

DESIGN AND VALIDATION OF MODULAR, REINFORCED CONCRETE BUNKERS

Michael J. Roth, P.E.*, Thomas R. Slawson, PhD, P.E.
US Army Corps of Engineers, Engineer Research and Development Center
Vicksburg, MS, 39180

ABSTRACT

The United States Army Corps of Engineers (USACE), Engineer Research and Development Center (ERDC), has recently completed an experimental development and validation effort focused on the performance of reinforced concrete bunkers for use in Iraq and Afghanistan. The experimental work considered two similar structures – a “field-improvised” design observed to be in use in-theatre and one developed by ERDC to meet specific warfighter requirements. Three objectives directed the experimental program, and included:

1. Comparison of the protection levels provided by the two structures to determine if ERDC modifications enhanced survivability,
2. Evaluation of the effects of a high-yield blast event on the bunkers, and
3. Validation of the ERDC modified bunker’s protection levels when exposed to an array of indirect fire threats.

Research efforts conducted to achieve these objectives included numeric predictions of bunker performance, field experimentation to validate threat protection levels, and numeric simulations to determine the effects of structural modifications. Results of these research efforts are presented herein.

1. INTRODUCTION

During the time period of August/September 2003, ERDC was contacted through the USACE, TeleEngineering Operations Center (TEOC) by U.S. Army forces with a request for design of a reinforced concrete bunker. The bunker was to be constructed with materials of typical strength and quality, and should be easily transportable for movement between base camps. To facilitate transportability, maximum section weights were limited to 15,000 lb, and overall width was limited to 8 ft. The structure was required to provide protection for a minimum of 25 to 30 soldiers, and design threats ranged from light mortar to heavy artillery.¹ Dependent upon the threat considered, it was deemed acceptable to selectively place the structure above or below ground.

¹ Based on feedback received since September 2003, rockets have also been included in the threat array.

Upon receipt of the design request, available resources were reviewed for a protective structure meeting user requirements, but none were identified. Therefore, through the ERDC Survivability and Protective Structures (S&PS) program, a plan was established to develop a bunker meeting end user requirements through the utilization of available predictive methods. After providing initial feedback, a field evaluation would follow to validate the structure’s protective performance. In accordance with this plan, construction drawings were provided to the requestor at the end of September 2003, and experimental trials were conducted in July/August 2004. A picture of the ERDC developed bunker is shown in Figure 1.



Figure 1. ERDC developed bunker

During this same time period, ERDC became aware of a reinforced concrete bunker, referred to as a “SCUD bunker,” which was becoming proliferate in the theatre of operations. The bunker, shown in Figure 2, was generally constructed with reinforced concrete “c” sections and jersey barriers placed across each end. Sandbags were placed around the body of the bunker with the presumable intent of increased protection from direct and indirect fire weapons.



Figure 2. SCUD bunker

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE 00 DEC 2004	2. REPORT TYPE N/A	3. DATES COVERED -	
4. TITLE AND SUBTITLE Design And Validation Of Modular, Reinforced Concrete Bunkers		5a. CONTRACT NUMBER	
		5b. GRANT NUMBER	
		5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)		5d. PROJECT NUMBER	
		5e. TASK NUMBER	
		5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Army Corps of Engineers, Engineer Research and Development Center Vicksburg, MS, 39180		8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)	
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited			
13. SUPPLEMENTARY NOTES See also ADM001736, Proceedings for the Army Science Conference (24th) Held on 29 November - 2 December 2005 in Orlando, Florida., The original document contains color images.			
14. ABSTRACT			
15. SUBJECT TERMS			
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified	UU
			18. NUMBER OF PAGES 8
			19a. NAME OF RESPONSIBLE PERSON

From observation, it appeared that the sandbag/concrete walls would generate good protection levels from moderately sized threats, but vulnerabilities stemming from a lack of entrance shielding were a concern. Thus, based on similarities in both construction and probable use, it was determined to experimentally evaluate the “SCUD bunker” along with the ERDC developed structure. The objective of the experimental work would be to assess vulnerabilities of the structure and determine comparative protection levels between it and the ERDC structure.

This work was jointly conducted as a part of STO IV.EN.2002.03, “Protection Against Terrorist and Conventional Attacks in Contingency Environments,” and the “Basecamp Protection/Survivability Demonstration Program.”

