrete since the MSE structure absorbs high levels of energy during dynamic events yet maintains its basic structural integrity. This explosive energy absorption capability comes directly from the mass and flexibility inherent in an earthen structure faced with discrete precast units.

A precast concrete segmental 3-hinge arch system called TechSpan™ (see Figure 1) was introduced by RECo in 1986, adding to its line of products which combine highly efficient precast concrete designs with granular fill materials to support major loads. TechSpan's efficiency derives from customizing the design of the structural elements through FEM modeling and from precision fabrication techniques. These innovative prefabricated concrete arches are used for bridges, tunnels, culverts and military structures such as munitions magazines and shelters. As with MSE magazines, the hinged arch design and the incorporation of backfill as an element of the FEM model give TechSpan the inertia and flexibility to absorb explosive energy while remaining structurally intact.



TYPICAL TechSpan ARCH SYSTEM

Figure 1

III. Redesigning the Standard Earth Covered Magazine (USACE Des. 33-15-74) Using FEM Software and Prefabricated Segmental Components

Introduction

The standard earth-covered magazine protects stored munitions by resisting blast forces imposed from the outside (*i.e.*, as from the explosion of an adjacent magazine). The structure must be strong enough to absorb these forces with minimal displacement while permitting safe access to the stored materials. It must be electrically continuous for lightning protection, including reinforcing bars, doors and miscellaneous metal. In addition, the construction materials must be cost effective and readily available. The TechSpan™ system satisfies all these requirements and the Finite Element Method permits full evaluation of all applied forces.

TechSpan Precast Arch System Characteristics

TechSpan is a precast concrete arch system which offers the high quality control inherent in plant-poured concrete and the design flexibility of shape-adjustable forms. The forms include a fixed frame, a flexible skin and adjustable-length screws to produce the exact shape required by the design. Arches can span up to 20 m (66 ft) with varying vertical clearances, allowing optimization to meet the requirements of each project. The arch is fabricated as two half arches which are erected in an offset pattern so that each segment bears against the two segments opposite it. Segments are joined in the field by a crown beam (required in magazine applications, optional for civil works depending on loading conditions) and both the crown beam and the 12 mm (0.5 in) wide inter-segment joints can be waterproofed.

Arch thickness under high embankment loads is typically 300-400 mm (12-16 in), while storage magazine design requirements are met with a 200 mm (8 in) thickness. The segment width for magazine applications is 1.5 m (5 ft), meaning the magazine length can also be varied by this increment. The TechSpan elements are supported on reinforced concrete strip footings 1560 mm wide by 406 mm thick (5.1 ft wide by 1.3 ft thick), sized for an allowable bearing pressure of 144 kPa (3000 psf) based on permanent loading conditions and 432 kPa (9000 psf) peak pressure during a blast event. Modifications to the foundation system can be made to accommodate unusual or less suitable bearing conditions. Lightning protection is achieved by clipping, welding or brazing all rebar within or extending between the arch segments, the crown beam and the footings.

Arch Structural Design - FEM Analysis Using BOPRE and STAAD-III

The TechSpan arch has three hinges - one at the crown where the two precast half-arches meet and one on each side at the base. The shape of the arch is a funicular curve, a curve along which, at any point, the bending moment (due to the weight of the fill above the arch, the self weight of the precast elements and the horizontal earth pressure) is equal to zero. Therefore, at any section through the arch, the only permanent forces being resisted are the axial compressive force and the shear force. Although some temporary bending moments are introduced by the backfilling process, they completely dissipate as the backfill reaches its final design height.

The BOPRE FEM Software

The shape of the funicular curve is determined based on the permanent loading condition which, for storage magazines, is 0.6 m (2 ft) of earth fill above the arch crown. Finite Element Method modeling software called BOPRE (see Figure 2) is used to determine the arch shape. BOPRE performs a two-dimensional analysis, taking a cross section through the arch and subdividing it into a mesh of concrete elements and their surrounding soil elements, then analyzing the forces applied to each concrete element. This method allows a complex structure subjected to complex loads to be analyzed as a series of much smaller, simpler structures, and to be reanalyzed over time to account for changing loading conditions such as backfill placement and dynamic forces. The program is based on Duncan's model of soil-structure interaction and accounts for the Marston effect, both of which are discussed below. The FEM results define the arch structural characteristics and reinforcement, as well as provide data to allow sizing of the footings for the permanent load conditions.

