Effects of Aging and Environmental Conditions on Ammunition/Explosives Storage Magazines – Paper 2

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Abstract

The Defense Ammunition Center (DAC)/U.S. Army Technical Center for Explosives Safety (USATCES) recognized the need to establish the 'structural health' status of aging ammunition/explosives storage magazines. A recent accidental explosive event in an earth covered magazine demonstrated that legacy assumptions for structural failure may be unknown and potentially adversely affect safety. Aging and the effects of environmental factors may have an effect in the structural performance of the storage magazines when subjected to explosions. DAC requested the assistance of the University of Oklahoma (OU), USACE-ERDC (Vicksburg), and USACE Engineering and Support Center to determine the 'structural health' of aging magazines, evaluate remediation methods, and perform structural analyses to duplicate structural conditions found in situ magazines. The key goals of the effort (July 2008 thru May 2010) are to gain an accurate estimate of scope of the problem of deficient magazines, to collect and archive data on the structural health of existing magazines, to identify practical remediation methods for risk-graded magazine renovation efforts, and to create a long-term health monitoring program for continuation of this important effort. Environmental conditions that could adversely affect the structural health of the magazine were determined and several installations (CONUS and OCONUS) were visited to perform visual inspections and gather material samples that were

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14. ABSTRACT

The Defense Ammunition Center (DAC)/U.S. Army Technical Center for Explosives Safety (USATCES) recognized the need to establish the structural health status of aging ammunition/explosives storage magazines. A recent accidental explosive event in an earth covered magazine demonstrated that legacy assumptions for structural failure may be unknown and potentially adversely affect safety. Aging and the effects of environmental factors may have an effect in the structural performance of the storage magazines when subjected to explosions. DAC requested the assistance of the University of Oklahoma (OU), USACE-ERDC (Vicksburg), and USACE Engineering and Support Center to determine the structural health of aging magazines, evaluate remediation methods, and perform structural analyses to duplicate structural conditions found in situ magazines. The key goals of the effort (July 2008 thru May 2010) are to gain an accurate estimate of scope of the problem of deficient magazines, to collect and archive data on the structural health of existing magazines, to identify practical remediation methods for risk-graded magazine renovation efforts, and to create a long-term health monitoring program for continuation of this important effort. Environmental conditions that could adversely affect the structural health of the magazine were determined and several installations (CONUS and OCONUS) were visited to perform visual inspections and gather material samples that were laboratory tested. Modeling this effort after the proven DoD Bridge Inspection program, a magazine inspection checklist was developed. A web-accessible data archive was developed to support storage and retrieval of magazine inspection data. This presentation will provide discussions of environmental conditions that adversely affect the structural health and life of a magazine. The results of the material testing will be compared to design conditions. The results of finite element structural analyses performed to assess and predict the structural condition found in the site inspection will also be discussed.

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Background

DoD missions require the storage of ammunition and explosives. Earth-covered magazines, or ECMs, are a common form of military structure used to store volatile chemical products, including explosives and sensitive fuels. While there are many types of ECMs on DoD installations, the various structural forms are variations on a common theme - a steel or reinforced concrete structure with either a single- or double-curvature roof (i.e., vaults or domes), a headwall (including a door), and a rear wall, with earth cover over all components except the headwall. This effort concentrates on the reinforced arch type structures depicted in Figures 1 and 2.

Figure 1. Exterior view of typical ECM.

Figure 2. Interior view of typical ECM.

Earth-covered magazines have been built for decades in the United States, and many of these structures are showing signs of age, including degradation of the structural concrete due to various environmental effects, as well as larger-scale structural vulnerabilities arising from cracks and other forms of concrete structural degradation. Some magazines were built with less-than-optimal steel reinforcement, and hence their structural health is suspect. Others have experienced substantial degradation and corrosion of the reinforcement, resulting in similar concerns about structural health. And periodically, explosives accidents occur within these magazines, and the resulting loss of life and property yields concerns about how aging may affect magazine performance.

This project was designed to initiate a scientific study of the effects of aging on earth-covered magazines, including physical and chemical inspections of a wide variety of magazines from five different geographically-diverse sites. These inspection results were then catalogued within an information archive so that these records could be preserved, compared, and evaluated over time. In addition to these physical inspections, various structural analyses were also performed.

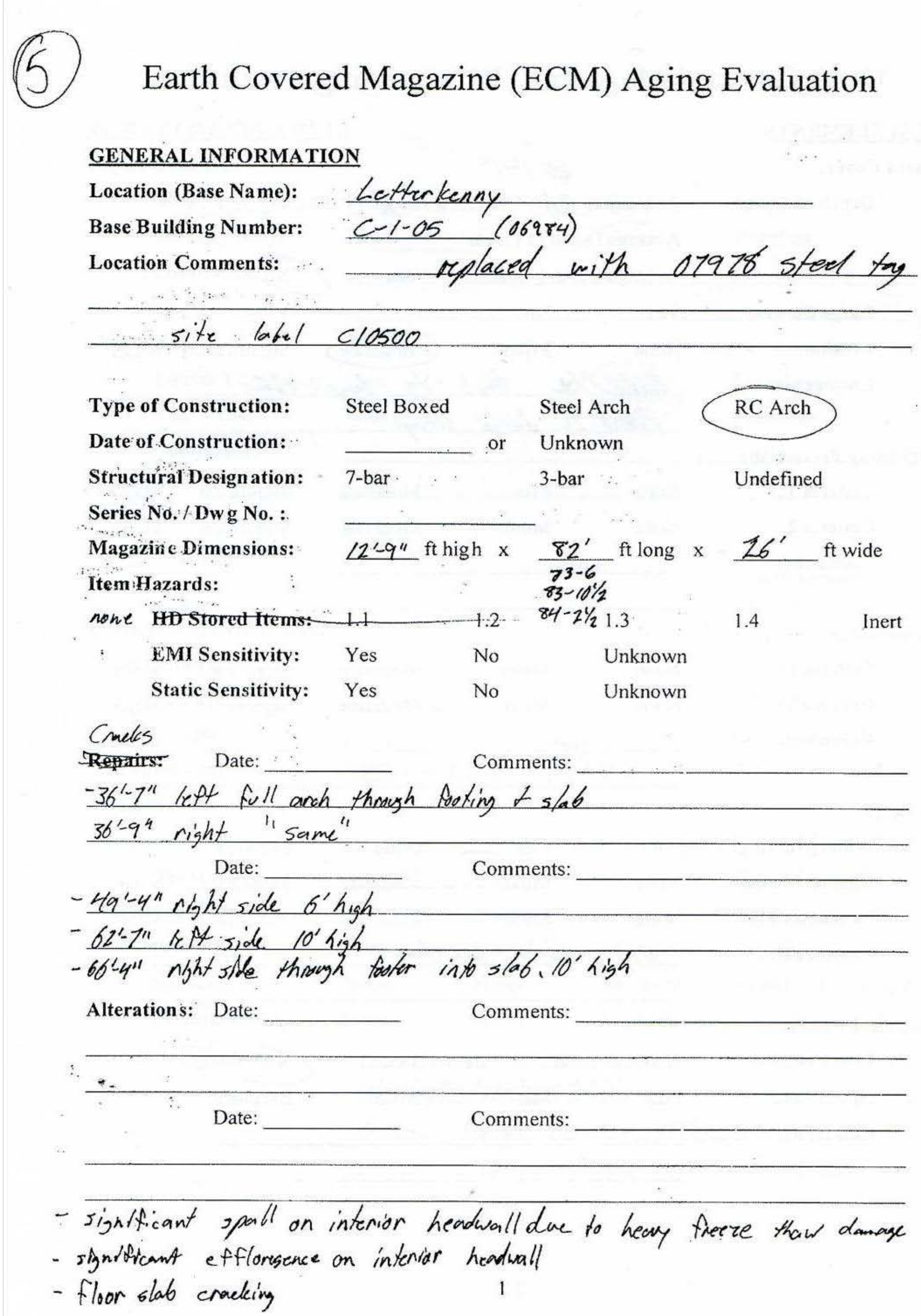
Inspection Activities

Inspection overview - Various factors were considered when selecting sites to be inspected. These factors include: the presence of environmental conditions that would prompt degradation, explosives safety risk associated with the contents of ECMs, the adverse impacts of an accidental detonation, the ease of access to the ECMs, and the impact of the inspection on the current user of the ECMs at the installation. For example, an aging ECM at an installation that stored high quantities of ammunition/explosives adjacent to heavily populated real estate would be a prime candidate for inspection.

The six sites visited were the Letterkenny Army Depot in Franklin, PA; Sierra Army Depot in Herlong, CA; Red River Army Depot in Bowie, TX; McAlester Army Depot in McAlester, OK; Redstone Arsenal in Huntsville, AL; Milan Army Ammunition Plant in Milan, TN, and Wheeler Army Air Field on Oahu Island, HI.

Once a site was selected, the visit was coordinated with the installation points of contacts. The intent of the site inspection was relayed to installation personnel. The personnel understood that the purpose was to determine the health status of the ECMs rather than an invasive inspection. A date for the site visit was agreed, and that date did not adversely affect installation work activities. The installations provided entry and access requirements and any restrictions, and the research team adhered to these policies. Ample planning time was required, as it required up to 30 days after initial contact to arrange a typical site visit. Upon arrival, it was customary to provide briefings to site personnel on the purpose of the site visit and to describe all planned activities. Upon departure, it was customary to provide installation personnel with an exit evaluation of the results from the visual inspections. Inspection checklists were completed for approximately twenty ECMs at each of the sites visited. Non-destructive and destructive testing were performed at the Milan, Letterkenny and Sierra sites, and concrete core samples from the destructive tests were later analyzed in a controlled laboratory setting atthe ERDC. The site inspection teams included members from the USAESCH, ERDC and OU.

***Inspection Checklist* –** The team began the first inspection with a checklist of anticipated data to be gathered. It soon became obvious that the flow of gathering this information could be improved and with each site visit the checklist was revised based on these observations. The inspection checklist used on the most recent site visit is the result of editing the list based on these lessons learned during the inspections. A portion of an inspection checklist is shown in Figure 3.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Earth Covered Magazine (ECM) Aging Evaluation

GENERAL INFORMATION

Location (Base Name): Letterkenny

Base Building Number: C-1-05 (06984)

Location Comments: replaced with 07978 steel tag

site label C10500

Type of Construction:	Steel Boxed	Steel Arch	RC Arch (circled)
Date of Construction:	______ or	Unknown	
Structural Designation:	7-bar	3-bar	Undefined
Series No. / Dwg No. :	______		
Magazine Dimensions:	12'-9" ft high x	82' ft long x (73-6, 83-10½, 84-2½)	26' ft wide
Item Hazards:			

none ~~HD Stored Items: 1.1 1.2~~ 1.3 1.4 Inert

EMI Sensitivity: Yes No Unknown

Static Sensitivity: Yes No Unknown

Cracks
~~**Repairs:**~~ Date: ______ Comments: ______

-36'-7" left full arch through footing & slab

36'-9" right " same "

Date: ______ Comments: ______

- 49'-4" right side 6' high
- 62'-7" left side 10' high
- 66'-4" right side through footer into slab, 10' high

Alterations: Date: ______ Comments: ______

Date: ______ Comments: ______

- significant spall on interior headwall due to heavy freeze thaw damage
- significant efflorescence on interior headwall
- floor slab cracking

1

Figure 3. Field inspection form.

Site Inspection Results

Results from Sierra - Twenty ECMs were visually inspected at the Sierra Army Depot. Based on visual inspections, each individual magazine was given an overall rating that indicated the health status for that structure. Of the twenty structures that were inspected, five were considered to be in "Good" condition, twelve were considered to be in "Fair" condition, and three were considered to be in "Poor" condition. All of the structures exhibited a major transverse structural crack at the mid-length of the structure. Approximately 90% of the structures exhibited diagonal cracking at the intersection of the headwall and the arch where the cracks extend from the headwall into the arch. Three of the visually inspected magazines were recommended for concrete coring and laboratory testing. All of the concrete cores were taken in accordance with ASTM C 42.

Results from Letterkenny **-** Twenty ECMs were visually inspected at Letterkenny Army Depot. Nine structures were determined to be in "Good" condition. Eleven structures were determined to be in "Fair" condition. None of the structures that were examined were classified as "Poor". All but one of the structures exhibited a major structural crack at the mid-length of the structure. This crack ran transversely around the arch through both the footer and the floor slab. 50% of the structures had diagonal cracks that extended from the headwall to the arch at the front of the structure. Four of the visually inspected magazines were recommended for concrete coring and laboratory testing. All of the concrete cores were again taken in accordance with ASTM C 42.

Results from Wheeler **-** Twelve ECMs at Wheeler Army Airfield were examined. These are concrete box structures, not concrete arch structures as the rest of the magazines inspected. Ten of the structures examined were determined to in "Good" condition and two were considered to be in "Fair" condition. None of the structures were considered to be in "Poor" condition. 50% of these structures exhibited minor transverse cracks, all of which were very fine and narrow cracks. None of these structures exhibited any major structural damage.

Results from Milan **-** Twenty ECMs at Milan Army Depot were visually inspected. These structures were all concrete arch magazines. Eleven of these structures were classified as being in "Good" condition and nine were classified as being in "Fair" condition. None of the structures examined were considered to be in "Poor" condition. 90%of the structures inspected had a major structural crack at mid-length of the structure. These cracks extended transversely across the full arch and through both the footers and the floor slab. 40% of these structures had diagonal cracks that propagated from the headwall into the arch. Four of the magazines from Milan were recommended for concrete coring in accordance with ASTM C 42.