2. BLAST EFFECTS

The geometric configuration of the ERDC developed bunker was driven by a desire to minimize line-of-fire into the entrance. Based on the resulting entrance configuration, shown in Figure 3, it was of interest to determine what impact this would also have on the migration of shock waves through the body of the bunker. Therefore, the structure was included in an arena experiment conducted at Eglin Air Force Base, FL, in which it was exposed to the blast effects of a high-yield charge simulating a vehicle borne improvised explosive device or a unitary high explosive warhead. The experimental objective was to draw a comparison between the pressure-impulse environment experienced in the free field and the pressure-impulse environment experienced inside the structure at the same standoff.

To allow for comparison between the two bunkers’ performance in the blast environment, the “SCUD bunker” was also included in the experiment at the same standoff.

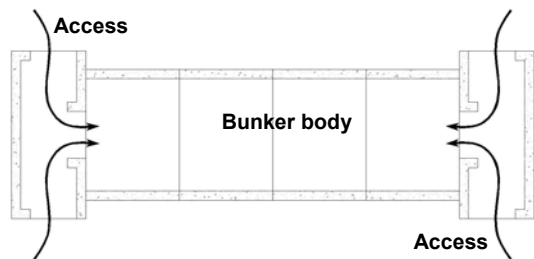


Figure 3. Entrance configuration of ERDC bunker

Prior to conducting the experiment, the code BLASTX (Britt, Ranta and Joachim, 2001) was utilized to develop preliminary predictions of the internal pressure environment for both structures. For comparison, and for the purpose of evaluating the effects of modified bunker geometry, after the experiment the ERDC bunker was re-modeled with a more rigorous hydrocode, CEBAM (Klutter and Stahl, 2004).

To evaluate worst-case conditions, the ERDC bunker was oriented with the structure’s long axis perpendicular to

the shock wave. This created the most favorable condition for shock flow into the entranceways and subsequently into the body. Likewise, the “SCUD bunker” was oriented with the long axis parallel to the shock wave to again create the most favorable conditions for flow into the structure. Orientation of the structures with respect to the charge is shown in Figure 4.

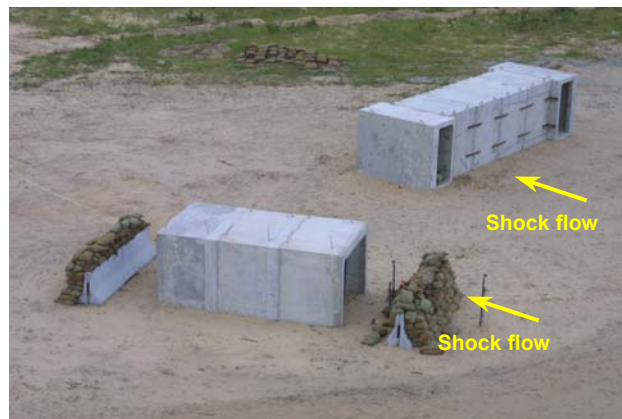


Figure 4. Bunker orientation

2.1 Pretest BLASTX predictions

BLASTX is a mid-range fidelity blast effects code that was originally developed to compute the effects of shock wave flow into, and through, buildings and rooms. In comparison to a code such as CONWEP (Hyde, 2004), BLASTX does not simply use curve-fit data and scaling to predict pressure effects at standoff, but performs ray tracing calculations and nonlinear shock additions to determine pressures due to multiple reflections and refractions from complex boundary conditions. In doing so, it is able to take into consideration blast propagation into structures with complex geometry, and was thus selected for pretest calculations.

Although BLASTX considers geometrical effects on pressure flow, its predictive capability in this scenario is limited because of the “open air” environment in which the structures exist. As noted before, BLASTX is generally designed to compute blast propagation through a series of connected rooms or spaces. Therefore, to perform the simulation the physical test environment was represented as a series of connected rooms. To do this, two large rooms were created to represent space to the front and back of the bunker. These two rooms were separated, and a smaller series of rooms were placed in between to represent the bunker itself. Openings were placed between the two large rooms and the bunker rooms such that pressures were allowed to flow out of the first large room, through the bunker, and into the second large room. This is shown schematically in Figure 5. Due to the obvious impact of this approximation on shock flow and structure engulfment, accuracy of the model predictions will be clearly influenced.