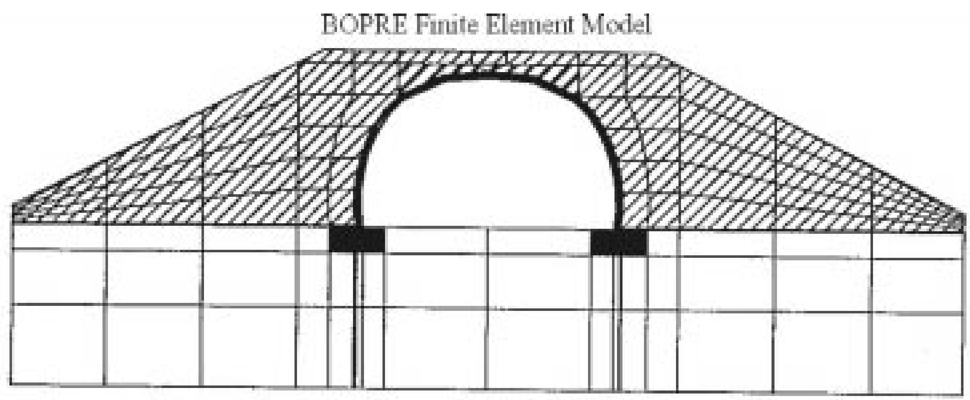


Figure 2

The Duncan Model

To optimize the design of TechSpan structures, soil-structure interaction must be taken into account. The arch elements are relatively thin compared to their other dimensions, making them structurally efficient but also making the behavior of the adjacent soil an important consideration in the design. Working at the University of California/Berkeley in 1980, J. M. Duncan *et al* developed a powerful model to represent both the soil characteristics and the soil-structure interaction. The model is powerful because it requires only a limited number of soil parameters which are easily measurable and/or are known for a wide range of soils.

The Duncan model uses the soil's initial tangent modulus, E_i, and the asymptotic stress difference, $(\sigma_1 - \sigma_3)_{ult}$ (closely related to the ultimate soil strength), both of which are available from the non-linear stress-strain curve for the soil (see Figure 3). The model also takes into account

- unloading/reloading behavior (*i.e.*, during construction), which differs from primary loading,
- non-linear volume changes, and
- ultimate shear strength (based on cohesion and friction angle).

Duncan effectively models the soil-structure interaction under the conditions found in munitions magazines, including stress variations due to the load/unload/reload cycles typically experienced during construction.

