

BLAST-RETROFIT WALL SYSTEMS USING COLD-FORMED STEEL STUDS

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ABSTRACT

Blast-retrofit of in-fill wall systems such as steel-stud walls is of current interest to the engineering community and government agencies. To be able to develop and advance blast-retrofit technologies, it is crucial first to be able to develop prediction methodologies and engineering design tools. Therefore, this paper will present the analytical modeling and experimental evaluation of steel-stud wall systems under blast loads. The results of the static full-scale wall tests as well as the component tests are used to evaluate the structural performance of the walls and provide recommendations for blast-retrofit systems. The analytical and experimental results are used to develop the static resistance function for the wall systems, which is incorporated into a single degree of freedom (SDOF) dynamic model. The SDOF dynamic model of the walls will enable designers to predict the level of performance of the wall system under any explosion threat level. Such information is very valuable to engineers designing for explosion protection. The paper will discuss the performance of the blast-retrofit wall systems under static and dynamic field tests.

Keywords: Explosion, in-fill wall, cold-formed steel stud, blast-resistant, design

INTRODUCTION

Much research has been done, and continued research efforts are being made to improve the safety of infrastructure against natural hazards. Few research efforts have been made to mitigate the impact of manmade hazards, such as explosion on the civilian infrastructure that are most vulnerable to terrorist attacks. The recent rise in the incidence of terrorist bombings of high

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Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE 2003		2. REPORT TYPE		3. DATES COVERED 00-00-2003 to 00-00-2003	
4. TITLE AND SUBTITLE Blast-Retrofit Wall Systems Using Cold-Formed Steel Studs				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) Research Civil Engineer, US Army 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 16th ASCE Engineering Mechanics Conference Jul 16-18, 2003, University of Washington, Seattle					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	unclassified	unclassified	Same as Report (SAR)	12	

profile buildings has led to increased fervor in the development of a variety of blast resistant construction systems, which may be applied to the exterior walls of buildings. Many commercial buildings today are constructed using reinforced concrete or steel frames with in-fill wall systems. The in-fill systems currently constructed are designed to resist only natural loads such as wind, and to some extent, earthquake loads. For these infill wall systems, the design criterion is specified by a midpoint deflection limit within the elastic response (AISI 1996).

Steel stud members have the desired combination of strength and ductility for blast resistance. The steel stud walls can be constructed as retrofit walls placed inside existing exterior walls, or as exterior infill or curtain walls used in new construction. To design blast-resistant walls using steel studs, it is necessary to ensure a ductile wall performance under large deformations due to blast loads. Ductile performance requires that selected ductile components yield, but continue to carry loads and absorb energy through significant plastic response. Thus, the potential failure modes of the connections must be prevented.

In this paper, the research effort to prevent anchorage failure is presented first followed by the full-scale wall and component static tests to arrive at the static resistance function. The analytical prediction and design method is then briefly summarized. The dynamic field test to validate the analytical model and design procedure is presented followed by a summary and future recommendations.

ANCHORAGE DESIGN

Researchers at the U.S. State Department, U.S. Army Corps of Engineers, U.S. Air Force Research Laboratory, and at the University of Missouri have been collaborating recently to develop a design method to predict the response of fully-anchored steel stud walls exposed to blast loads.

The original concept for anchoring these steel studs involved cutting the flanges of the steel stud approximately 6" from the end of the stud, and then bending the stud at the web to form a "foot" at the top and bottom of the stud. A hole was then punched in this foot to allow anchor bolting of the stud to the floor and ceiling slab (Figure 1). The bolt holes into the slab were staggered to prevent failure of the slab due to a tension crack joining the holes in the concrete, resulting in failure of the anchoring system, as occurred in an earlier experiment.



FIG. 1. (a) Connection detail using clipped flanges and bent web; (b) failure mode

This method was used successfully in a full-scale dynamic experiment, EWRP-2 and described in US State Department Technical Information Bulletin (DOS, 2001) and by Wesevich (2001). However this method does not significantly increase the connection capacity from that of the conventional two-screw method, since the capacity of the connection is limited by the tension required to either fail the stud web in shear (a very localized failure), or failure by the foot pulling over the anchor nut or washer in bearing failure (Figure 1b).