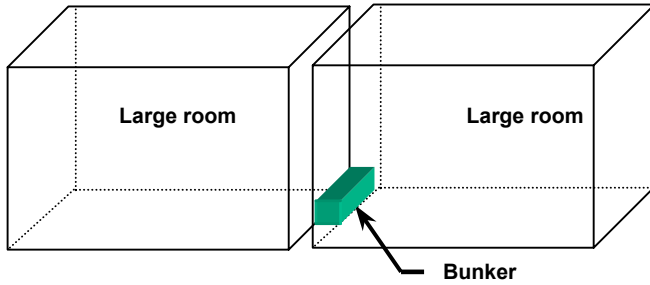


Figure 5. BLASTX model

To generate output data for comparison to experimental results, pressure-time histories were written at key locations for both structures as well as at a free field location for the same standoff. For the ERDC bunker, output was generated at the quarter point and the midpoint of the bunker body. For the “SCUD bunker,” output was generated at the midpoint of the structure only. Pressure-time histories for these locations are shown in Figure 6. Impulse-time histories are shown in Figure 7.

Due to critical technology protection requirements, all pressure and impulse data have been normalized to generate peak free field values of 10 psi and 10 psi-msec, respectively. This data manipulation does not affect the outcome of the discussion since the primary objective is to establish relative comparisons between internal/external environments and between the bunkers themselves.

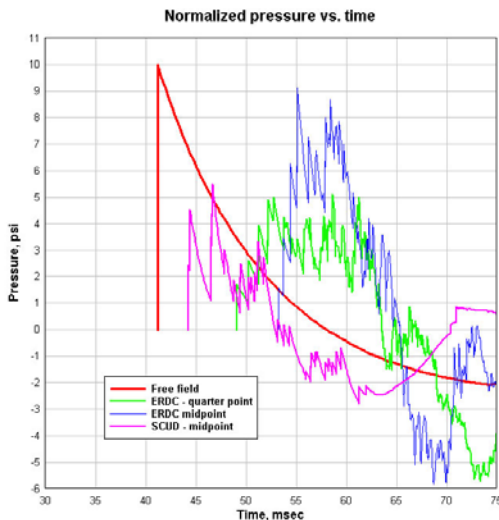


Figure 6. Normalized BLASTX pressure predictions

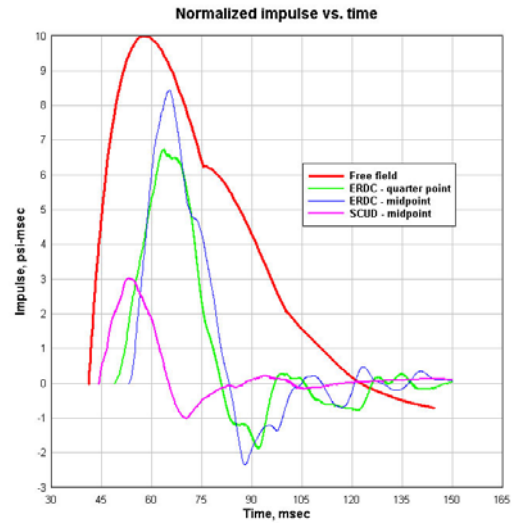


Figure 7. Normalized BLASTX impulse predictions

As seen in Figure 6, peak pressures at the quarter point of the ERDC bunker and at the midpoint of the “SCUD bunker” are predicted to be reduced by approximately 50 percent below the free field conditions. In contrast to the quarter point prediction, only a 10 percent peak pressure reduction is expected at the midpoint of the ERDC bunker. This increase in pressure at the midpoint is generated by a combination of the shock fronts propagating from each end.

From Figure 7, all locations within the structures are predicted to experience reductions in impulse. The greatest reduction is estimated in the “SCUD bunker” at 70 percent, and reduction in the ERDC bunker is estimated at between 16 percent and 33 percent. The reason for significant deviation in impulse reduction is the predicted increase in pressure duration within the ERDC bunker generated by reflections off the internal surfaces.