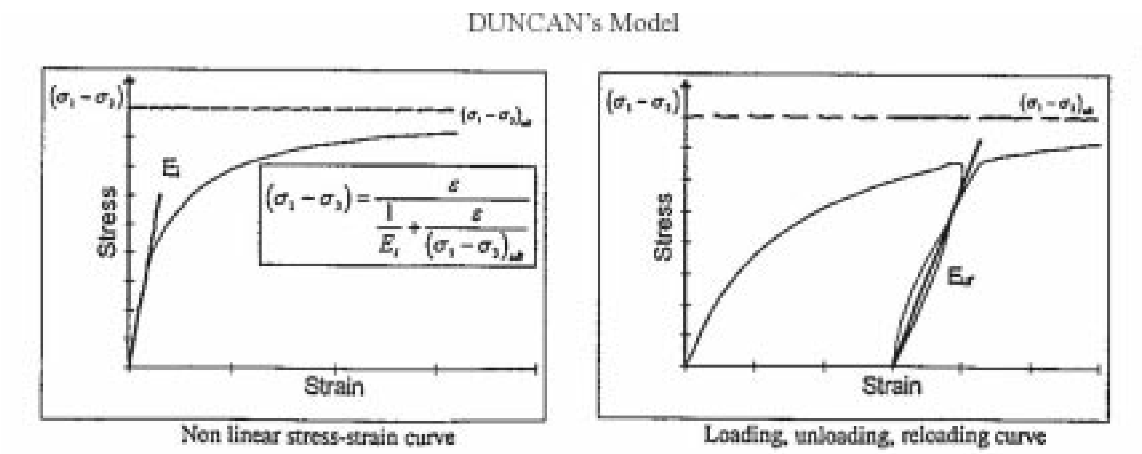


Figure 3

The Marston Effect

When a rigid or incompressible structure is buried under a (relatively) compressible fill there is an interaction between the two. Fill compression on each side of the structure exceeds that occurring directly over it, inducing a downdrag force on the column of soil above. The structure is said to "attract" the load, increasing the vertical stress on the structure beyond what would normally be calculated. M. Marston studied this effect and developed the Marston coefficient, $K_2 = \sigma_v/\gamma z$, the ratio of the vertical stress above the structure to the stress at the same location if the structure were not present (γ= unit weight of the fill, z = depth at this location). Marston's coefficient depends on the fill height, its compressibility, and the shape and rigidity of the structure, and can have a value as large as $K_2 = 1.5$. Most Marston coefficients have been derived for rigid cast-in-place concrete structures, whereas TechSpan structures are considerably more flexible, so coefficients available from reference literature are not applicable to TechSpan.

The Marston effect is accounted for in the design of TechSpan, however, through the incremental nature of the FEM analysis process and without the need for product-specific coefficients. Marston's effect is implicitly accounted for when each FEM iteration adjusts for the then-current field properties and erection phases of both the structure and the soil. TechSpan's flexibility, however, means the Marston coefficients derived from those FEM calculations are smaller than those derived for cast-in-place structures. To check the validity of the results, the FEM model can be run using a TechSpan arch having a very thick section to represent a rigid structure, in which case there is excellent agreement between the FEM and the theoretically-derived Marston values. Thus, the FEM model used in TechSpan storage magazine design is considered to adequately include the Marston Effect.

STAAD-III Three-Dimensional Model

The STAAD-III program is a standard, commercially available software package which addresses the three-dimensional finite element structure evaluations required to analyze a storage magazine under blast load conditions. Using the arch curvature developed by BOPRE, and taking into account the restraints provided by the crown beam and the footings, STAAD-III models the magazine and applies the blast loads using a time history analysis. To analyze the TechSpan arch, each segment is divided into discrete elements as shown in Figure 4.

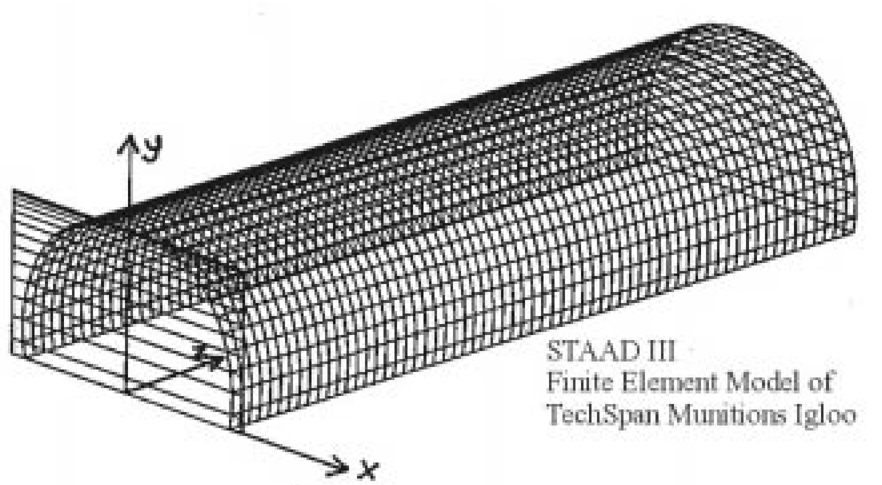


Figure 4

The TechSpan magazine is made up of 1.5 m (5.0 ft) wide precast segments separated by 12 mm (0.5 in) open joints. Unlike cast-in-place concrete magazines, the TechSpan magazine is not longitudinally continuous, with the exception of a reinforced concrete crown beam (0.3 m (1.0 ft) thick by 1.07 m (3.5 ft) wide). The crown beam of the TechSpan magazine joins the segments at the top, producing a total crown thickness of 0.5 m (1.67 ft). However, the crown beam is bisected vertically along it's centerline (directly over the arch hinge point) by neoprene joint material, producing the equivalent of two parallel but independent crown beams while maintaining the hinge behavior at the top of the arch.