The key to utilizing steel studs in blast resistant systems is designing the steel stud connection so that the connection does not fail but the stud itself fails due to yielding of the steel stud cross section in tension, and eventual failure due to strain elongation limits at the section, which has yielded. The ductile behavior allows for significant energy absorption during plastic elongation of the steel stud, while limiting the reaction forces required at the steel stud connections to the floor and ceiling. The initial study conducted by researchers at the University of Missouri–Columbia, and the U.S. Army Engineer Research and Development Center, ERDC focused on the development of an anchoring system to attach the steel stud to floor or ceiling slab in order to develop the full tensile capacity of the cross section of the steel stud (Muller 2002). Conventional steel stud anchoring consists of attachment of the steel stud to a steel track using two (or in some cases, four) self-tapping screws. These screw connections are insufficient in developing the full tension capacity of the steel studs (Roth 2002). The approach to designing the required anchorage involved static analyses and laboratory testing so that the connection capacity exceeds the tensile yield capacity of the stud.



FIG. 2. Steel stud specimen loaded in tension; note six bolts were required to yield the steel stud cross-section

The concept chosen for development uses a steel angle slightly narrower than the web width of the stud, with the vertical leg of the angle attached to the web of the stud, and an anchor bolt through a pass hole in the horizontal leg of the angle anchored into the floor and ceiling. This

angled connection was designed to prevent connection failure in a variety of modes:

1. Shear failure of the angle-to-stud connecting bolts
2. Tension failure of the angle/stud in cross-section
3. Block shear between bolt holes in steel stud
4. Bearing failure in steel stud directly below bolt holes

Static tension experiments were conducted to verify the number and size of bolts required at the connection of the angle to the studs (Shull 2002). Calculations determined that six bolts were required to cause the steel stud to yield in cross-section, as shown in Figure 2.

The next objective was to determine the required combination of anchor washers or material thickness of the angle connector to prevent pullover of the anchor bolt that will be used to attach the steel angle to the concrete floor or ceiling slab. This was determined experimentally using a tension-loading machine with various combinations of angle steel thicknesses, washer sizes and thicknesses. The loading geometry for these experiments provided a more extreme loading condition than the actual blast loaded stud wall, but this experimental method would provide a conservative design. After several iterations of these parameters, 1/2"-thick steel angle was chosen as the best candidate to prevent pullover of the anchor bolt as shown in Figure 3. The anchor bolt connection into the slab was designed according to the CCD anchor design methodology as described in the ACI 318-02, Appendix D (2002) using appropriate factors for anchor spacing and edge effects.



FIG. 3. Stud-to-floor anchorage using a 1/2"-thick steel angle

Once the connection details were determined and tested, the next step was to determine the load versus deflection response of a transversely loaded steel stud wall, which can be used for dynamic modeling. One approach involved loading the stud or a stud pair via a "loading tree" that distributed the load from hydraulic actuators to sixteen equally spaced points on the stud. The static experimental program to develop the resistance function is summarized next.

STATIC RESISTANCE FUNCTION

To be able to conduct dynamic modeling and arrive at engineering design tools for blast loads, it is necessary to first develop the load-deflection response of the wall under uniform

pressure: static resistance function. The performance of the steel stud wall depends, among other things, on the response of the individual stud components that make-up the wall. The elastic as well as the plastic response of the steel studs to failure is obtained through static full-scale component and wall tests. The experimental setup described here is for blast-retrofit wall systems, in which the connections are sufficiently designed to utilize the studs' full strength and ductility by ensuring failure to occur in the studs, as discussed in the previous section.

The component tests are conducted by loading a stud or a stud pair via a “loading tree” that distributed the load from hydraulic actuators to sixteen equally spaced points on the stud (Figure 4). Note the wooden blocks used as bearing stiffeners at the loading points to prevent local buckling, and the vertical steel guides which prevented torsional buckling of the section. The load and deflection response to failure is recorded, and equilibrium is then used to calculate an “equivalent” pressure per unit width. Another device that was used to obtain a static resistance function on a full-scale wall section is the static uniform resistance chamber located and operated by the University of Missouri–Columbia. This device is capable of applying a uniform load to a 12' by 10' wall section using a vacuum pump (Figure 5). A typical response of a steel stud component test and a wall test are shown in Figure 6.