2.2 Field Experimentation

During the field experimentation, pressure time histories were recorded at 14 locations. Data acquisition was accomplished with Kulite XT190 pressure gages. To design the instrumentation layout for this experiment, gage orientation posed an interesting dilemma. In the free field, gages can be oriented either parallel or normal to the shock front path such that they measure incident or reflected pressures, respectively. However, in a condition where the shock waves are reflecting off multiple surfaces, as is the case inside the bunkers, there is not a clear orientation that measures either incident or reflected pressure. Rather, any gage orientation will measure a combination of both. For this reason, where possible two gages were placed at each measuring location, one placed parallel with the ground surface and one placed perpendicular. By using multiple gages in this fashion, although neither will be truly incident or reflected, a comparison can be made between the two and a general idea of the pressure environment at that location can be obtained. From the data gathered, it was found that

inside the bunker, orientation of the gage induced little variation in recorded pressure.

In the following figures, recorded pressure-time and impulse-time histories are presented. For the ERDC bunker, records are shown for a single gage at the quarter point location and for a single gage at the midpoint. For the “SCUD bunker”, a record is shown for the midpoint only. For comparison to the free field environment, a record is shown from a gage placed flush with the ground and at the same standoff as the center of the structures. As was done for the BLASTX output, pressure-time and impulse-time data are normalized to 10 psi and 10 psi-msec, respectively, for the free field gage. Pressure-time histories are shown in Figure 9, and impulse-time histories in Figure 10.

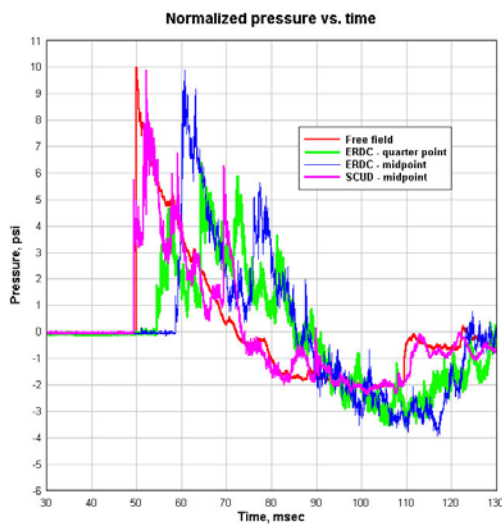


Figure 9. Normalized pressure-time history

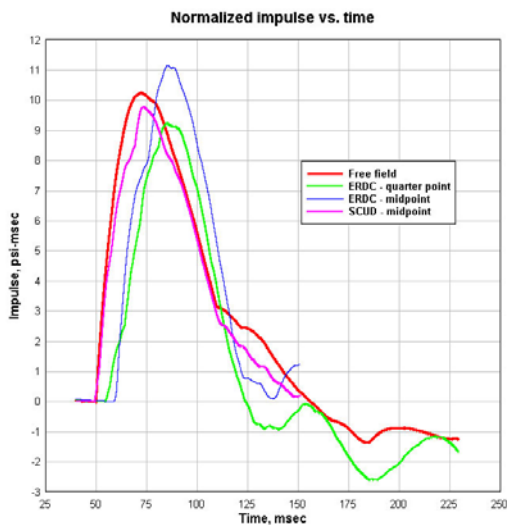


Figure 10. Normalized impulse-time history

From Figure 9, peak pressure at the quarter point of the ERDC bunker was reduced by 36 percent and peak pressure at the midpoint matched that in the free field. This is in general agreement with the trend seen in BLASTX.

However, in contrast to the BLASTX prediction, peak pressure at the midpoint of the SCUD bunker also matched that of the free field rather than being reduced by nearly 50 percent as predicted. This deviation stemmed from inaccuracies made in representing the bunker geometry within BLASTX.

From Figure 10, the computed impulse at all locations remained nearly unchanged from that of the free field. Maximum reduction was seen at the quarter point of the ERDC bunker with an 8 percent decrease, and at the midpoint of the ERDC bunker a slight increase of 10 percent was observed.

2.3 CEBAM simulation

After the field experimentation, the ERDC bunker was modeled in the hydrocode CEBAM. The objective of the modeling exercise was to determine what influence structural modifications might have on the bunker’s performance in the blast environment. The modeling effort was conducted by first simulating the physical experimentation as a means to provide comparison between the model and the recorded pressure-time histories. With the first simulation as a baseline, a second CEBAM calculation would then be made to consider modifications in the bunker geometry and the resulting effects on internal pressures.