Results from McAlester- Twenty ECMs were visually inspected at McAlester Army Ammunition Plant. McAlester is one of the only places in the world that contains a large variation of magazine types. Four types of magazines were examined. The first was a large reinforced concrete box structure, non-earth-covered, with one large loading dock. Five of these reinforced concrete boxes were inspected, and none of the structures were considered to be in "Good" condition. Three of these structures were considered to be in "Fair" condition and two were considered to be in "Poor" condition. 50% of these structures exhibited wing wall separation from the structure. The tensile forces were great enough to cause the rebar that attaches the wing wall to the structure to break.

The second type of structure encountered at McAlester was a triple-igloo with one large loading dock that was earth-covered. Four of this style of magazines was visually inspected. One of these was considered to be in “Good” condition and three were considered to be in “Fair” condition. All of these magazines exhibited cracking that extended vertically from the floor slab towards the top of the arch.

The third structure type was a reinforced concrete triple-arch that was earth-covered and had one large common loading dock. One of these magazines was considered to be in “Good” condition, three were considered to be in “Fair” condition, and one was considered to be in “Poor” condition. All of these structures had diagonal cracking originating at the interior door corners. One of the magazine structures had large areas of de-lamination with aggregate segregation around the arch.

The fourth type of structure was a reinforced concrete arch structure that was earth-covered. Six of this style of structure was visually inspected. One was considered to be in “Good” condition, four were considered to be in “Fair” condition, and one was considered to be in “Poor” condition. All but one of these structures exhibited a major transverse structural crack at the mid-length of the structure. Also all of these structures had diagonal and vertical cracks extending from the door corners.

***Results from Red River* -** Twenty ECMs were visually inspected at Red River Army Depot. These structures were all reinforced concrete arch structures. Of the twenty structures that were inspected seven were considered to be in “Good” condition, twelve were considered to be in “Fair” condition and one was considered to be in “Poor” condition. 95% of these structures exhibited a major transverse structural crack at the mid-length of the magazine. Also all of the structures showed vertical and diagonal cracking at the corners of the doorway.

Conclusions Based on Site Inspection Results

Site Inspection Observations –After the inspections were completed, a common pattern of cracks was observed in ECMs. The crack patterns, and lists of possible causes are cataloged below. The causes are based primarily on engineering judgment.

1. At the top of the arch there were generally one to three longitudinal cracks running the length of the igloo. These cracks were located at: the center of the arch, 4-6 feet left of center, and 4-6 feet right of center (Figure 4).

   Possible causes for this pattern of cracking include relaxation of the arch supports at the spring line reactions (foundation), point loads at the apex of the arch (heavy machinery driving over ECM, etc.) that were not anticipated during design (or larger than anticipated), incorrect design assumptions such as the soil and/or foundation not creating the required confining stiffness, deterioration of the concrete, or insufficient reinforcement.

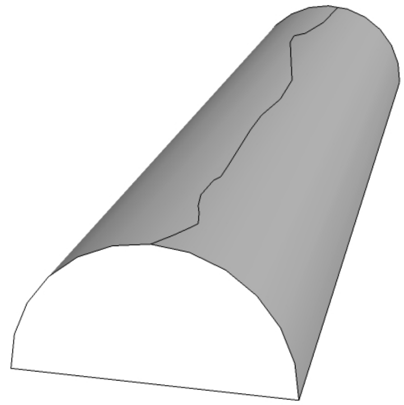

Figure 4. Longitudinal crack along the apex of the arch.

2. The floor slab often had the same longitudinal cracks as the arch. There were generally one to three longitudinal cracks running along the length of the igloo. These cracks were located at the center, at 4-6 feet left of center, and at 4-6 feet right of center.

   Possible causes for the floor slab cracks are the same as for the cracks along the apex.

3. There was often one large transverse structural crack (1/4" to 1/2" wide) located near mid –length of the ECM. In addition to the large transverse crack, there were also smaller transverse cracks along the length of the building (Figure 5).

   Possible causes for these transverse crack patterns include point loads at the apex of the arch (heavy machinery driving over ECM, etc.) that were not anticipated during design, foundation settlement at the center of the length (or heaving of the ends), deterioration of the concrete, or insufficient reinforcement.

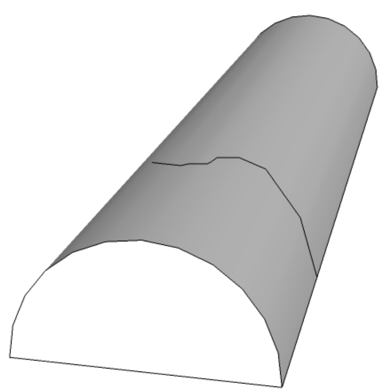

Figure 5. Transverse (or lateral) crack (generally near mid-length).

4. The back wall sometimes contained a small vertical crack at the center of the wall from the top of the footing wall to the vent box.

5. The headwall generally contained two to three cracks radiating from the corners of the doors and some showed impact damage at the door jambs where heavy machinery had likely bumped the door jamb.

6. Headwalls were often cracked at the arch connection (Figure 6). A possible cause of this damage pattern is bending of the headwall against the stiffer arch structure, which creates cantilever bending.

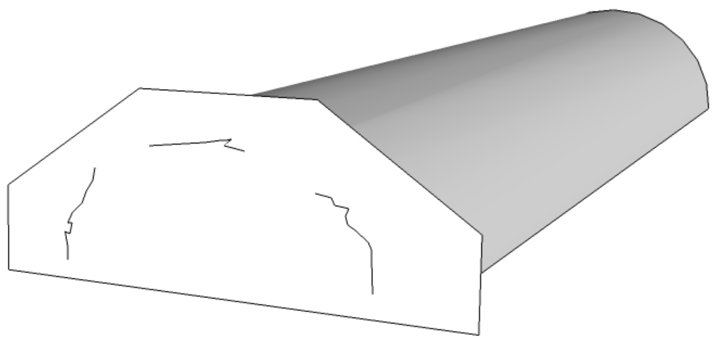

Figure 6. Headwall cracking along the arch.

Igloos with heavier headwalls, or headwalls with pilasters, often contained cracks at 45^0 radiating out from the headwall longitudinally (Figure 7). A possible cause of this damage pattern is rotation of the heavier headwall away from the arch structure.

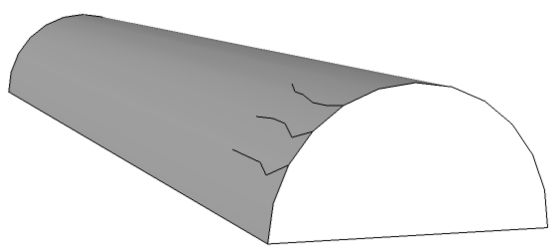

Figure 7. Cracks radiating from the headwall.

There were a few differences in damage patterns observed. For example, some installations with more expansive soils show more crack separation and attendant water problems, and some ECMs are water tight while others contain puddles of water. These differences were observed even between installations where aging and soil types would be expected to be similar.

Chemical Reactions Background

Acid attack: Portland cement concrete is a highly alkaline material and is not very resistant to attack by acids. The deterioration of concrete by acids is primarily the result of a reaction between the acid and the products of hydration of cement and carbonate aggregates. Calcium silicate hydrate may be attacked by acids with a pH of 5 or less which may exist in the environment of the concrete structure. In most cases, the chemical reactions result in the deterioration of the microstructure and the dissolution of water-soluble calcium compounds that are then leached away. Based on the location chosen to inspect, there was some background knowledge about the surrounding environmental conditions. With that background knowledge it was easier to detect deterioration during visual inspections. The degree of aggressiveness of the acid attack determines how rapidly structural integrity is lost. Acid attack will eventually cause loss of structural strength and the ability to protect the reinforcing bars from corrosion. This can be seen as loss of section, spalling, or efflorescence.

Aggressive-water attack: Some waters have been reported to have extremely low concentrations of dissolved minerals. These soft or aggressive waters leach calcium from the cement paste or aggregates. It should be noted that this phenomenon does not have a high frequency of reporting in the United States. Aggressive-water attack, although rarely seen, serves to deteriorate the chemical binder that holds concrete together. This type of deterioration could also be seen as efflorescence, spalling, or loss of section.

Alkali-carbonate rock reaction (ACR): Certain carbonate rock aggregates have been proven to be reactive in concretes. The results of these reactions have been characterized as destructive. The destructive category is apparently limited to reactions with impure dolomitic aggregates and are a result of either dedolomitization or rim-silicifation reactions. Visual investigation of those reactions that are serious enough to disrupt the concrete in a structure will generally show map or pattern cracking, i.e., a general appearance that the concrete is swelling. Swelling of the internal concrete causes extreme pressures that eventually overcome the tensile strength of the structure. These pressures will cause spalling, map cracking, discoloration, or bulging, which in turn eventually affects the structural integrity. ACR can reduce the intended service life based on the deterioration rate.

Alkali-silica reaction (ASR): Some aggregates containing silica that are soluble in highly alkaline solutions may react to form a solid non-expansive calcium-alkali-silica complex. Alternatively, they may form an alkali-silica complex, which can consume considerable amounts of water and subsequently expand, damaging the concrete. ASR damages concrete by the silica forming a gel in the open pore spaces and then expanding. Over time the pore spaces fill with this gel and expand to create extreme tensile pressures. These pressures cause micro-scale cracking and eventually develop into structural cracks. These cracks generally show up as map cracking. There is also a white substance that has a bluish tint to it. Once these expansive pressures start to damage the structure it will compromise the structural integrity. Visual examinations of those concrete structures affected will show map or pattern cracking and a general appearance that indicates the concrete is swelling.

Sulfate attack: Naturally-occurring sulfates of sodium, potassium, calcium, or magnesium are sometimes found in soil or in solution in ground water adjacent to concrete structures. The sulfate ions go into solution and can attack the concrete. There are two sequential chemical reactions that take place in sulfate attack on concrete. The first reaction is when the sulfate reacts with the free calcium hydroxide which is liberated during the hydration state of the cement to form calcium sulfate (gypsum). After this first reaction, the gypsum reacts with the hydrated calcium aluminate to form calcium sulfoaluminate (ettringite). Both of these reactions cause a large increase in volume. The second reaction is mainly responsible for the volume change of the concrete, and when such volume changes occur in concrete it causes extreme pressures that overcome the tensile strength of the concrete. These extreme pressures seen either as shrinkage or expansion will cause cracking. Visual inspection of these structures will show map or pattern cracking and a general deterioration of the concrete.

Carbonation of concrete: The high alkalinity of the concrete can be reduced over a long period of time by carbonation. Carbonation occurs in concrete because the calcium bearing phases present are attacked by the carbon dioxide of the air and converted to calcium carbonate. The pH of fresh cement paste is about 12.5 – 13, where fully carbonated paste has a pH of 8.5 or below. The range of pH in the concrete will be determined by the use of phenolphthalein. By saturating a freshly broken surface of concrete with phenolphthalein the surface will change color to purple if the pH has dropped below 9.5.

Corrosion of the reinforcing steel: Steel reinforcement is normally placed within 2 inches of a concrete surface. Under most conditions, Portland cement provides good protection to the reinforcing steel. The protection of the steel is generally accredited to the high alkalinity of the concrete. The steel is also protected by the relatively high electrical resistance of the concrete.

Still, corrosion of the reinforcing steel is one of the most frequent causes of damage to concrete structures. The high alkalinity of the concrete can be reduced over a long period of time by carbonation. The electrical resistivity can also be decreased by the presence of chemicals in the concrete. The chemical most commonly applied to concrete is chloride salts in the form of deicers.

In most cases with ECMs this form of deterioration may not present a problem. However, a majority of these structures have loading docks or concrete padded areas outside the door. In areas where large amounts of snow are accumulated it is possible for de-icer salts to be used to keep the loading area free of ice. As the chloride ions penetrate the concrete, the capability of the concrete to carry electrical current increases. If there are differences within the concrete such as moisture content, chloride content, oxygen content, or if dissimilar metals are in contact, then there is potential for a corrosion cell to occur. The anodes will experience corrosion (generally the reinforcing steel) where the cathodes will remain undamaged. As reinforcing steel corrodes it expands and causes tensile pressures to force the concrete/reinforcement steel bond to break.

Corrosion of the steel will cause spalling, section loss of the steel, and eventually the loss of all tensile strength to the concrete. Improper location of the reinforcing steel is another issue that will affect the performance of a concrete structure. If the reinforcing steel is not properly located it may not function structurally as intended. One of the more common issues with misplacement of the reinforcing steel is insufficient concrete cover. Since the concrete cover over the steel is reduced, it is much easier for corrosion to begin.

All of these deterioration conditions can cause the concrete to separate into large structural sections. During a blast event the separated sections provide areas of least resistance for the blast loads, and these separated components may concentrate momentum. This phenomenon may alter the size (i.e. larger than usual) of the secondary debris, and especially for low loading density events.

Laboratory Testing of Material Samples

Laboratory Testing Procedures - Upon return to the CMB laboratory in Vicksburg, MS, the concrete core samples (20 from Milan, 15 from Sierra, and 22 from Letterkenny) were logged into the CMB check-in system with a unique CMB identification number. The laboratory test procedures for the concrete core samples were selected to help determine the current condition of the concrete used in the associated Earth Covered Magazines. These tests determine if alkali-silica or alkali-carbonate reactions have taken place, their effects on the concrete, and help estimate the future performance of the concrete. The tests and their purpose are described below:

- Unconfined compressive strength test – to determine compressive strength of the concrete,
- X-Ray diffraction test – to determine (semi-quantitatively) the mineralogy of the concrete aggregates,
- Carbonation test – to determine the depth of carbonation and an indication of the Ph in the concrete,
- Rhodamine B test – to determine if alkali aggregate reactions are taking place in the concrete, and
- Aggregate color test – to give a general idea of the mineralogy of the aggregate.