FIG. 4. Loading tree component test Setup

The analytical model shown in Figure 6 is divided into three regions: (1) linear elastic region until yield-buckling (Yu 2000); (2) post buckling softening region; (3) tension membrane region. From experiments, it is observed that in some instances the studs experience a “softening” region after yield-buckling and before going into the tension membrane region. For example, the stud shown in Figure 6 did not experience a softening region. In other instances, the studs could go into tension membrane after a well-defined softening region after the yield-buckling is achieved. The shape of buckling at the stud mid-span might control such responses. Therefore, the analytical predictions are developed to give a “low-end (LE)” and a “high-end (HE)” resistance function to completely represent both possible behaviors (Lane 2003).

The analytical static resistance function was used along with a single degree of freedom (SDOF) model to develop a wall analysis code (SSWAC 2.3) for the dynamic modeling of steel stud walls under blast loads. The code was used to design two stud wall systems, and their response was verified in the field using live explosives. In the following section, the results of the dynamic field testing are presented.



FIG. 5. Typical stud-wall test setup: (a) wall before test; (b) wall after test – studs developed full capacity signified by the rupture of a stud at the middle section

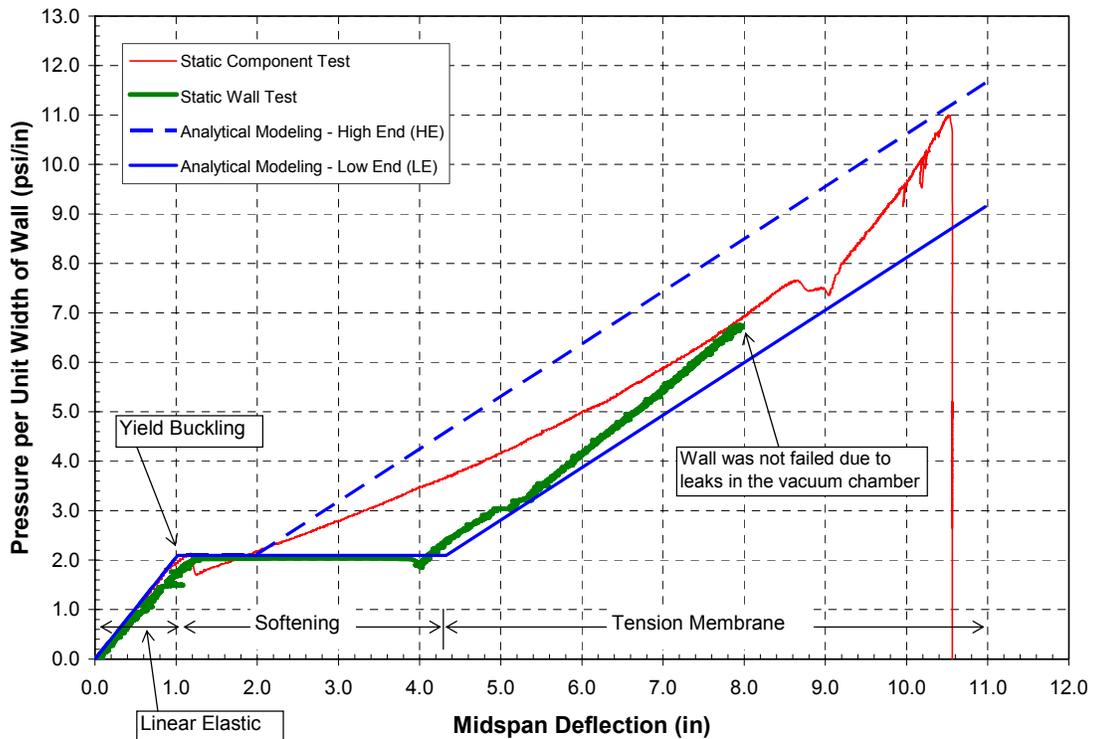


FIG. 6. Typical static resistance function of steel stud wall and component systems

FULL-SCALE DYNAMIC VERIFICATION

The results of the static experiments were used to develop a resistance function defining the uniform load versus deflection behavior of the steel studs as discussed in the previous section. The resistance function for the steel studs used in the dynamic field test is shown in Figure 7.