When the CEBAM calculations were initiated, it was believed that even with a fairly coarse mesh, the code would be capable of replicating the experimental results. However, after multiple attempts at code execution it was determined that the model was not accurately simulating the shock environment impinging on the structure, and resultantly, the magnitude of peak pressures at measured locations did not correspond to the measured event. However, even though the model was not accurately predicting the pressure peaks, it did appear to be simulating shock flow through the structure with moderate accuracy. From this, it was determined that the model results could not be used for comparison of pressure magnitudes, but since these results were showing the proper pressure trends, they could still be used to evaluate the influence of structural changes. For the purpose of data presentation, the pressure records have been scaled to generate 10 psi peak pressure for the midpoint gage. Since all curves were scaled by the same factor, this did not affect the relative results.

Results from the baseline simulation are shown in Figure 11. Records are given for locations at the bunker body’s entrance, quarter point, and midpoint. Note that just as was seen in BLASTX and the experimental data, when the shock first propagated through the structure, pressures were at a reduced magnitude. But after wave coalescing at the midpoint, increased pressure conditions were generated.

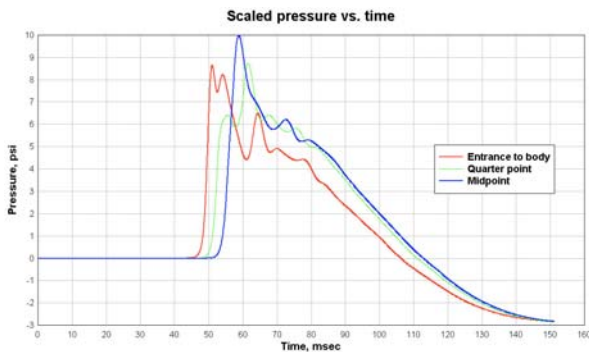


Figure 11. CEBAM baseline simulation

The factor inducing peak pressure magnification is the symmetrical orientation of the charge to the structure, and the subsequent symmetrical shock flow through the body. Although it can be argued that this condition only exists for a very small band of threat locations, it is of interest whether manipulation of the bunker geometry can alleviate even the small potential for these conditions. As an attempt to resolve this question, the bunker geometry shown in Figure 12 was modeled next. In this configuration the entrances were modified, and while still allowing ingress/egress from either end, they disrupt symmetrical propagation of the shock wave through the structure.

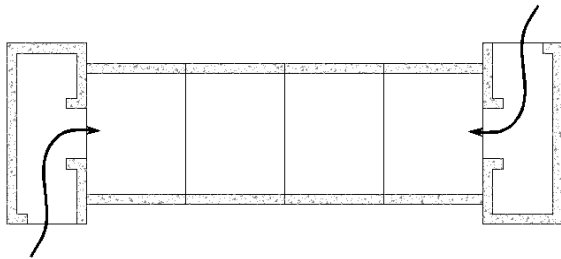


Figure 12. Modified bunker configuration

Simulation results from the modified configuration are shown in Figure 13. The curves have been scaled by the same factor as used for baseline results, and thus direct comparisons can be made between the two simulations. In contrast to the first results, the peak pressures showed a continuously decreasing trend as the wave moved toward the center of the structure. And, rather than observing an amplitude magnification at the midpoint, the gage showed a more constant low level pressure for extended duration.

From these results, it can be estimated that the alternative structural configuration did in fact disrupt the shock wave coalescence and would result in reduced internal pressures. However, since human lethality in blast environments is a function of both pressure and impulse, it cannot be conclusively stated that the changes enhanced overall survivability. But, since only peak pressure trends are being extracted from CEBAM, considerations of impulse are not being made. Therefore, to fully validate the effects of these changes the structure should be re-evaluated in a hydrocode, with true structure loading, to fully assess the effects of the modification.