In addition to these tests, the following checks were performed:

- The aggregates were sorted and checked for consolidation. This was done to determine if the concrete was vibrated properly and the aggregates were evenly distributed throughout the concrete and also if the concrete was well consolidated.
- The samples were checked for pull-out. If the aggregates pull out of the concrete, this would be an indication of how well the aggregate and the cement paste bond together.
- The samples were checked for entrained or entrapped air. This is an indication of how well the concrete was vibrated during placement and also if there is sufficient air voids in the concrete for freeze/thaw.

The ASTM tests methods used to obtain, prepare, and examine the concrete cores are listed below. Details and explanations of these test methods and standards are separately published by ASTM as indicated below.

- ASTM C 295, “Standard Practices for Petrographic Examination of Aggregates for Concrete.”
- ASTM C 33, “Standard Specification for Concrete Aggregates.”
- ASTM C 294, “Standard Descriptive Nomenclature for Constituents of Concrete Aggregates.”
- ASTM C 856, “Petrographic Examination of Hardened Concrete.”
- ASTM C 42, “Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete.”
- ASTM C 39, “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.”
- ASTM C 496, “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.”

Other test methods and standards were also used in determining the condition of the concrete cores. These methods include the following:

- The Geological Society of America (GSA) Rock Color Chart was used to determine the color and label all the aggregates. The mineralogy of all the core samples were determined using X-ray diffraction (XRD) analysis. XRD patterns were run on each of the samples as randomly oriented packed powders. A Philips PW1800 Automated Powder Diffractometer system was used to collect the XRD patterns employing standard techniques for phase identification. The run conditions included Cu Kα radiation and scanning from 2 to 65º 2θ with collection of the diffraction patterns accomplished using the Windows-based version of Datascan, and analysis of the patterns using the Jade program (both from Materials Data, Inc.). In preparation for XRD analysis, a portion of the sample was ground in a mortar and pestle to pass a 45-µm (No. 325) sieve size. Random powder mounts of bulk samples were analyzed using XRD to determine the mineral constituents present in each sample.
- The high pH of fresh or "young" concrete can be reduced over time due to carbonation. Carbonation occurs in concrete because the calcium-bearing phases present in concrete are attacked by atmospheric carbon dioxide and converted to calcium carbonate, as outlined earlier in this document.
- Alkali-Silica Reaction (ASR) is the deleterious reaction between the high pH in portland cement pore fluid and certain siliceous rocks or minerals, such as opaline chert, strained quartz, and acidic volcanic glass, present in some aggregates. The products of the reaction may cause abnormal expansion and cracking of concrete in service. The presence of ASR was determined by the use of ASR-specific chemical stains (Gutherie and Carey 1997). These stains are rhodamine B and sodium cobaltinitrite. The test is best applied to freshly broken surfaces. Surface preparation involved wetting with deionized water, followed by treatment with the stains. The first stain applied was sodium cobaltinitrite, which was left on the surface for approximately 30-60 seconds. Next, the surface was rinsed with water to remove excess stain. The persistence of the yellow color is an indication of the presence of potassium rich silica gels, generally thought to represent active ASR. After the second rinse is finished, the second reagent, Rhodamine B, is applied and excess rinsed off after approximately 30 seconds. This stain leaves a pink color in locations containing calcium rich silica gels. These are generally thought to represent older ASR.

Laboratory Results

A petrographic examination in accordance with ASTM C 856 and ASTM C 895 was performed on all sampled materials. The fine and coarse aggregates from the various concrete core samples were compared to determine the level of variation in the aggregates used to produce the concretes at each installation location. The aggregate particles in the concrete cores ranged from rounded to angular in shape. It was determined from the XRD patterns that the fine and coarse aggregates from the concrete cores were principally composed of minerals listed in Table 1 below.

Table 1. Concrete core sample mineralogy.

Sample Locations	Mineralogy
Sierra	Anorthite, and Quartz
Milan	Chert (cryptocrystalline Quartz)
Letterkenny	Quartz, and Microcline

A typical XRD pattern of an aggregate sample is shown in Figure 8. The lines intersecting the abscissa of the plot in Figure 8 represent identified peaks used for sample identification.

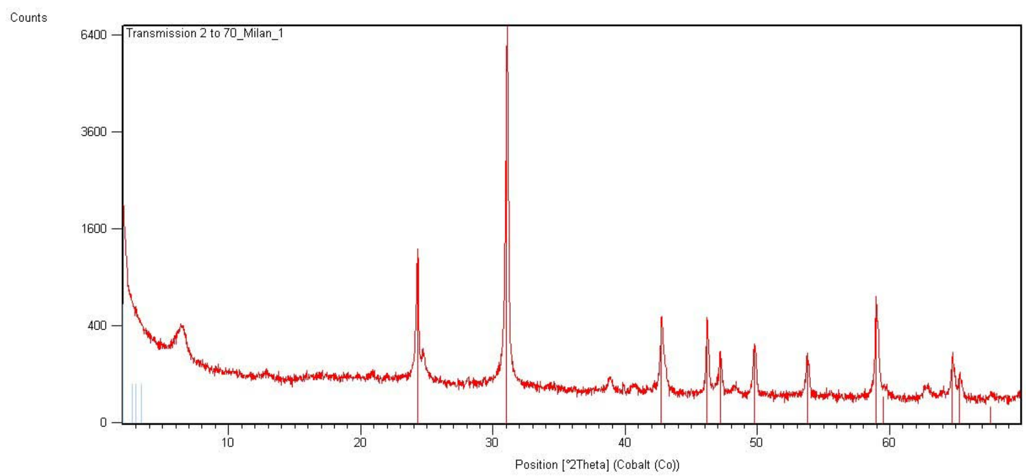

Figure 8. XRD patterns of aggregate samples from concrete cores.

Implementation of the aggregate color test determined aggregate particles found in the cores from Sierra varied from Medium Dark Gray 4 N4 to Olive Gray 5Y 3/2 to Dark Yellowish Brown 10YR 4/2 to Dark Yellowish Orange 10YR 6/6. The color of the aggregate particles found in Letterkenny cores varied from White 9 N9 to Light Gray 7 N7 to Medium Gray 5 N5 to Dark Gray 3 N3. The color of the aggregate particles in the cores at Milan varied from dark yellowish orange 10YR 6/6 to brownish gray 5YR 4/1 to grayish orange 10YR 7/4 to grayish blue 5PB 5/6.

The aggregate particles in all of the core samples exhibit very dense and hard characteristics. The aggregates in the concrete cores that were sampled appeared well sorted, with little to no segregation or poorly consolidated concrete (Figure 9).

Figure 9. Concrete core from ECM.

However, there are some small vug holes that were noticed in one of the cores (Figure 9). These vug holes are generally caused by poor, improper, or incomplete consolidation of the concrete. Yet, it is impossible to get all the entrapped air out of the concrete, and the vug holes noted in these cores are minor.

The carbonation test required a core sample to be broken so that a fresh surface could be saturated with phenolphthalein. Once the fresh broken surface had been saturated, the color of the concrete would change to purple if the concrete's pH is above 9.5. Figure 10 shows the freshly broken surface of a concrete core. Figure 11 shows the same core surface after phenolphthalein has been applied.

Figure 10. Freshly broken core sample for application of phenolphthalein.

As can be seen in Figure 11, the pH has dropped around the concrete surface of the cores, however the internal portion of the core has a pH higher than 9.5. As can be seen Figure 11 below, the carbonation is severe at a depth of ¾ inch and has moderate carbonation to a depth of

2 inches. The average depth of carbonation on all of the cores from Sierra is roughly 1 ½ inches. This condition is favorable for inhibiting steel corrosion provided the reinforcing steel has sufficient concrete cover. Table 2 details the average depth of carbonation for the different samples.

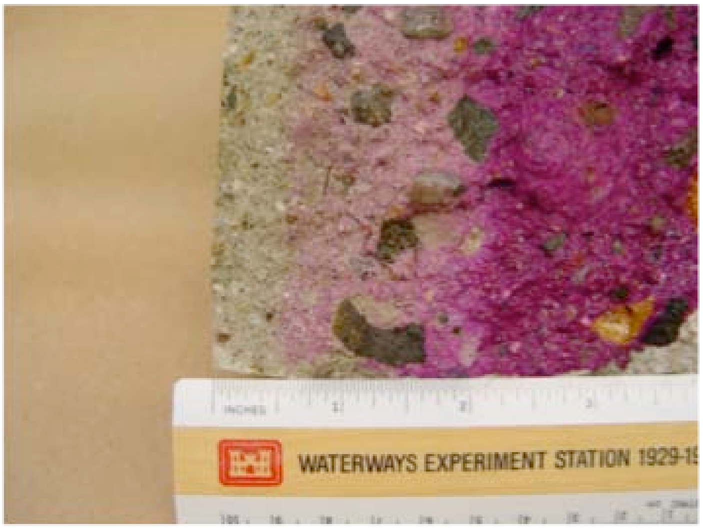

Figure 11. Core sample after application of phenolphthalein.

Table 2. Carbonation depths in core samples.

Sample Locations	Carbonation Depths (inches)
Sierra	1 ½
Milan	1
Letterkenny	¾

The ASR staining method uses a freshly broken surface of concrete. A core specimen was prepared by breaking open a core to provide a fresh surface. The concrete was washed and loose material was removed (Figure 12), and the sample was then treated with the two stains to determine if any ASR gel was present. The color change from the application of both, sodium cobaltinitrite (Figure 13), and rhodamine B (Figure 14) indicated a lack of ASR gel.

Figure 12. Core sample prepared for ASR staining test.

Figure 13. Core sample after application of sodium cobaltinitrite.

Figure 14. Core sample after application of rhodamine B.

Test results of unconfined compressive strength of the concrete core samples are presented in Table 3.

Table 3. Unconfined compressive strength for core samples.

Sierra Unconfined Compressive Strength lb/in^2	**Milan** Unconfined Compressive Strength lb/in^2	**Letterkenny** Unconfined Compressive Strength lb/in^2
3624	6000	6090
4341	5940	6422
4042	6985	5819
3092	6636	6006
3380	4563	5627
	7415	6953
	4632	6905
	6647	6451
	3923	5810
	6675	6216
		4588
		5927

The compressive strength data reported in Table 3 indicate strong, sound concrete with a minimum compressive strength of 3092 psi recorded. In the compressive strength tests, there were very few coarse aggregate pullouts, which indicate that there is a strong bond between the paste and aggregate (Figure 15).

Figure 15. Fractured surface of concrete core (taken from Sierra).

Conclusions Based on Laboratory Results

Based on the XRD data, the aggregate mineralogy of Sierra was determined to be comprised mainly of anorthite and quartz, Milan was comprised mainly of chert (cryptocrystalline quartz), and Letterkenny was comprised of mainly quartz and microcline. The carbonation tests showed signs of varying depths of carbonation. These depths range from severely carbonated to moderately carbonated concrete. The average depth of carbonation for the core samples from Sierra was approximately 1 ½ inches, the average depth of carbonation for Letterkenny was 1 inch, and the average carbonation depth of Milan was ¾ inch. All of the reinforcing steel still incased in concrete has a pH higher than 9.5, provided the steel still has sufficient concrete cover. From the three locations that concrete cores were taken, none had any visual signs of alkali aggregate reactions taking place. The findings of the unconfined compressive strength resulted in average strengths above the required minimum. From the compressive strength samples, it was also determined that there was a good paste/aggregate bond based on there were very few aggregate pull-outs.

Service Life Based on Laboratory Results

Based on the laboratory data and the known averages service life of these structures, calculations can be made to help give a rough estimate of what the remaining service life of the structures is. This estimate is solely based on the laboratory data. This estimate could increase or decrease based on the maintenance and remediation methods used on the structure. With the average length of service of these structures being in the 50 year range, some calculations can be made to determine the actual rate of carbonation vs. the assumed 0.039 inches (1mm) per year carbonation progression. With the actual carbonation progression rate calculating the time it will take for this front to reach the reinforcing steel the service life can be determined. The laboratory data from Sierra showed signs of carbonation at 1 ½ inches (38.1mm) depth, which was the most extreme case of the three sites where cores were taken. By knowing the depth of carbonation and the approximate service life the actual carbonation rate can be obtained. Therefore, with the data from Sierra, the calculations can be made to determine that the carbonation front will progress from 1 ½ inches (38.1mm) to 1 ¾ inches (45.08mm) depth at 70 years of service life. Based on the compressive strength data and provided the reinforcing steel has sufficient concrete cover, the conclusion can be made that these structures will last another 20 years. Again, note that proper maintenance and repair could extend the service life of these structures beyond the calculation of 20 years.

Proposed Remediation Measures

The fundamental problem of aging of ECMs requires a range of remediation methods for its cost-effective solution. Some of the most important remediation techniques are outlined below, in terms of the end-result patterns that occur because of the chemical, mechanical, and environmental hazards that were presented earlier in this report.