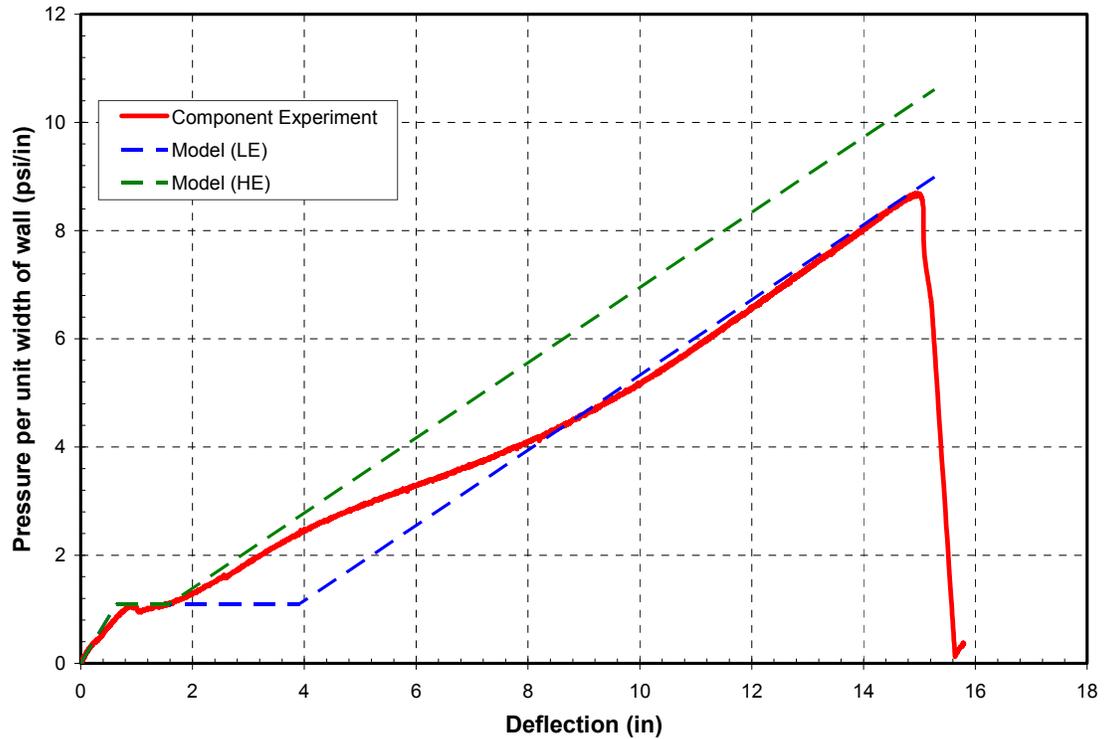


FIG. 7. Static resistance function for steel stud used in the dynamic field tests



FIG. 8. Connection detail at top of stud showing attachment to embedded steel plate

This resistance function was then used in a single degree of freedom model to predict the behavior of the wall system when subjected to blast loads. As part of the Blast Response of Exterior Walls (BREW) research program, a full-scale blast experiment (BREW-1) was conducted at the Air Force Research Laboratory range at Tyndall AFB. The purpose of the experiment was to validate the performance of the anchor systems in developing the full tensile capacity of the studs, to demonstrate the contribution of the mass to the wall response, and to compare the results of the experimental data to the preliminary model. Two steel stud walls with blast-design connections were tested. The steel stud walls consisted of 600S162-43 studs (AISI 1996), with a specified yield strength of 33ksi, with single studs spaced 16" apart. The walls were approximately 144" tall, and were attached at the bottom to a reinforced concrete slab using concrete anchors, and at the top to a steel plate (representing either a steel beam, or an embedded steel plate in concrete) using a steel angle welded to the plate, and a hole in the vertical leg of the angle to allow for a hinged connection (Figure 8). One wall contained a brick façade consisting of 7-9/16" Wide x 2-3/16" Tall x 3-1/2" Deep clay bricks with an area density of 30.5 lb/ft². The façade of the other steel stud wall consisted of a typical External Insulation and Finish System (EIFS) exterior with an area density of approximately 1.5 lb/ft². The exterior side of the studs was sheathed with 16-gauge sheet steel, and the interior studs were sheathed with a product consisting of 1/4" gypsum board glued to 20 gauge steel sheets to provide a finished interior surface while preventing secondary fragmentation from the gypsum board (Figure 9).