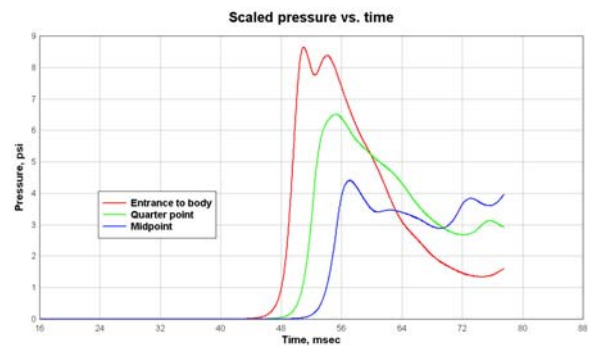


Figure 13. CEBAM simulation of modified structure

2.4 Comparison of results

One result of the research's blast assessment component is the opportunity to evaluate the validity of the predictive methods employed. Since the CEBAM calculations did not yield results which would support cross-method comparisons, only BLASTX can be evaluated for the accuracy of pre-experimental predictions. As indicated, the concern in the BLASTX calculations was the gross approximation of the experimental environment as a series of interconnected rooms. For the ERDC bunker, this approximation did not appear to significantly influence the results. From the data, pressure deviations between predicted and observed results ranged from 10 to 23 percent, and impulse deviations ranged from 17 to 27 percent. In contrast, the "SCUD bunker" deviations between predicted and observed were much greater. Predicted pressures deviated from the observed by 45 percent, and impulses deviated by nearly 70 percent. At the time the BLASTX calculations were performed, it was known that the "SCUD bunker" model was a less accurate representation of the real-world conditions, and the effect is evidenced in the model results.

From evaluation of these results, it is concluded that BLASTX can be used to simulate explosive events in the free field environment with relative accuracy, but close attention must be given to formulation of the model.

3. PROTECTION FROM INDIRECT FIRE WEAPONS

To evaluate the structures' protection levels when exposed to indirect fire weapons, two series of experiments were conducted in August 2004 at Fort Polk, LA. The experimental objective was two-fold, and included:

1. Assessment of the effect of entrance geometry on shielding of fragments generated by near-miss hits, and
2. Assessment of the ERDC bunker's response to the effects of an array of indirect fire weapons under direct hit and near miss conditions.

3.1 Entrance geometry effects on fragment intrusion

An integral component of any protective structure should be a weighted balance between closure of the entranceway to enhance protection and open access to promote rapid ingress/egress. As a part of the ERDC bunker development, these countering goals were considered and a compromised entrance configuration was developed. To accomplish the objective of fragment threat mitigation, an access path requiring a 90-degree turn was established. By eliminating a direct path into the structure, a large shielded area in front of the bunker mouth was created. To further enhance protection, small stub walls were placed along both walls of the entrance. By placing walls in this fashion, the line-of-fire into the structure was further reduced. The net result was a nearly complete elimination of direct line-of-fire into the structure's main body. To address the need of rapid ingress/egress, two entry points were provided on each end. By configuring the structure in this manner, access can be quickly gained from any direction while optimizing threat protection. In Figure 3, a schematic depiction of the entrance configuration is shown.

In contrast to the entrance configuration developed for the ERDC bunker, the jersey barriers included in the "SCUD bunker" provide only partial entryway shielding. Although these jersey barriers will provide protection from contact detonations directly in front of the structure, threat protection levels are compromised for detonations occurring at an angle to the entrance, as well as for proximity fuzed weapons. In a worst-case condition, the bunker protection level is completely eliminated for rounds landing in the space between the barrier and the bunker.

Based on the above considerations, it was determined to quantify the effect of entrance geometry on survivability level by detonating multiple fragmenting munitions at the entrance to each structure and documenting the effects. Three detonations were conducted against the "SCUD bunker" and two against the ERDC bunker. The weapon chosen for use was a light mortar. This round was selected based on availability and its representation of a typical naturally fragmenting, cased munition.

To quantify fragment intrusion into the structure, witness panels constructed from 3/8 in. plywood and 1/2 in. foam insulation were placed inside the bunkers. The panels were generally oriented transverse to the fragment flight path, and provided an indication of how many fragments entered. Fragment impacts on the witness panels were categorized as those striking the foam but not perforating the plywood, and those perforating the entire witness panel. In accordance with common convention, fragment impacts perforating the plywood were considered lethal, and all others were considered non-lethal.

As examples of the experimental setup and collected data, results from two detonations are discussed below.