***Characterization of Structural Vulnerabilities* -** There are a wide range of material vulnerabilities that affect reinforced concrete structures, and the hazards that compromise concrete materials have been discussed in considerable detail already. But these various material problems result in a relatively small set of structural vulnerabilities, and this section is oriented towards characterizing these larger-scale structural problems, so that appropriate remedies can be identified.

The most important structural vulnerabilities include the following:

- Concrete cracking on a scale that compromises the structural integrity of the ECM, e.g., the longitudinal through cracks that were identified as a common feature of structural deterioration in a wide variety of those ECMs inspected during this project,
- Spalling of concrete sufficiently widespread to compromise the inside surface of the ECM, including large-scale spalling that exposes the embedded reinforcement to corrosion and other deleterious effects,
- Corrosion or other degradation of structural steel reinforcement, and
- Overall degradation of the concrete structural components to the point where their structural resistance cannot be guaranteed against common or extreme loadings.

***Overview of Best-Practices Remediation Methods* -** Remediation measures should follow a risk-graded approach, in that the appropriate remediation techniques should be derived both from the underlying structural vulnerability and the associated use of the ECM. For example, an ECM that routinely is filled with the most volatile explosives might require more comprehensive remediation measures even if its structural vulnerabilities are relatively minor, because the risk of structural failure is large due to its everyday use. Conversely, a seriously-deteriorated ECM might not warrant an extensive remediation program if that ECM was not used to store explosives, e.g., if it were slated for near-term closure.

Appropriate remediation measures for the vulnerabilities enumerated above include the following techniques:

- Concrete cracking can often be remedied by injection of appropriate adhesives, e.g., using epoxy to bond the separate concrete components.
- Concrete spalling generally requires removal of the damaged surface material, followed by appropriate mechanical roughening of the underlying intact concrete, which is then covered with a coat of concrete with an aggregate size appropriate to the thickness of the covering layer, e.g., gunite for thin layers of surface replacement.
- Corrosion of reinforcement is generally remedied by a process similar to that used for spalling, but with a much more comprehensive removal of concrete matrix material. If the reinforcement has only minimal corrosion, then its surface can be removed and then the concrete matrix can be replaced so that the structural composite behavior can be regained. If the corrosion of the reinforcement is more severe, then it may need to be replaced entirely in the region where the worst corrosion is present (i.e., damaged rebar is removed and new reinforcement is then spliced into place), and the resulting structural composite response regained by placement of new concrete around the repaired reinforcement sections. Some placement of formwork is generally necessary to successfully repair such more extensive damage due to corrosion.
- Overall degradation of the concrete structural components is remedied by a similar process carried out on a much larger scale. Replacement of concrete (and underlying reinforcement, if necessary) is effected by removal of existing material and replacement with new material, including the use of formwork when necessary (and for extensive repairs, formwork is generally necessary). If this degradation has compromised the reinforcement, then replacement of steel is carried out as given above, i.e., by removal of compromised reinforcement and attachment of the new steel bars to existing material that lies outside the zone of degradation and repair.

Finally, the logical extreme for these remediation techniques is large-scale replacement of the ECM structure, either in substantial part or in its entirety. The lifecycle cost of smaller-scale repairs should always be weighed against the cost of simply replacing the structure with a new one.

Structural Analysis of ECM Structures

Several different forms of ECM structural analysis were carried out during the project, in order to determine whether such analyses could aid in predicting the response of magazines to effects such as concrete deterioration with age. Three types of analysis were performed by the project team, namely:

- a simple load-to-failure physical test on a scale model of an ECM,
- a state-of-practice reinforced concrete analysis using a nonlinear concrete model, and
- a three-dimensional soil-structure interaction model of the coupled ECM/Soil system utilizing linear-elastic material response for both components, but permitting future investigations into fully-inelastic material characterizations for both ECM structural components and for all aspects of the surrounding soil.

Theory - The primary component of an ECM structure is its vaulted roof which is diagrammed in the Figure 16. The curvature of the roof creates an arch or singly-curved shell idealization, so that membrane response of the vault can provide resistance to distributed loads. It is worth noting that when loads on a curved structure are not distributed (e.g., heavy machinery operating on top of an ECM), the resulting strength of the structure can readily be compromised.

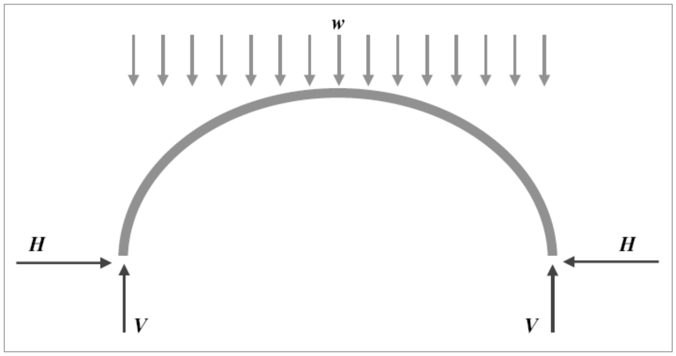

Figure 16. Vault structural idealization.

In such a structure, vertical loads (idealized as the distributed loading w in the figure above) are resisted via both bending of the vault, and coupling of the vault's bending response to its membrane (i.e., axial) resistance. If the entire loading can be carried by membrane resistance, then the shape of the vault is referred to as funicular, and this response is well established in the structural engineering profession, e.g., the funicular shape required to carry a uniformly distributed load is a parabola, and the funicular shape required to carry a uniform load as measured along the length of the member is the familiar catenary curve. Thus parabolic arches and catenary cables are commonly found in bridges and related structures. The treatment of the reactions at the supports of a curved structure is especially important.

In the figure above only the force reactions at the supports are shown (though moment reactions are always possible in monolithic structures such as ECMs). The vertical reaction V is proportional to the product of the applied load w and the span of the vault. The horizontal reaction H, which in classical structural analysis is termed a springing-line reaction, is also proportional to this product, but is inversely proportional to the depth of the vault. Thus a shallow arch shape generates large springing-line reactions, and some means of resisting these reactions must be found if the structure is to be stable. In a monolithic ECM structure, these reactions are provided both by a tensile tie between the vault walls (i.e., membrane resistance provided by the presence of the ECM floor slab), but also by soil resistance along the nearly-vertical sections of the ECM vault walls. The particular distribution of these soil pressures is difficult to deduce, since the soil's resistance to outward displacement of the vault walls is dependent on many factors, including the soil type, its degree of compaction, the flexibility of the vault wall, and whether soil has eroded away from the ECM. Thus there is considerable uncertainty inherent in structural analyses of ECMs, and this aspect of their computational simulation has led the project team to carry out several different threads of analysis so that general results can be determined for comparison to field inspection data.

Selection of Representative Structure Foundation Representation - An accurate characterization of soils used in the full variety of ECMs is beyond the scope of this project, so two specific forms of foundation response were considered in these initial structural analyses:

• a rigid foundation that provides for no lateral or vertical displacement of the base of the vault, and

• a compliant foundation where both the soil underlying the ECM and the soil that covers its top and sides can be modeled for appropriate degrees of soil flexibility and inelasticity.

The first foundation idealization is the one most commonly used in structural analyses of arched structures, while the second is feasible when a full three-dimensional finite element model of the structure can be realized. Both types are developed in the material below. For the three-dimensional fully-coupled model of ECM soil-structure interaction, the initial analyses utilized linear-elastic material models for both the ECM and the foundation soil. While these models are not entirely realistic, they do permit an initial set of material characterizations to be considered so that more refined analyses can be carried out in future research.

Earth Covering Considerations - The earth covering can be idealized either as a mere applied load, which is appropriate if zero displacement vault wall support idealizations are utilized, or as an active part of the ECM/Soil structural system is considered, if a fully-coupled finite-element analysis is deployed. For each structural analysis performed by the research team, the relevant earth covering idealization was utilized in all calculations.

Structure Characterization - The structure of the ECM is characterized by a cylindrical barrel-vault structure, and standard ECM plans were used to generate the geometry of the representative ECM. The supports of the structure are modeled either as rigid or as due to foundation response, depending on the complexity of the computer model. The deformation of the ECM structure was carried out using appropriate shell element technology, so that the essential coupling of bending and membrane response of the ECM structure could be accurately modeled. All three of the computer models were compared in qualitative terms to a scale-model physical representation of a typical ECM, in order to provide a degree of validation of the structural analysis results.

Laboratory Scale Model Testing - Based on similarities in ECM response observed at disparate inspection sites, the project team constructed a simple scale model as depicted in Figure 17 of a reinforced concrete ECM vault structure, and loaded it to failure to determine whether common forms of ECM deterioration (e.g., longitudinal cracking at the apex of the vault, and lateral cracking midsection, etc.) could be simulated using laboratory testing. The simple scale model is shown in the figure below, where it is being constructed by OU graduate student Andrew Ngheim. The scale model utilizes a reusable vault mold (so that testing results can easily be repeated) that simulates reinforced concrete ECM structures using a mortar and wire fabric composite construction. The resulting scale model structure is placed in a loading box that restrains the structure from any displacement at its springing-line supports, and loads are applied to the top of the structure until it fails.

Figure 17. Vault scale model under construction.

The scale model was based on a simple ECM design, realized at 1/20th the geometric scale. Scaling of the concrete aggregate and the steel reinforcement was realized using a rectangular wire fabric and a fine-grained concrete mortar. The geometric parameters for the ECM scale model are given in Table 4:

Table 4. ECM scale model geometry.

	Approximate (feet)	1:20 Scale (feet)	1:20 Scale (inches)
Width	25	1.25	15
Length	80	4	48
Thickness	1	0.05	0.6
Height of Wall	2	0.1	1.2
Total Height	14.5	0.725	8.7

The geometry of the scale model is shown in Figures 18 and 19. Note that the construction of this model assumes a rigid support at the headwall, so that the structural response is of a shell in single curvature.

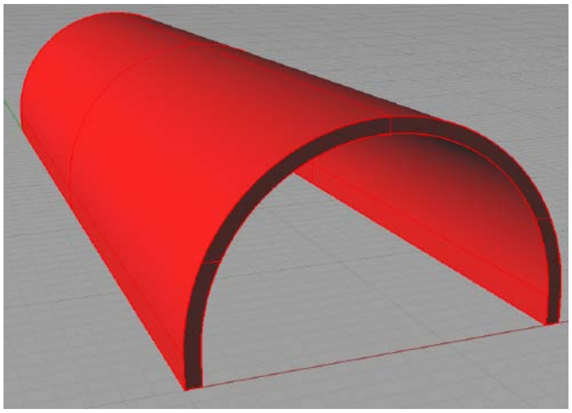

Figure 18. ECM scale model geometry end view.

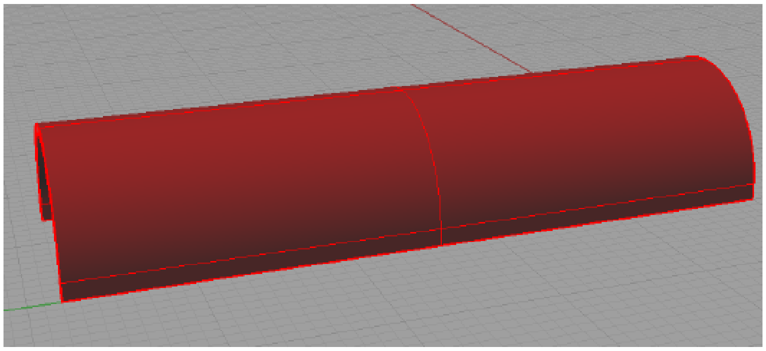

Figure 19. EC scale model geometry side view.

The model ECM used a wire fabric arranged in 1/2-inch squares composed of 19-gauge steel wire to simulate the embedded reinforcement. The mortar was approximately 1/2-inch thick, so that a wall thickness of approximately 10 inches was used for the actual ECM. The curvature of the scale model was obtained by using a 14-inch diameter PVC pipe for the mold. This provided both accurate geometry and it facilitated removal of the ECM scale model from the model. The resulting scale model is then constructed of mortar, and left to cure until the mortar has reached an appropriate strength as Figure 20 displays.

Figure 20. Finished ECM scale model.

The scale model ECM was then loaded to failure in the University of Oklahoma's Donald G. Fears Structural Engineering Laboratory, as shown in Figure 21. The model was placed in a box and covered with sand. The sand was then covered with a large steel plate to distribute the load evenly, and a load cell was applied to the top of the plate. There was a hole in the bottom of the box that allowed a camera to be placed inside the structure to monitor the structure during loading.

Figure 21. ECM scale model under loading.

Scale Model Results **-** The structure was loaded to 5,000 lbs, where cracks were observed. The load cell was increased and the structure was loaded to 11,600 lbs. At this point the structure had many cracks and a distinct crack pattern could be seen, as shown in Figure 22.