FIG. 9. Pretest exterior photo of BREW-1 structure showing EIFS and brick façade on steel stud walls anchored using blast-resistant connection design; walls during construction (left)

The walls were subjected to a blast loading with 33-psi peak reflected pressure and 200 psi-msec peak reflected impulse as shown in Figure 10. The post-test photos shown in Figure 11 and the deflection measurements shown in Figure 12 demonstrate the dramatic difference in wall response resulting from the inertial effects of the mass of the wall. The deflection measurement at the center of the steel stud wall with the brick façade indicated a peak inward deflection of 6.8 inches, with a residual deflection of 5.2 inches. The preliminary model predicted that the wall

would survive and predicted a peak center deflection of approximately 11 inches. Note that the current model considers only the mass of the façade, and does not yet include any increased resistance provided by the bricks. The model also assumes a uniform pressure over the walls and a one-way action, which does not represent the field response completely. In addition, the resistance of the external and internal sheathing was not accounted. All of which might have contributed to the prediction model being slightly softer than the experiment.

The deflection measurement at the center of the steel stud wall with the EIFS façade measured the gage maximum of 32 inches inward deflection, and gave no indication of when the steel stud wall failed. The steel studs that failed on the EIFS wall during testing were eased back into place during post-test forensics in order to estimate the plastic deflected shape when stud failure occurred. The average peak mid-span plastic deflection that occurred at stud failure was measured to be approximately 14 inches. This compares well to the EIFS-steel stud model that predicted stud failure at approximately 18 inches (plastic plus elastic) deflection, although the theoretical response is somewhat softer than experiment.

Reflected Pressure and Impulse vs Time
Blast Response of Exterior Walls, Experiment 1 (BREW-1)
Loading of Front Face of Structure

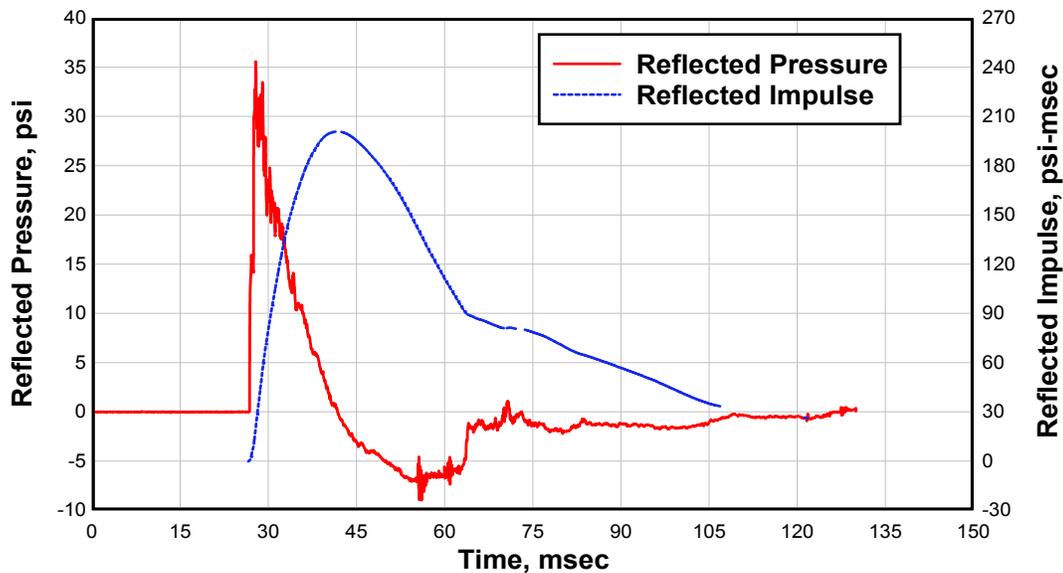


FIG. 10. Reflected pressure and impulse waveforms measured of wall surface for BREW-1