The portal and rear walls of the TechSpan magazine are identical to those used in the cast-in-place magazine (Des. 33-15-74), except for modifications to the connection details where they join the TechSpan structure. These walls are known to perform satisfactorily as designed, so they are not described in further detail here. For the FEM analysis, the walls are divided into coarse elements since the STAAD-III program treats the blast forces as a series of concentrated loads applied at the nodes along each arch.

The excellent performance of the TechSpan arch under blast load conditions is due to the discrete elements used in its construction and, specifically, to the interaction among those discrete elements. This statement refers to the whole system, including the backfill, not just to the precast units. Under design load conditions, either the portal or the rear wall receives the force of the blast, transmitting that force directly to the arch segments at the end and to the crown beam above. The crown beam distributes the load to the tops of the remaining arch segments, with each side of the structure acting quasi-independently due to the beam's neoprene longitudinal joint. The open joints between arch segments allow each segment to respond to the blast forces independently, with the footing providing only vertical restraint (the grouted keyway is unreinforced and the grout bond can break, so horizontal resistance is limited to friction at the point of bearing).

The response of the precast units is further damped by the backfill surrounding the structure (see Figure 5). Due to the relatively uniform grain size of the granular backfill, void space naturally occurs between the soil particles. The backfill layer closest to the precast pieces is not compacted, further damping the blast forces, while the second backfill layer out from the arch is only lightly compacted. This relatively loose soil configuration deforms inelastically as it absorbs forces from the arch and inhibits arch segment movement. The result, as documented by the STAAD-III FEM analysis, is a structure natural frequency of 6.6 cycles/sec and structure displacement of less than 0.25 cm (0.1 in) under a worst-case blast design load.

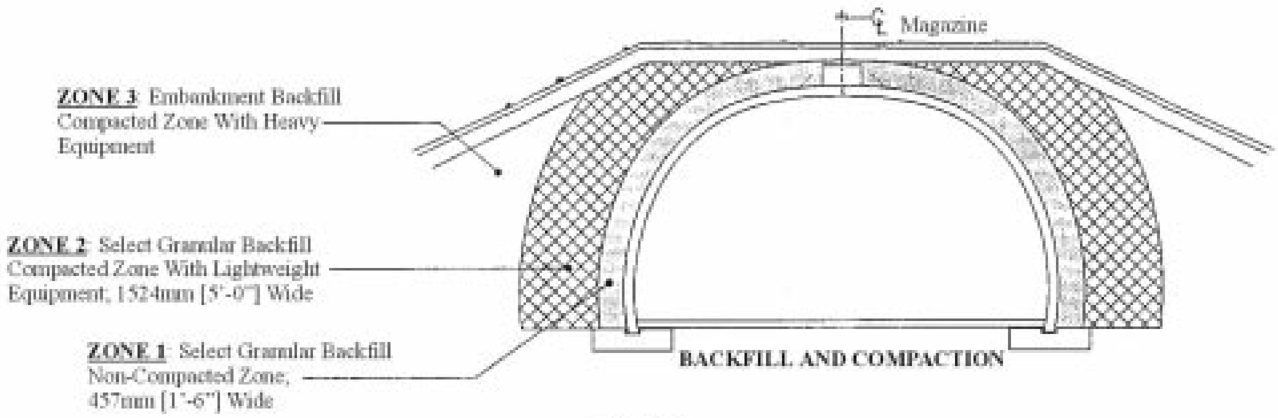


FIGURE 5

<u>TechSpan Munitions Magazine Arch Construction</u>

A three-person crew and a crane can erect 10 to 20 m of TechSpan per day, depending on specific dimensions (see Figure 6). The reinforced concrete footings have a keyway for positioning the arch segments which are placed against the inside face of the keyway and held with wooden wedges. To start, two full-width segments are erected simultaneously, one aligned with the end of the structure and the other offset downline by half a segment width. The third arch segment bears against the exposed half of the second and extends downline by another half segment width, and the process continues to the end of the structure. Half-width pieces are added to finish both ends.