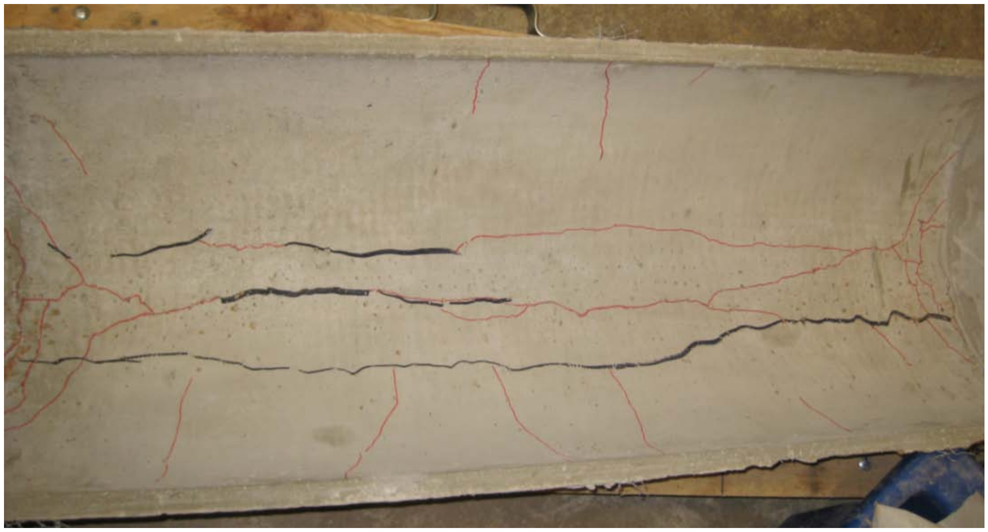

Figure 22. Cracking of ECM scale model.

The crack patterns observed in the scale model (created by vertical loading) are consistent with those observed at several inspection sites. This provides a good measure of confidence in this simple laboratory experiment in ECM response, and suggests that more refined experiments might be of considerable utility for future work on this topic. In particular, experiments that capture the actual pressure state in the earth covering would be especially useful, as this simple initial test did not determine that important loading parameter.

Finite Element Analysis - Two separate shell-based finite element analyses were carried out for the typical ECM structure, one using the reinforced concrete dynamics code Perform 3D (Computers and Structures, Inc) and one utilizing a full three-dimensional continuum finite element model (Terascale, Anatech Corp). Perform 3D represents the current state-of-practice in engineering mechanics and structural engineering venues and supports idealization of a rigid constraint at the springing lines. So this analysis most naturally compared to the laboratory scale model test.

Perform 3D Analysis – Perform 3D is a widely-used structural analysis tool optimized for transient response of reinforced concrete structures. This application was utilized by the project team to analyze a typical concrete ECM, using many of the same structural idealizations developed for the ECM scale model test, e.g., supports, headwall attachment, rigid foundation, etc. The base parameters for the Perform 3D model analysis are tabulated below.

- Length- 80’
- Width – 26.5’
- Height - 13.25’
- Longitudinal reinforcing - #5 bar at 12” on center
- Nodes – 2’ on center on radius & 4’ on center longitudinally

- Steel –
- E=29,000 ksi
- Fu= 50 ksi
- Dx = 0.4

- Concrete –
- E=3,000 ksi
- Fu = 3 ksi
- Dx=0.004

- Shear wall materials-
- G= 2,000 ksi
- Dx= 0.004

- Dead load of concrete - 112.5 psf
- Load applied at nodes downward (soil weight)
- Soil assumed to weight 120 pcf and is 2’ deep at upper most node.

The resulting nodal loading is shown in Figure 23 below.

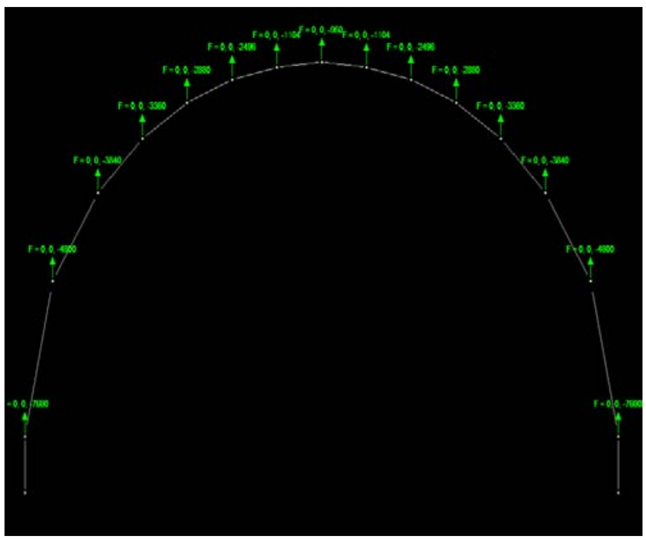

Figure 23. Soil gravity loads in Perform3D analysis.

Note that Perform3D always graphs vertical loads as upwards, so that these soil loads are actually acting downward on the underlying ECM. The initial configuration for the Perform3D model is shown in Figure 24.

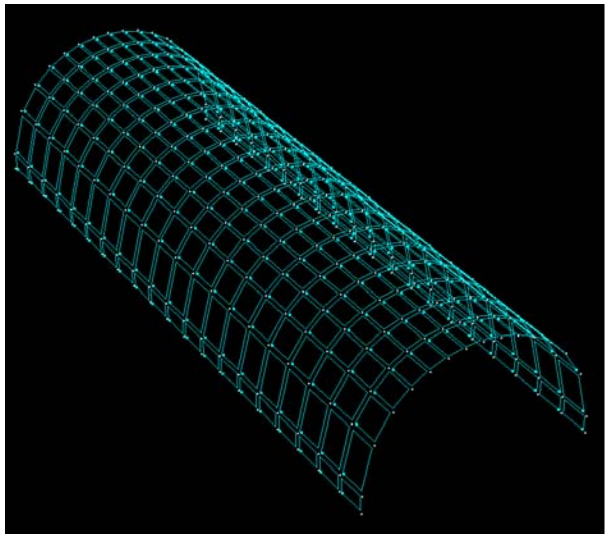

Figure 24. Undeformed configuration for Perform3D analysis.

Support conditions for the Perform3D model are shown in Figure 25. Note that displacement constraints are applied at the springing lines, and at the ends of the vault. This set of displacement constraints would overestimate the resistance of an actual ECM, since these supports are not necessarily fixed, but are instead partially constrained by the endwalls and by the soil foundation and fill materials. Some supports along the endwalls were intentionally left off to model more accurately the endwall conditions.

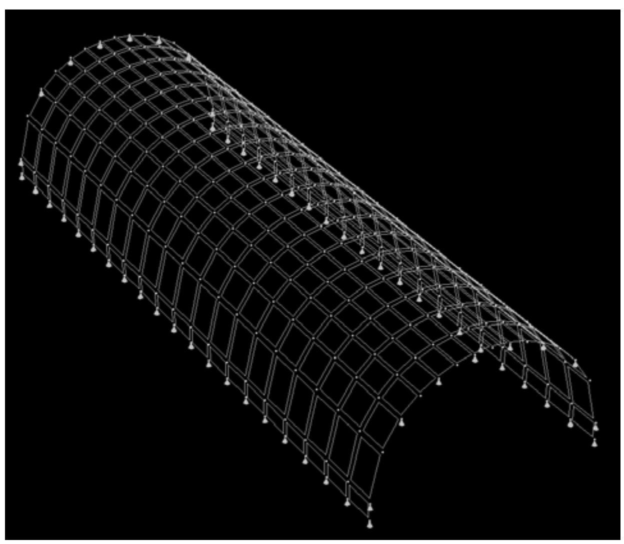

Figure 25. Support conditions for Perform3D analysis.

Perform 3D Results - Vertical loads are applied to the structure by idealizing the soil as a vertical pressure load. The resulting deformation pattern is shown in the figure below, with the resulting displacements greatly exaggerated to better demonstrate their effect. Note that the springing line supports and the endwalls constrain the displacement field, but that by neglecting the resistance of the soil fill, this analysis does not include the support provided by the passive response of the soil. Since this earth fill is an essential component of this class of magazine, this idealization forms a potentially serious limitation on the accuracy of this state-of-practice analysis approach. In Figure 26, with the endwalls providing restraint to the arch more closely resembles the deterioration observed in field surveys of ECM structures. Figure 27 below graphs the response of the vault when the displacement field for this curved structural element is detached from the resistance provided by the endwalls. In both cases, it is clear that longitudinal cracking near the apex of the vault and lateral cracks at mid-span are likely, and this structural deterioration matches what has been observed in the field.

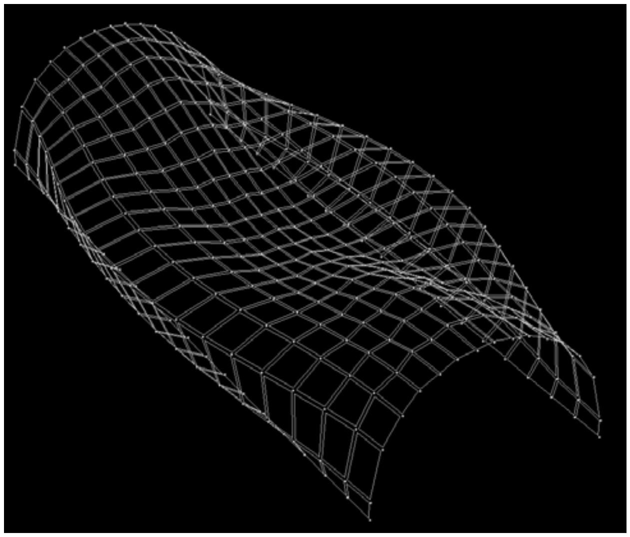

Figure 26. Displaced configuration for Perform3D analysis.

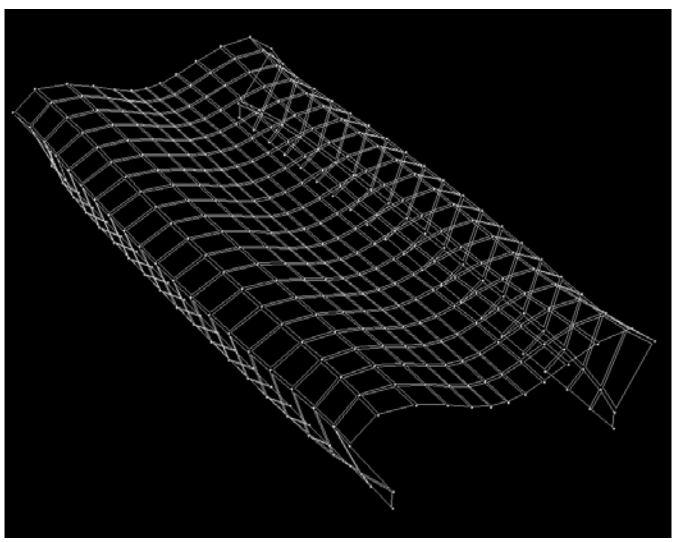

Figure 27. Alternative displaced configuration for Perform3D analysis.

Terascale Analysis - In order to better gauge the effect of ECM-soil interaction, a full three dimensional continuum finite element model has been developed for a typical ECM. The geometry of this model is shown in the following two figures, with the soil elements colored red in Figure 28, and the concrete elements colored blue in Figure 29. All of the resulting surfaces are then defined so that they can be specified, e.g., so a zero displacement condition can be applied at the bottom of the soil component to simulate a rigid underlying foundation material. Endwalls are also readily modeled, though they are not shown in Figures 28 and 29 in the interest of clarity.

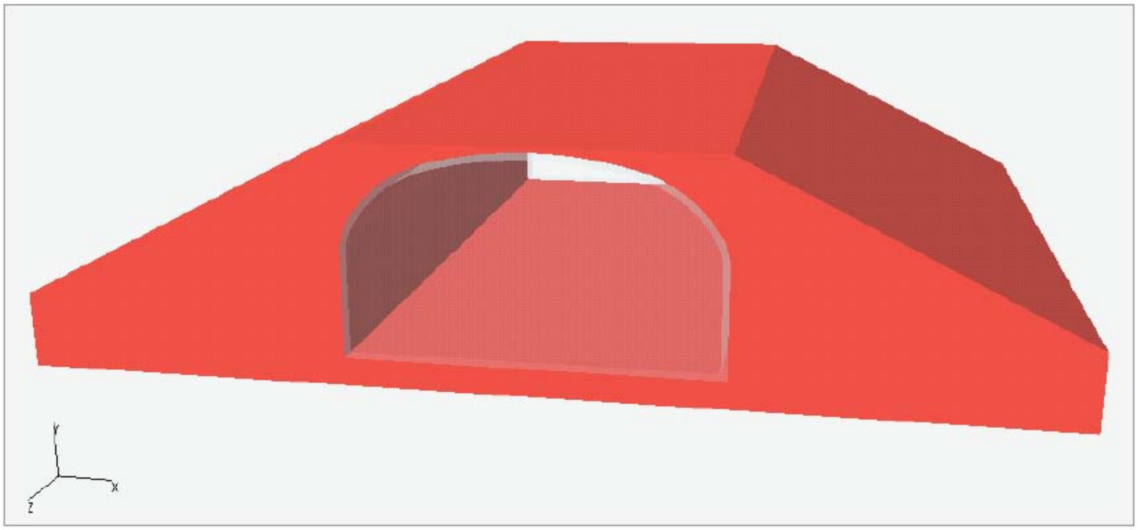

Figure 28. Soil components for fully-coupled ECM/soil analyses.

Figure 29. Concrete components for fully-coupled ECM/soil analyses.

A high-resolution 3D finite element mesh was generated using the ECM geometry, and the resulting collection of elements is shown in Figure 30. Here, the soil elements are transparent and the concrete vault elements are colored blue.