Round 1

The first round was located at an angle to the entrance to simulate a near miss contact detonation. The round was placed to optimize fragment line-of-fire into the structure from this position. Post-shot observations revealed over 50 perforations of the plywood. A picture of the round location is shown in Figure 12.



Figure 12. Round 1 placed outside "SCUD bunker"

Round 2

The second round was utilized to evaluate the protection level provided by the ERDC bunker entrance. For this scenario, the weapon was placed in near direct contact with the entrance. As with the previous structure, the round was oriented to provide the most probable fragment intrusion into the structure. A moderate amount of small concrete debris was found in the witness panel, as were several small fragments. However, observations revealed no perforations of the witness panel. Since the witness panel was not perforated, the debris entering the structure was considered non-lethal. The weapon in place is shown in Figure 14.



Figure 14. Round 2 placed at entrance to ERDC bunker

3.2 Response to weapons' effects

As the second component of the weapons evaluations, the ERDC bunker was exposed to a series of statically detonated fragmenting munitions in both direct contact and near miss conditions. The bunker's response was evaluated based on resistance to fragment penetration and air blast

breaching, and where applicable, dynamic structural response. As with the blast effects experimentation, critical technology protection requirements dictate that much of the data generated not be released in this forum. For this reason, specific reference will not be made to weapon type, rather, weapons used in each test will be generically categorized. Categories used will be light, mid-range and robust threats. The complete experimental series included the detonation of eight weapons. Results from one light threat experiment and one mid-range threat experiment will be presented.

Foam/plywood witness panels (of the same construction as used in the fragment intrusion experiments) were used to document fragment perforation of the structure as well as to provide an indicator of shock wave induced concrete spall hazards. Also, internally mounted digital video cameras (30 frames per second) were used to provide an indicator of the threat posed to occupants. The cameras were able to provide information regarding how much of the post-test debris was high-velocity spall and how much was low velocity/low hazard ejecta. To provide a measure of dynamic structural response, permanent deformation of the walls or roof was measured by passive means.

Round 1

Round 1 was categorized as a light indirect fire weapon, and was statically detonated in direct contact with the bunker's roof. Based on the weapon's net explosive weight, structural failure of the roof under the impulsive load was not of concern. Therefore, the experiment's focus was to determine the capability of the concrete section to mitigate fragment perforation and back face spall.

To provide a prediction of the concrete section's performance, the USACE code CONWEP was used. From CONWEP, using the as-constructed material strength no fragment perforation was predicted. Furthermore, the concrete section required to eliminate back face spall was estimated to be 88 percent of that provided.

From post detonation observations, the weapon induced an approximate 26 in. diameter spall on the back face that extended to a depth of approximately 62 percent of the section thickness. Little damage was evident on the top of the roof in the area directly beneath the weapon. Based on the condition of the interior witness panel and information from the internal video, only a small portion of the spall appeared to have been ejected at high velocity. The remainder seemed to fall as a residual effect of the material ejected by the shock wave. From these observations, the hazard posed to occupants was deemed to be low. The internal spall surface is shown in Figure 15.



Figure 15. Internal spall surface from Round 1

As seen, there was an obvious discrepancy between the results of CONWEP and the observed performance. The cause is not known, but several contributing factors may be considered. Upon review of the spall zone, at the apex a foreign concrete object (such as a concrete brick) was observed to have been cast into the roof, creating a discontinuity in the structure. This may have weakened the roof at that location adequately enough to allow spalling to occur. Another factor may have been the spacing of the reinforcing steel. Tighter spacing reduces spall potential, and the spacing used may have been slightly larger than that assumed in CONWEP. Although the factors above may have affected performance, ultimately, shock wave induced spall is a complex phenomenon influenced by any number of variables. Thus, the generalized prediction that should have been taken from CONWEP – that the concrete section was on the border of the thickness required to prevent spall – was correct.

Round 2

Round 2 was categorized as a mid-range indirect fire weapon. Because of the results observed from Round 1, as well as predictions of dynamic response, it was determined that the structure would not acceptably survive a direct hit from the weapon without modification. Therefore, sandbags were placed on the roof and the weapon was statically detonated on top of them.