FIG. 11. Post test exterior views of BREW-1 showing large deformation and failure of low-mass wall with EIFS façade and response of higher mass wall with brick Façade

Measured Center Deflection of Steel Stud Walls
Blast Response of Exterior Walls, Experiment 1 (BREW-1)
Steel Stud: 600S162-43, 16" Spacing, $F_y = 33$ ksi

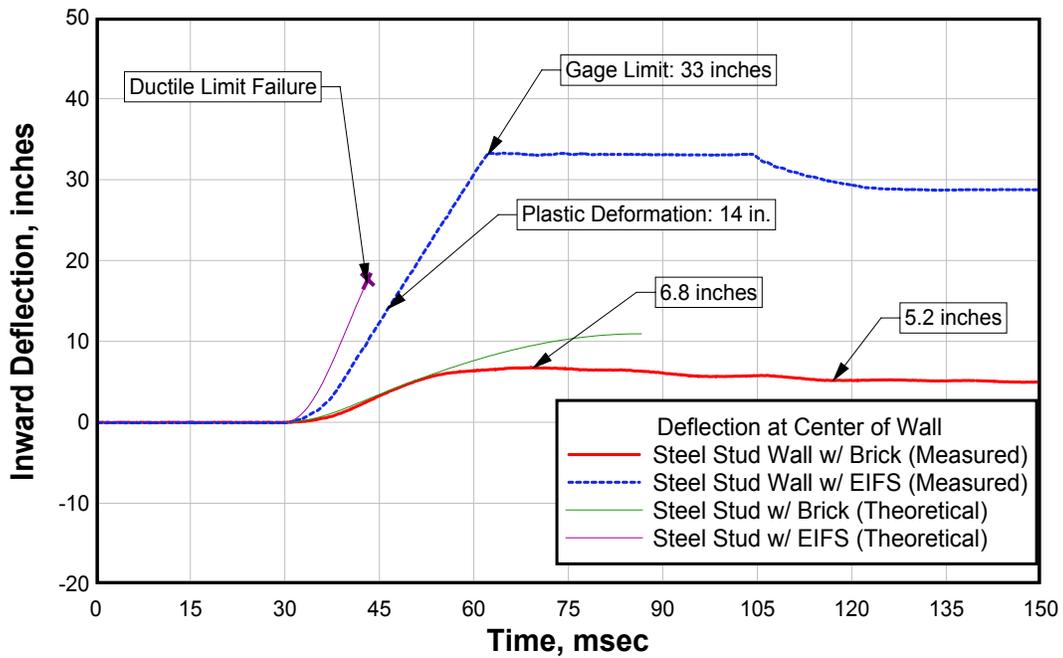


FIG. 12. Measured and predicted deflections at center of steel stud walls for BREW-1

SUMMARY

Properly anchored steel stud walls have proven to be an effective solution for construction of blast resistant walls for either new or retrofit construction. Some research has been performed to date to develop design methodologies for the required connection details, and to understand plastic post-buckling behavior and strain limits of the steel studs. The effectiveness of mass at reducing the response of the wall to blast loadings is dramatically demonstrated in the experiment and in the model. The theoretical resistance functions and preliminary design code provide a conservative prediction of the steel stud wall dynamic response, allowing engineers to design a blast-resistant steel stud wall that will survive a given explosion threat.

ACKNOWLEDGMENTS

The authors would like to acknowledge the diligent efforts, funding, and encouragement of the members of this research team comprised of several agencies including the U.S. Army Engineer Research and Development Center (Dr. Beverly DiPaolo and Dr. Stan Woodson), the US Department of State (Mr. Wayne Ashbery, Mr. Donald Moffett, Mr. Russ Norris, Dr. Ali Amini), the Center for Cold-Formed Steel Structures, University of Missouri-Rolla (Dr. Roger LaBoube), and The US Army Corps of Engineers Protective Design Center (Mr. Patrick Lindsey). Finally, we thank ERDC Chief of Engineers for permission to publish this paper.

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