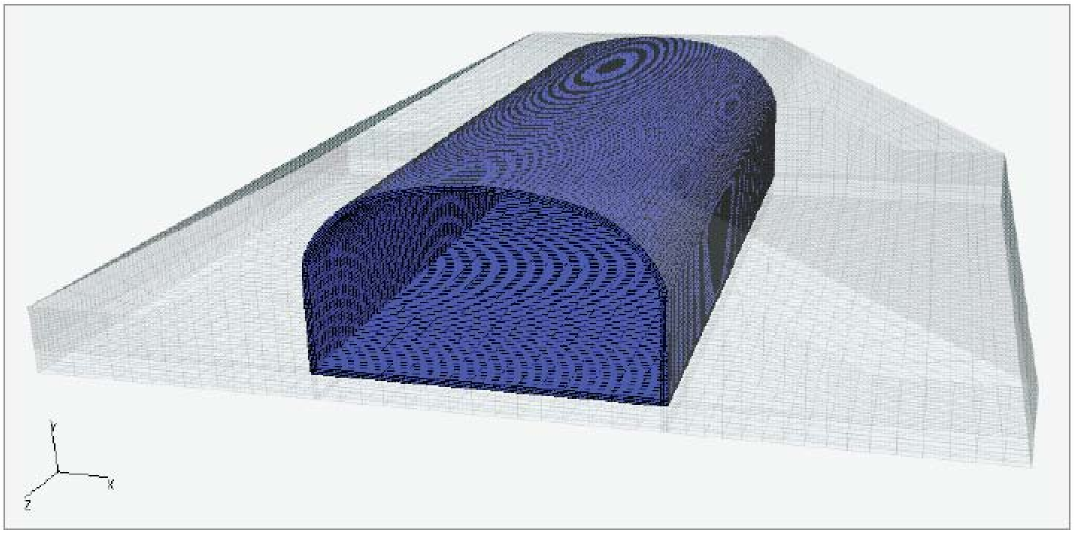

Figure 30. Front view of finite element mesh for coupled ECM/soil analyses.

For initial analysis processes, no endwalls were included in the analysis, and the effect of the endwalls was similar to that found in the Perform3D model, i.e., either a full coupling between endwall and vault could be modeled, or the vault could slide along the vertical surface representing the endwall. This latter support condition was used to generate the results shown here. In all of the analyses only self-weight of the vault/soil system is considered. This particular transient analysis code is capable of performing blast simulations for both external and internal shock loadings, but these initial structural investigations did not include such transient effects.

Terascale Results - The result shown in Figure 31 is the magnitude of the displacement field, which provides a good view of overall structural motion. In this particular example, the soil is considered to be very compliant compared to the vault structure, so that the vault floor embeds itself into the underlying soil. This bottom soil layer is in turn resting on a rigid support, so the soil exerts considerable resistance to the bottom slab of the vault component.

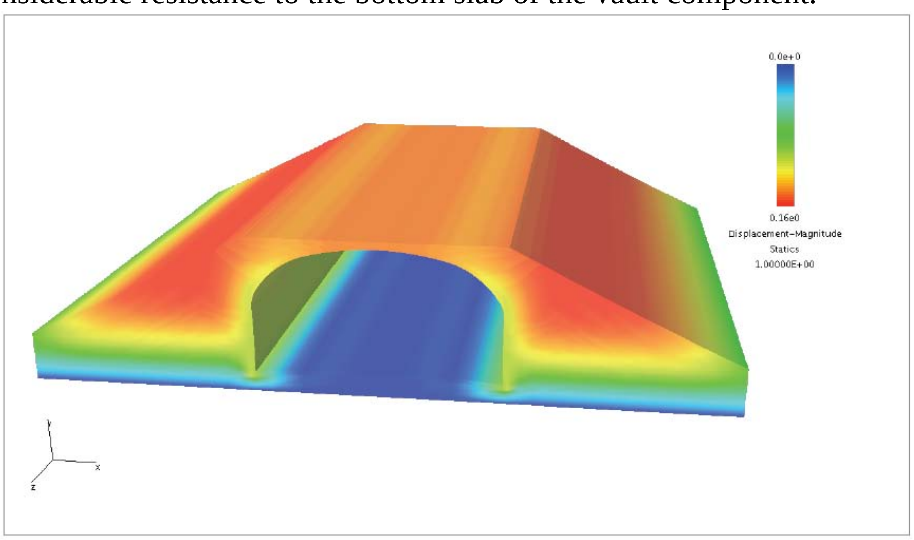

Figure 31. Self-weight displacement response for coupled ECM/soil analyses.

Next Figures 32 and 33 show the computed stresses on the vault and the surrounding soil, respectively. The first, Figure 32, shows the Mises stress on the vault component, as this scalar stress measure provides a good overall estimate of the severity of the effect of loading on the vault structure. As expected, the highest stresses are found at the spring-lines, and this result is in large part due to the embedding of the vault structure into the underlying soil. The second of these two, Figure 33, graphs the mean normal stress in the soil, so that areas of exceptional soil response can be identified.

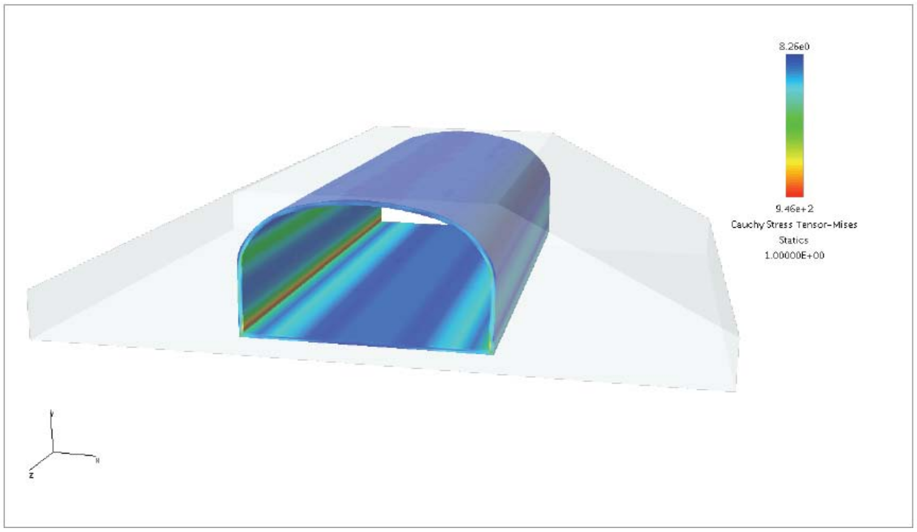

Figure 32. Self-weight vault stress response for coupled ECM/soil analyses.

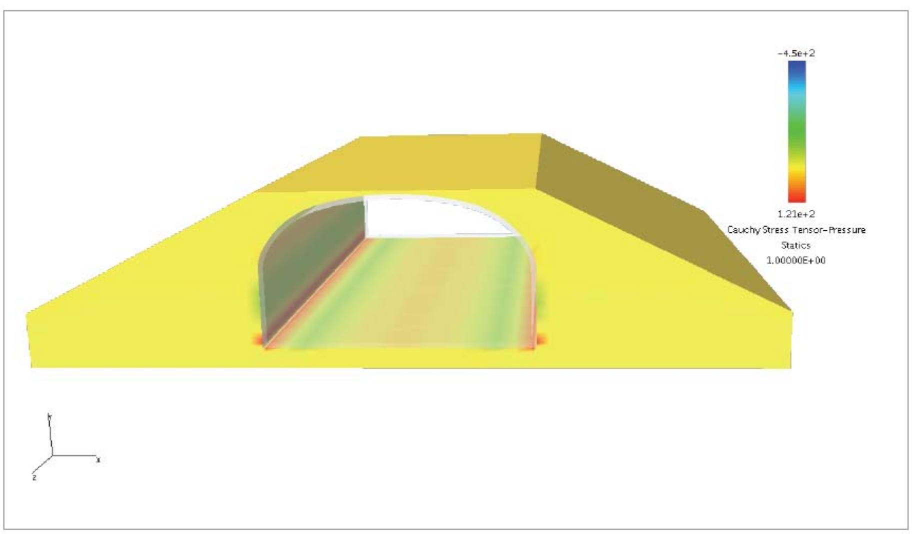

Figure 33. Self-weight soil pressure response for coupled ECM/soil analyses.

These initial results, along with related simulations performed using a range of soil compliance values, demonstrate that the behavior of ECMs is best approximated as a soil-structure-interaction problem, in that the compliance of the soil at the sides of the concrete vault is an important parameter in assessing the state of stress in the ECM structure. Further analyses are currently underway to provide a better means of gauging how much structural damage to an ECM can result from motion of the soil below, above, and to the sides of the concrete structure.

Analysis Conclusions **–** The computer models and laboratory models were able to recreate deformation patterns that resemble the crack patterns observed in the field. The laboratory model gives the best visual likeness to the longitudinal cracks seen in the field. The Terascale model (which included soil-structure interaction) verified several assumptions made by the other two models, namely that (a) the highest forces occur at the springing line reactions (this force is constrained by the foundation and the soil supporting the foundation) and (b) the highest concrete displacements generally occur at or near the apex of the arch along the length of the structure. The Perform 3D model and the laboratory scale model were both fixed rigidly at the spring-line reactions and do not allow relaxing of these reactions. Relaxing of the spring-line supports may occur and therefore an analysis with soil structure interaction such as Terascale is currently being pursued further.

Recommendations

Due to the results of site inspections, laboratory testing and structural analyses it is apparent to this team that the concern related to concrete degradation is very much warranted. The results of this initial effort establish there are ECMs in the DoD inventory that have less than desirable structural health. It is evident that analytical idealizations, and previously assumed test conditions, may not be representative of 'in place' structural conditions. Debris distances for the deteriorated state should be examined in light of current required quantity distances associated with accepted DoD exposures. Efforts to further inspect and store gathered data should be pursued in parallel with the debris study efforts. Further development of the data base should be pursued. Thus far, the inspection procedure and proposed structural health ratings have been based on the established nationally used Bridge Inspection Program, and thus further adaptation to storage magazines is needed. From lab data gathered in this initial effort, an accurate usable methodology to estimate remaining service life based on the visual inspection results should be developed. Due to limited access to some magazines, it is advisable to pursue analytically-oriented methods to predict degradation and remaining service life based on a limited visual inspection. In the short term, it is advisable to consider inspection of ammunition/explosives storage facilities in locations that pose the greatest risks to human life and property if an accidental detonation should occur.

Effects of Aging and Environmental Conditions on Ammunition/Explosives Storage Magazines – Paper 2

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34th DDESB Seminar, Portland Oregon

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US Army Corps of Engineers

BUILDING STRONG®

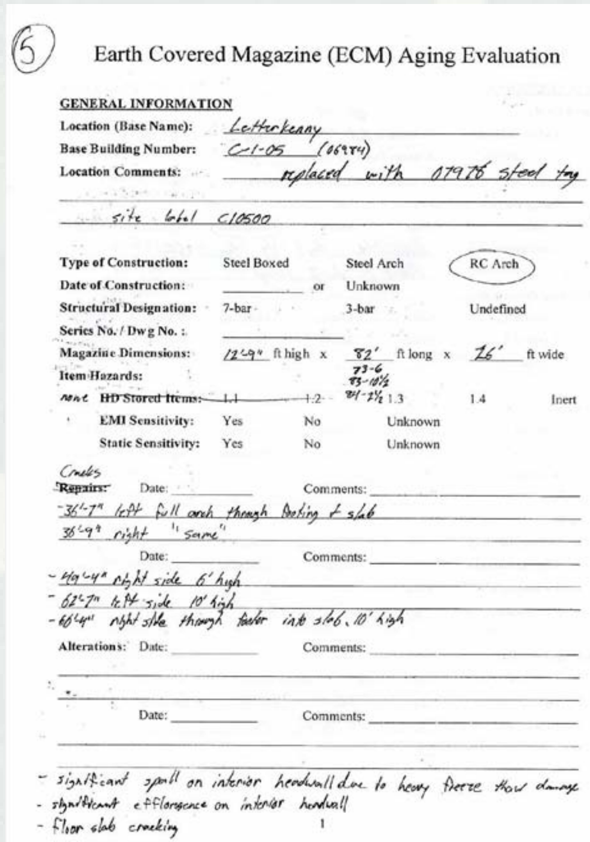
Effects of Aging on ECMs

- Background
- Field Survey
- Core Testing
- Database
- Modeling
  - Computer modeling
  - Small scale modeling

Effects of Aging on ECMs Background

- Engineering Research and Development Center (ERDC) and Oklahoma University was tasked to assess the concrete of the Earth Covered Magazines.
- ECM structures that were assessed were constructed between 1940’s and 1960’s.
- ECM structures designed service life?

Effects of Aging on ECMs Field Survey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Earth Covered Magazine (ECM) Aging Evaluation

GENERAL INFORMATION

Location (Base Name): Letterkenny

Base Building Number: C-1-05 (06984)

Location Comments: replaced with 07976 steel tag

site label C10500

Type of Construction:	Steel Boxed	Steel Arch	RC Arch (circled)
Date of Construction:	____ or	Unknown	
Structural Designation:	7-bar	3-bar	Undefined
Series No. / Dwg No.:	____		
Magazine Dimensions:	12'-9" ft high x	82' ft long x (73-6, 83-10½, 84-2½)	26' ft wide

Item Hazards:

none ~~HD Stored Items: 1.1 1.2~~ 1.3 1.4 Inert

EMI Sensitivity: Yes No Unknown

Static Sensitivity: Yes No Unknown

Cracks

~~Repairs:~~ Date: ____ Comments: ____

- 36'-7" left full arch through footing & slab
- 38'-9" right "same"

Date: ____ Comments: ____

- 49'-4" right side 6' high
- 62'-7" left side 10' high
- 66'-4" right side through footer into slab, 10' high

Alterations: Date: ____ Comments: ____

Date: ____ Comments: ____

- significant spall on interior headwall due to heavy freeze thaw damage
- significant efflorescence on interior headwall
- floor slab cracking

1

Effects of Aging on ECMs
Core Testing

- ASTM C 295, “Standard Practices for Petrographic Examination of Aggregates for Concrete.”
- ASTM C 33, “Standard Specification for Concrete Aggregates.”
- ASTM C 294, “Standard Descriptive Nomenclature for Constituents of Concrete Aggregates.”
- ASTM C 856, “Petrographic Examination of Hardened Concrete.”
- ASTM C 42, “Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete.”
- ASTM C 39, “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.”
- ASTM C 496, “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.”
- ASTM C 597, “Standard Test Method for Pulse Velocity through Concrete.”