The sandbags were placed with a two-fold intent. First, from previous arena experiments it was believed that the sandbags would provide an adequate shielding layer to prevent fragments from impacting the roof section. Second, the addition of sandbags would improve the roof's dynamic response by attenuating the shock wave and adding inertial resistance.

Prior to conduct of the experiment, a simple single degree of freedom (SDOF) model was used to predict the roof section's response to the dynamic load. The USACE code WAC was used, and the estimated permanent deformation was approximately 1.5 in.

From posttest observations, the weapon induced significant damage to the sandbag layer. However, no fragmentation damage was sustained in the concrete roof. Based on the roof's deformed shape and the crack patterns, it appeared to have failed in flexure and maintained a ductile failure mode throughout the response. Although the roof appeared to fail in flexure, it was not the same response (or rather the same loading) that was estimated in the SDOF model. Because of inherent simplicities included in an SDOF model, the loading was assumed to be uniform over the roof section and the failure mode was assumed to be a simple 3-hinged flexural failure. From the crack pattern, it is seen that the failure was flexural, but the loading was much more localized and induced a more spider web pattern. However, in this case the SDOF model did still closely predict the observed permanent deformation of 1.25 in. The roof damage inside the structure is shown in Figure 16.



Figure 16. Internal damage from Round 2

Based on the observations of bunker performance, by augmenting the structure with the appropriate soil cover or sand bag layers, a direct hit from this mid-range threat weapon should be expected to induce moderate structural damage and pose a low hazard to occupants. At greater levels of soil cover, the potential for structural damage could be reduced.

CONCLUSIONS

This experimental series was conducted to evaluate the performance of two concrete bunkers against an array of threats. One of the bunkers was observed to be proliferating in the current theatre of operations and one was developed in response to a TEOC request. To fully evaluate the bunkers' performance, a threat matrix was identified that included an array of weapons, among which were high-yield blast threats such as car bombs, near miss detonations of conventional fragmenting weapons, and direct hits of moderate to large mortars and rockets. The experiments were designed for two main objectives, which included: 1) comparison of the protection levels provided by the bunkers, and 2) evaluation

of the ERDC bunker's response to various indirect fire weapons.

In general, both the blast environment and the fragmenting weapons evaluations showed the ERDC bunker provided higher levels of occupant protection. Concerning exposure to a large blast event, with the exception of the pressure spike at the center of the structure, the ERDC bunker experienced a reduction in pressure over that seen in the free field. Because of internal shock wave reflections, impulse inside the bunker was not reduced. But with a reduction in peak pressure and constant impulse, the survivability level inside the bunker was increased over free field conditions. Furthermore, based on the implications of the CEBAM calculations, with slight modifications to the entrance configuration, the conditions that generated the midpoint pressure spike could be disrupted, and the survivability level would be further enhanced. In contrast, the "SCUD bunker" did not see a decrease in internal pressure or impulse, and thus did not provide an improvement over free field conditions. Likewise, for the near miss fragmenting weapon evaluations, multiple impact zones were identified which generated a significant hazard to occupants of the "SCUD bunker". However, even in the worst-case scenario, the ERDC bunker geometry eliminated a direct fragment flight path into the structure and reduced internal hazards to non-lethal fragments and secondary debris.

Concerning the ERDC bunker's response to indirect fire weapons, through experimentation, threshold survivability levels were identified for an array of threats ranging from light mortars to heavy artillery. Although the results cannot be presented in this forum, the general outcome was a determination of the necessary soil cover that must be added to the structure to prevent breaching and global structural damage.

ACKNOWLEDGEMENTS & DISTRIBUTION

Permission to publish by Director, Geotechnical and Structures Laboratory is gratefully acknowledged. Information in this paper is approved for unlimited distribution.

REFERENCES

- Britt, J. Robert, Ranta, Dale E., and Joachim, Charles E. (2001). "BlastX Code Version 4.2, User's Manual," Technical Report ERDC/GSL TR-01-2, U.S. Army Engineer Research and Development Center, Vicksburg, MS.
- Clutter, J. K., and Stahl, Michael. (2004). "Hydrocode simulations of air and water shocks for facility vulnerability assessments," *Journal of Hazardous Materials* 106A, 9-24.
- Hyde, David W. (2004). "ConWep Version 2.1.0.0," U.S. Army Engineer Research and Development Center, Vicksburg, MS.