ANALYSIS OF A FULL-SCALE BLAST TEST AND RETROFIT DESIGN

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ABSTRACT

A full-scale blast test was conducted on a room approximately 6.1m x 3.6m (20'x12') and 4 m (13') high, initially constructed with unreinforced masonry walls. The four walls were retrofitted with different quantities of Glass Fiber Reinforced Plastics (GFRP) to contain the blast load. In addition, a 5cm (2") thick layer of shotcrete was added to the inside of the two larger walls. The objective of this test was to validate the method of analysis that can be used to design effective retrofit techniques to contain blast loads.

Blast load consisted of a 0.91 Kg. (2lbs.) equivalent TNT placed near the center of the room. Instrumentation on individual walls monitored the blast pressure and the consequent displacement and velocity of the walls during the tests. Although the walls sustained extensive internal damage and plastic deformation, the retrofit was able to withstand the blast load. It was observed through static tests and the post-mortem analysis of the blast test that the stiffness of the masonry walls is completely lost at a very early stage and only the membrane action of the GFRP provides structural resistance to the blast load.

A software for the prediction of blast pressure was used and the results were compared with those from the actual test. A Single-Degree-of-Freedom (SDOF) dynamic model was used to model the structural response and was compared with the test data. A simple and approximate model of the nonlinear structural response due to arch action alone was able to capture the displacement and velocity profiles of the test data.

INTRODUCTION

Force protection of Department of Defense (DOD) facilities is becoming an increasingly important design and retrofit consideration. In the late 1990's, the Defense Threat Reduction Agency (DTRA), in association with the United States Army Corps of Engineers (USACE), had been charged with developing measures to retrofit Unreinforced Masonry (URM) walls to mitigate the effects of blast due to letter and package bombs.

The most recent research of URM walls reinforced with GFRP is in the area of seismic retrofitting. In recent years, Hamoud et al. [1], Eshani et al. [2], Albert et al. [3], along with a few other researchers have examined the behavior of URM walls subject to cyclic loading and reinforced with GFRP. While there exists a fair amount of research examining the behavior of concrete walls subject to blast, little has been done in the area of unreinforced and reinforced masonry.

FULL-SCALE BLAST TEST SETUP

A rectangular room with unreinforced masonry was built. The E glass, Hex-3R Wrap 430™ (unidirectional fabric) and Hex-3R Wrap 106G™ (0°/90° cross ply) manufactured by HEXCEL was used in combination with Sikadur® Hex 300/306 two part epoxy. Actual fabric weights applied to the walls in the vertical direction were 49 oz./ yd^2 and 98 oz./yd^2 for the East and West wall respectively. In addition to the same amount of GFRP, the North and South walls were reinforced with 5.1 cm (2") thick shotcrete. Adequate anchorage of the GFRP to allow it to develop its tensile strength is key to its successful use as a retrofit. This was achieved by wrapping the GFRP underneath steel angles that were anchored to the load-bearing beams above and below. Instrumentation for the walls included pressure gauges and accelerometers.

MODELING OF BLAST LOAD

The program BLASTX was used to predict blast pressure loads. BLASTX calculates the combined loading from all adjacent reflecting surfaces using a modified version of the LAMB shock addition rules and Mach stem corrections [4]. BLASTX also takes into account gas pressure development within and enclosure and calculates the decay of vented and unvented structures. The 0.91 kg. (2 lbs) charge was modeled as a spherical charge yielding an ideal blast. An example of blast pressure history computed is shown in Figure 1. The peak pressure corresponding to this wall is 0.59 Mpa (85 psi.). The blast duration was calculated to be 75 msec at which time the pressure decays to that of the ambient atmospheric pressure of 0.09 MPa (13 psi).