Effects of Aging on ECMs
Core Testing

ASTM C 42, “Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete.”

Ground Penetrating Radar

Shibuya 15 amp electric coring machine.

Concrete core produced from any of the coring equipment. All cores retrieved were 4 inches diameter. The lengths varied between 9 and 11 inches.

Effects of Aging on ECMs
Laboratory Testing

Petrographic examination of all cores retrieved.

All cores were examined in accordance to ASTM C 856

Compressive Strength test (ASTM C 39).

Sierra Unconfined Compressive Strength lb/in^2	**Milan** Unconfined Compressive Strength lb/in^2	**Letterkenny** Unconfined Compressive Strength lb/in^2
3624	6000	6090
4341	5940	6422
4042	6985	5819
3092	6636	6006
3380	4563	5627
	7415	6953
	4632	6905
	6647	6451
	3923	5810
	6675	6216
		4588
		5927

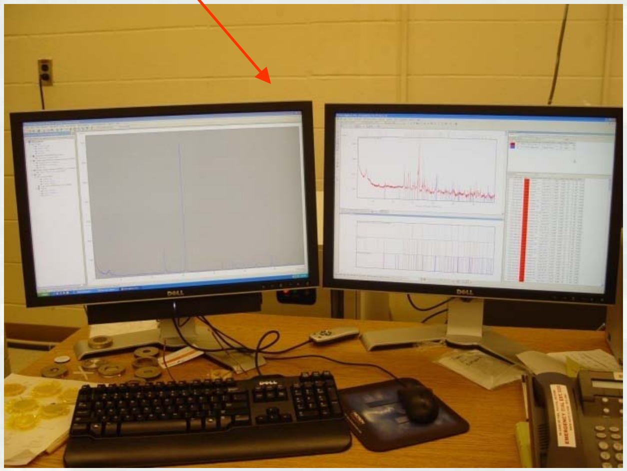
Broken specimen from Compressive Strength test.

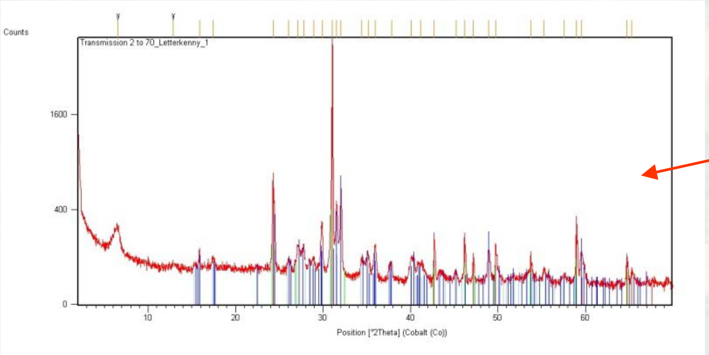
Effects of Aging on ECMs Laboratory Testing

X-Ray Diffraction test (XRD) were run to determine the concrete aggregate mineralogy

PANalytical X'Pert PRO DIFFRACTOMETER

Xpert Data Collector





XRD Analysis of sample with X’Pert Highscore Plus

Effects of Aging on ECMs Laboratory Testing

Staining test for Alkali-Silica Reaction


Freshly broken surface.

Surface after being flushed with sodium cobaltinitrite. No visible yellow stain indicates that there is no early stages of Alkali Silica Reactions (ASR) taking place

Surface after being flushed with rhodamine B. There was no visible pink staining, this indicates that there is no advanced ASR attack taking place

Effects of Aging on ECMs Laboratory Testing

Phenolphthalein Test

Freshly fractured surface.

Surface flushed with phenolphthalein. Notice the dark purple color of the area.

The dark color indicates that the PH of the concrete is above 9.5.

Effects of Aging on ECMs Laboratory Testing Results

- XRD analysis indicates that the mineralogy of the aggregates include anorthite, quartz, chert (crypotocyrstalline quartz),and microcline
- Carbonation of the samples ranged from ¾ inch to 1 ½ inch depth
- All aggregates in the cores retrieved were well consolidated. There was no evidence of segregation of the aggregates
- Compressive strengths resulted in strenghts above required minimum

Effects of Aging on ECMs Service Life

- Service life based on laboratory results
  - Average length of in service structure is 50 years
  - Assumed carbonation rate vs. actual rate
  - Carbonation front progression calculation
- Maintenance and Repair could extend service life beyond calculated service life

Effects of Aging on ECMs Database

Successfully logged in.

Facilities

NAME	DESIGNATION	ACTIONS
Letterkenny	Army Depot	Edit Destroy
Sierra	Army Depot	Edit Destroy
Red River	Army Depot	Edit Destroy
McAlester	Army Depot	Edit Destroy
Milan	Army Depot	Edit Destroy
Wheeler	Army Airfield	Edit Destroy

New facility

Effects of Aging on ECMs Database

Letterkenny (Army Depot)

Edit

Igloos

NAME	ACTIONS
B-2-07	Edit Delete
B-1-05	Edit Delete
B-3-06	Edit Delete
B-10-03	Edit Delete
B-K-01	Edit Delete
B-K-05	Edit Delete
C-1-05	Edit Delete
B-T-03	Edit Delete
C-3-07	Edit Delete
E-2-08	Edit Delete

Effects of Aging on ECMs Database

Home Audit Log Add User Edit Profile Logout (admin)

B-2-07

IGLOO	
Name:	B-2-07
LengthI:	82
LengthE:	84'-2"
Width:	26
Door Info:	Standard Hinged
Fill Info:	2
Lightning Protection:	Yes
Construction Type:	RC Arch
Structural Designation:	undefined
Pilasters:	
HEADWALL	
Shape:	
Height:	
Width:	
Thickness:	

Damages

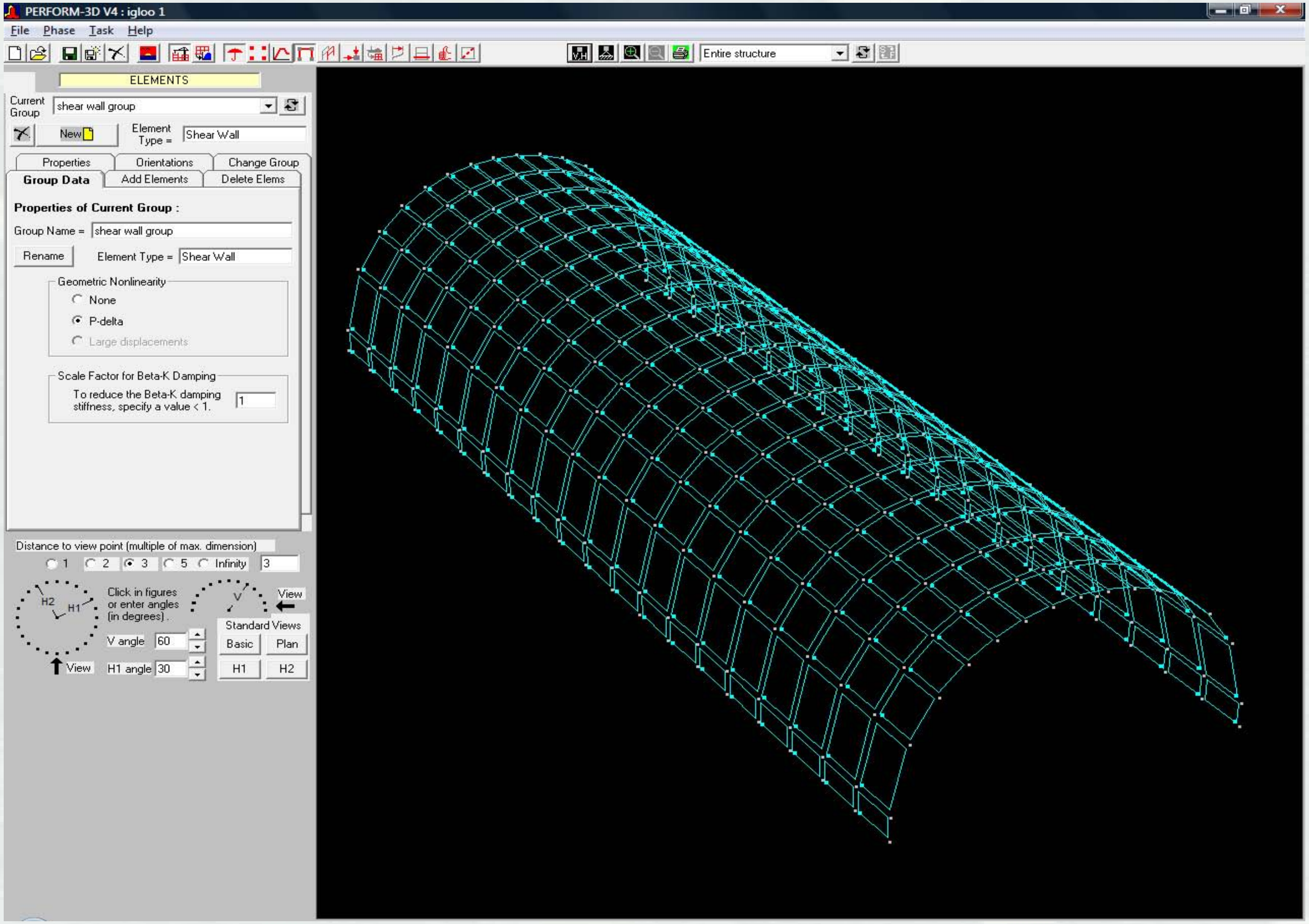
TYPE:	LOCATION:	STARTPOINT:	ENDPOINT:
honeycombing	Headwall		
Exposed cold rolled steel	Headwall		
Longitudinal Cracking	30'-2"	All the way across	
Transverse Cracking	48'-6"		
Transverse Cracking	52'-7"	Leftwall	
Transverse Cracking	59'-1"	Leftwall	
Cracking	Interior of headwall		
Longitudinal Cracking	Floor		
exposed rebar	Rearwall		
light honeycomb	Rearwall		

Edit | Back

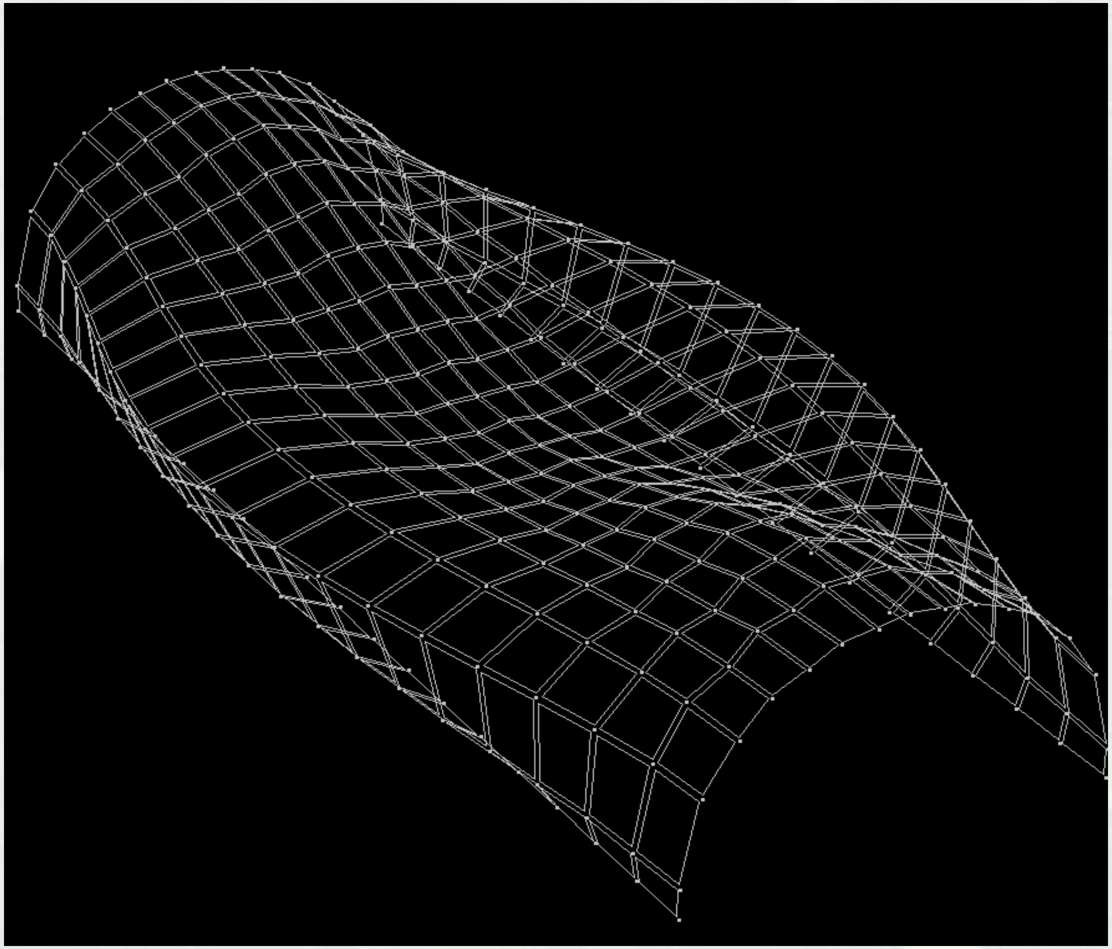
Effects of Aging on ECMs Computer Model

- Perform 3-D
  - Non-linear finite element program
  - Capable of modeling shear wall systems
- 80’ X 26.5’ X 13.25’
- Longitudinal reinforcing - #5 bar at 12” on center
- Nodes – 2’ on center on radius & 4’ on center longitudinally