Following erection of the arch, the keyway is grouted, impermeable membrane and filter cloth are installed over the joints between segments, and the structure is made electrically continuous by clipping, brazing or welding all exposed rebar. Backfill is placed in the specified lifts. No compaction is permitted within the first 457mm (1.5 ft) measured radially from the arch, light compaction is specified in the next 1524mm (5 ft), and normal compaction is required outside those limits. The backfill elevation differential on opposite sides of the arch must never exceed 0.45 m (1.5 ft) to maintain arch stability. Crown beam concrete is poured when backfill placement reaches the top of the arch, with final backfilling after the concrete has cured.

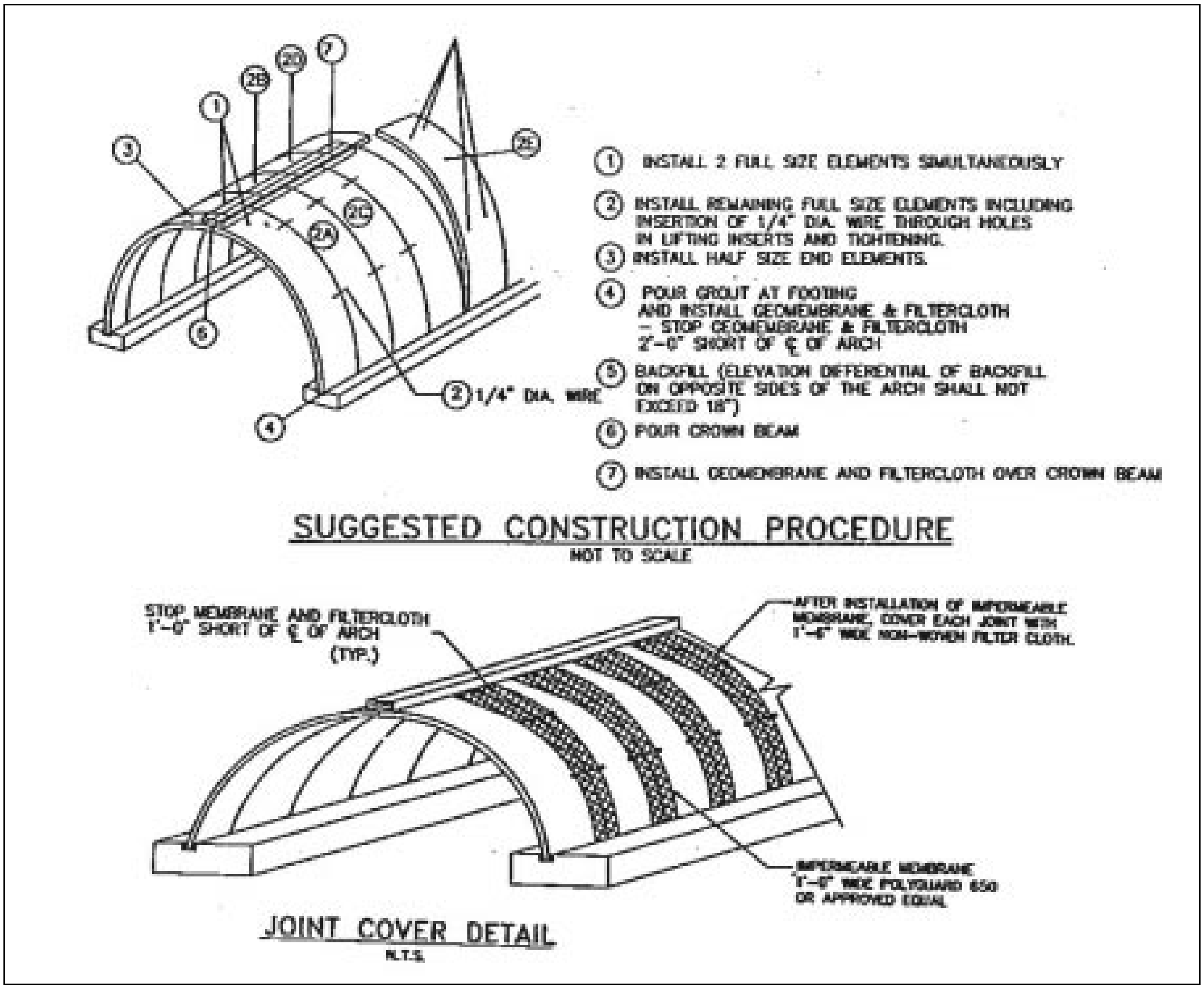
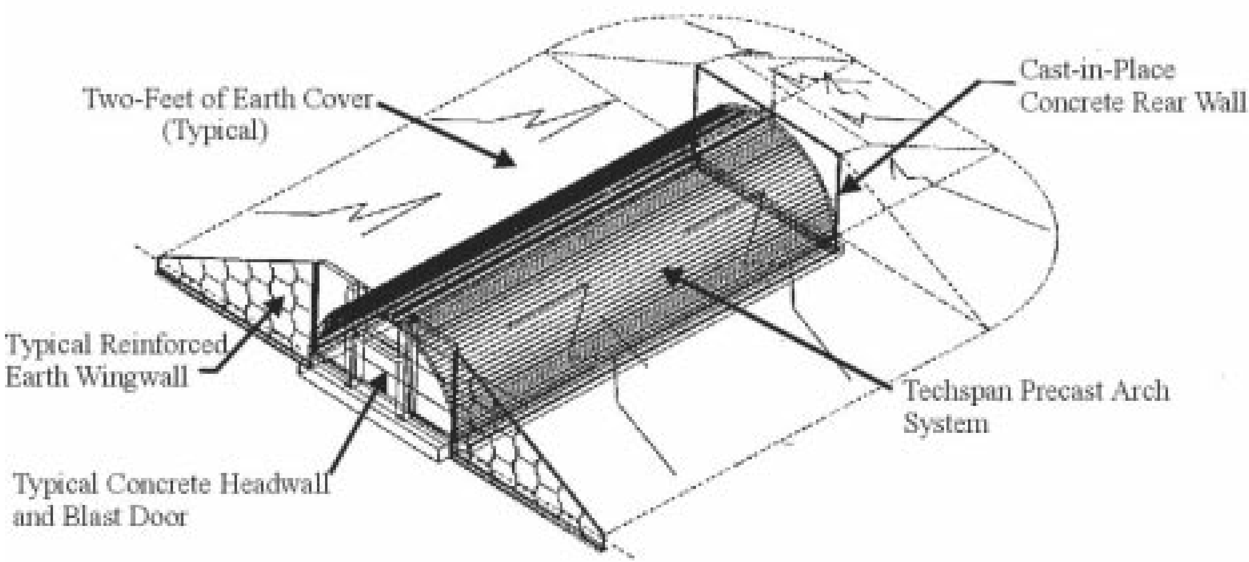


Figure 6

Conclusion

The TechSpan munitions storage magazine is a statically, dynamically and economically efficient structure. The arch shape is inherently efficient in supporting earth loads, while Finite Element Method modeling allows customized design of the arch segments to meet the dynamic loading conditions imposed by a blast event. An adjustable forming system allows precast pieces to be cast in the exact shape required by the model, and simple construction procedures assure speedy, accurate erection of the magazine. The nature of the TechSpan system, as a series of discrete elements working together, limits deflection of the structure to 0.25 cm (0.1 in) under design load. A pictorial view of a standard munitions igloo utilizing prefabricated concrete arch and wingwall components is shown in Figure 7 below.



MAGAZINE, PRECAST CONCRETE EARTH COVERED
USACE STANDARD DESIGN 421-80-05

Figure 7