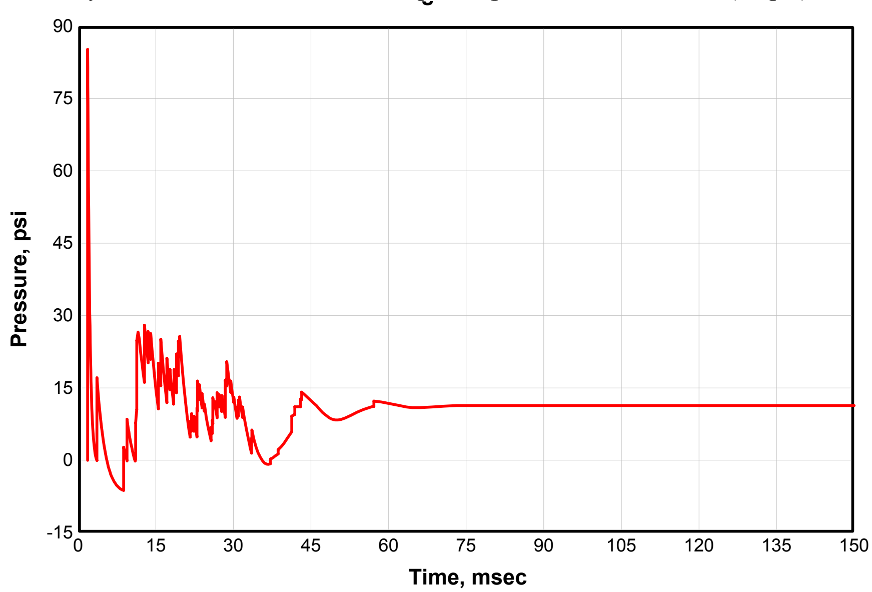

Figure 1. Predicted Pressure-time by BLASTX

OBSERVATIONS FROM BLAST TEST

Figure 2 shows the extensive damage to the inside face of the 'West' wall due to the blast. The front face of the masonry that faced the blast load was completely reduced to rubble. Some debonding can be observed as the light fabric at the top of this photo. In spite of the extensive damage, the GFRP was able to contain the blast and prevent any projectiles from escaping the room. The ability of the GFRP to withstand the blast pressure through large non-linear deformation will be the basis for the analytical model for predicting the response to blast load discussed later.

Figure 2. Complete destruction of masonry inside the West wall

Figure 3 shows the blast pressure history measured during the actual blast test and a gradually rising curve corresponding to the 'Impulse', defined as the area under the pressure-time history. The peak measured pressure was 0.52 MPa (75 psi.), which is was very close to the 0.50 Mpa rise in pressure predicted from the BLASTX analysis shown in Figure 1. The pressure also dissipates to zero at approximately 75 msec, similar to the BLASTX predictions. It must be mentioned that the peak pressure is less relevant to the determination of structural response and the design of adequate retrofits than the 'impulse'.

Figure 4 shows the measured displacement and velocity vs. time on the west wall. This was the only wall that was reinforced with GFRP only that could be adequately analyzed since the East wall had a door opening that led to considerable stress concentration (the door flew off 40 meters, 130' as a result of the blast).

ANALYSIS OF BLAST EFFECT

A simple method of determining the response of a wall to blast pressure is the Newmark's Beta Method. This is a piecewise integration of a single degree of freedom model (SDOF) (Equation 1) using a linearly decaying force over a short duration. The model is explained in the ASCE publication Design of Blast Resistant Buildings in Petrochemical Facilities [5]. The mathematical model simulates both elastic and plastic behavior of a system as it is loaded. It does not account for the unloading of the system. Predictions of wall displacements (u) were made using Newmark's Beta Method encoded in a Mathcad program.

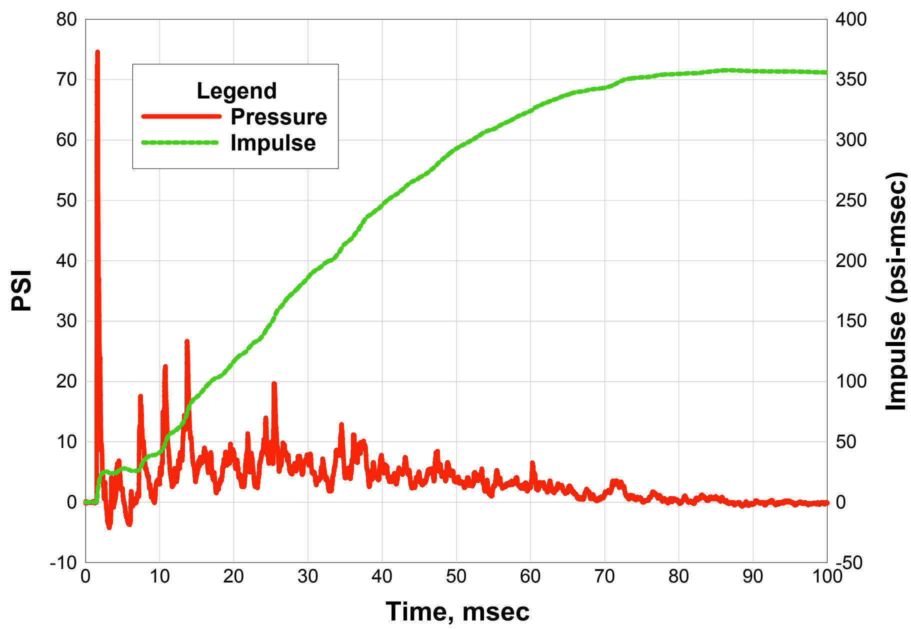

Figure 3. Measured blast pressure vs. time

Equation 1: (m is equivalent mass, c is damping, k is stiffness, p is blast pressure)

$$m\frac{d^2u}{dt^2}+2B(km)^{\frac{1}{2}}\frac{du}{dt}+k(u-DO)=P(t)$$

The stiffness 'k' used in this implementation is nonlinear due to the large deformation in the GFRP that resists the blast load. The membrane action of the GFRP was calculated based on an assumed parabolic geometry of the deflected shape. The resulting curvature of the GFRP membrane is used to compute the out-of-plane component of the tensile stress, which resists the blast pressure [6]. The result of this analysis is shown in Figure 5.