Effects of Aging on ECMs
Computer Model



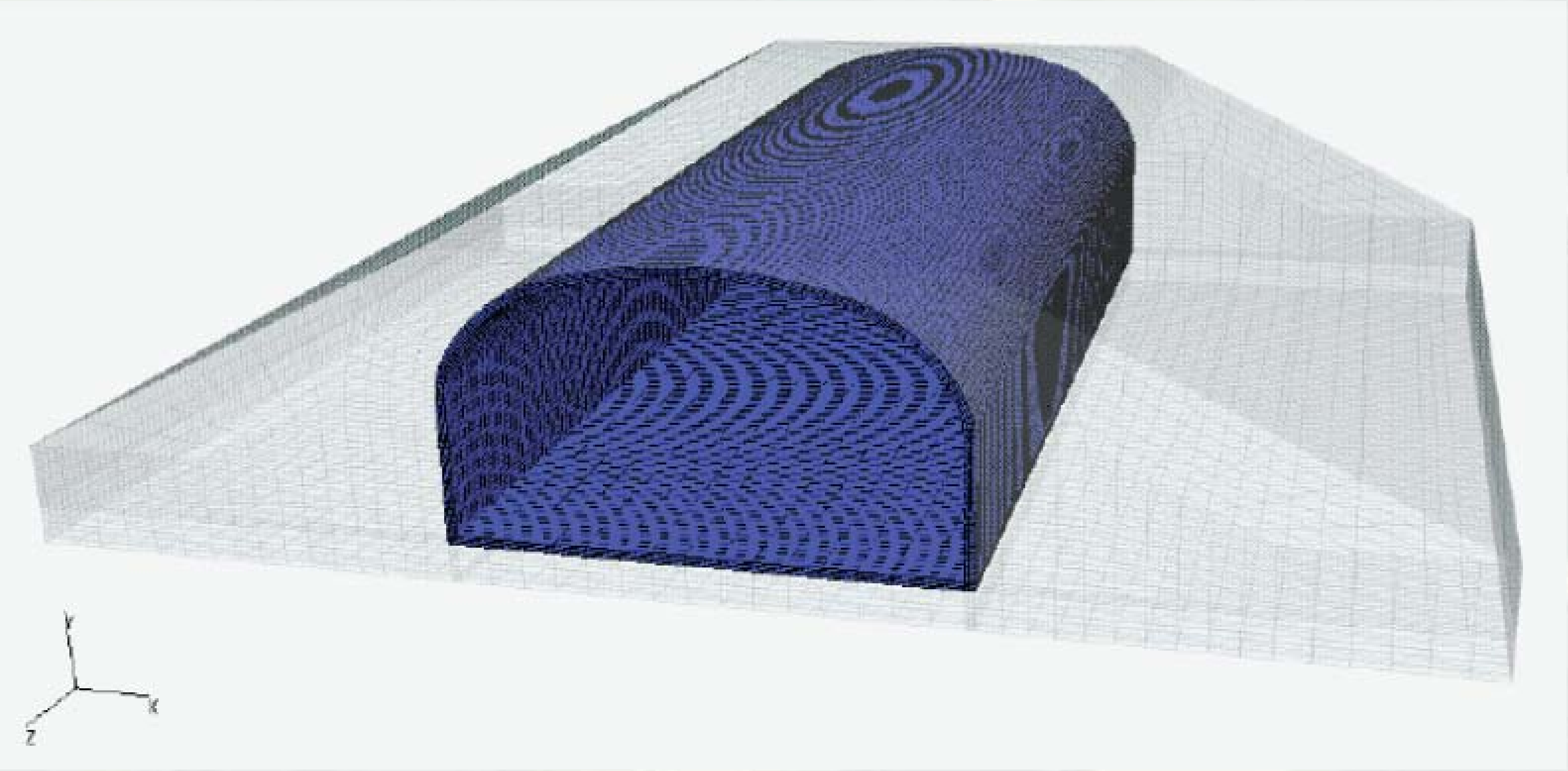
Effects of Aging on ECMs Computer Model



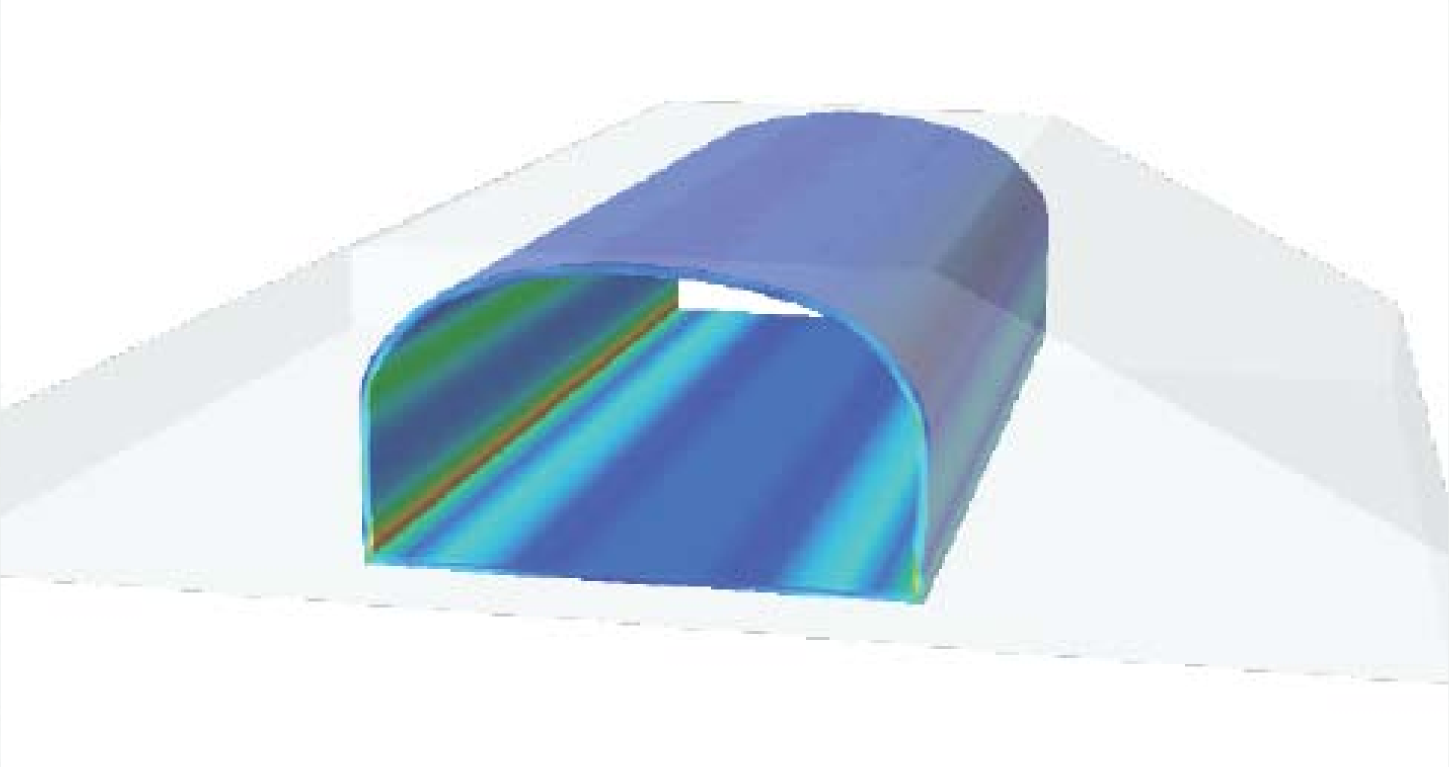
Effects of Aging on ECMs Computer Model

- Terascale software
  - 3-dimensional continuum FE analysis
  - Models ECM-soil interaction
  - Capable of static and dynamic analyses
- High-resolution 3D mesh
- Zero displacement at bottom of soil

Effects of Aging on ECMs
Computer Model



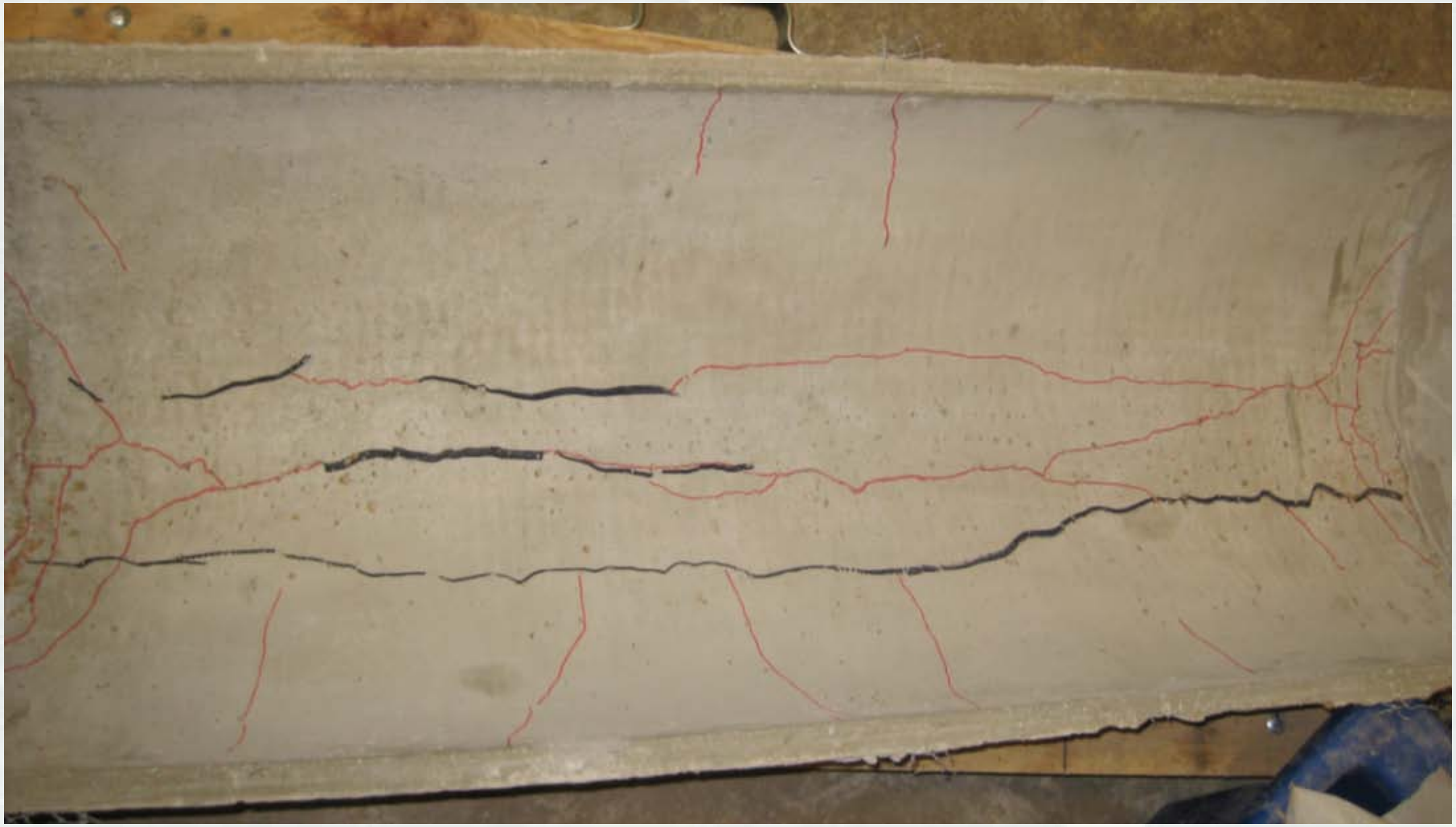
Effects of Aging on ECMs Computer Model



Effects of Aging on ECMs Scale Model

Effects of Aging on ECMs
Scale Model

Effects of Aging on ECMs
Scale Model



Effects of Aging on ECMs Structural Analysis Conclusions

- Computer and Laboratory Models recreated deformation patterns observed in the field.
- Terra Scale model verified:
  - Highest forces occur at the springing line reactions
  - Highest concrete displacement at arch apex
- Terra Scale is currently being persued further (includes soil structure interaction)

Effects of Aging on ECMs Recommendations

- Results from visual and laboratory inspection warrant the need to continue this effort
- Previously assumed testing may not be representative of “in place” structural conditions
- Debris distance for deteriorated state should be examined
- Further development of the data base should be pursued

- Current inspection process has been established based on Bridge Inspection Program thus further adaptation to storage magazines is needed
- From lab data collected a accurate usable methodology to estimate remaining service life based on visual data needs to be developed
- Limited access calls for the need to pursue analytically-oriented methods to predict degradation
- Short term consideration should be made to continuously inspect ECM's in locations that pose the greatest risk to human life

Effects of Aging on ECMs

Questions?