It can be seen that the actual maximum displacement of the wall was 33cm (13") in Figure 5 compared to a predicted maximum displacement of 28cm (11") in Figure 6. Likewise the predicted maximum velocity was 7.6 m/s (25 ft./sec) compared to 7.0 m/s (23 ft./sec.) observed from the test instrumentation.

CONCLUSIONS

Results of a full-scale blast test was presented. It was demonstrated that a properly designed GFRP retrofit can effectively contain a blast load of known magnitude. The BLASTX code for determining blast pressure history on walls is quite accurate. A simple SDOF analytical model using only the nonlinear stiffness of the GFRP due to membrane action can be used to predict the structural response of a wall with reasonable accuracy. A combination of these tools can now be used to design effective retrofits against internal or external blast loads.

ACKNOWLEDGEMENT

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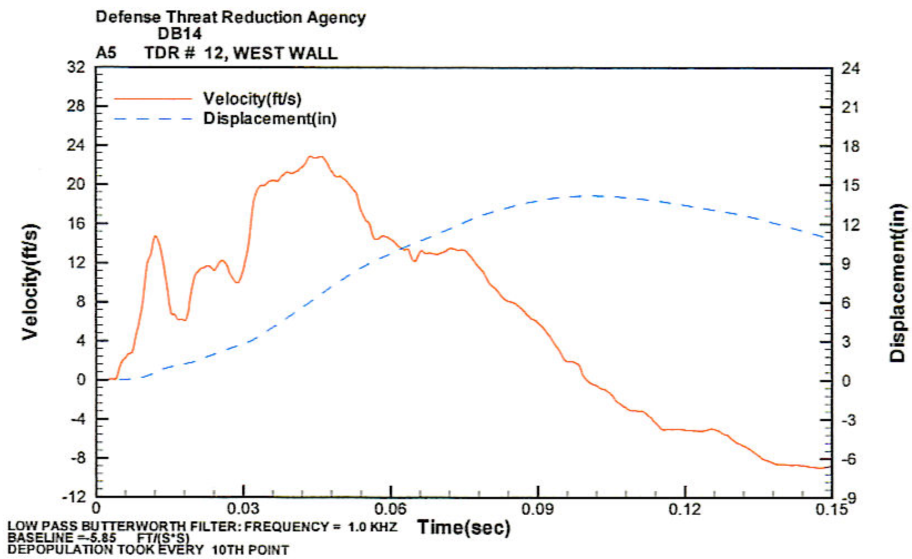

Figure 4. Actual velocity and displacement vs. time during blast
(1ft. = 0.305m, 1" = 2.54cm)

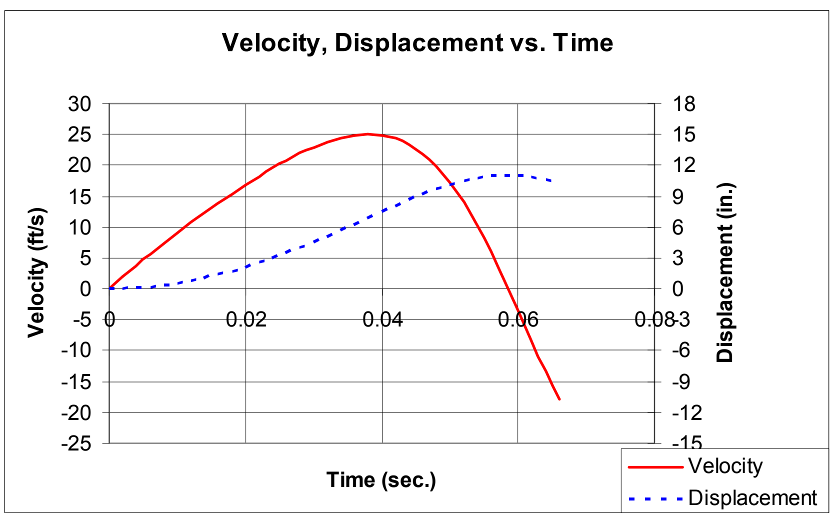

Figure 5. Velocity and displacement vs. time from analysis
(1ft. = 0.305m, 1" = 2.54cm)