SESSION I

STRUCTURAL RESPONSE A

BLAST LOADING OF CLOSURES FOR USE ON SHELTERS

George A. Coulter

U.S. Army Ballistic Research Laboratory
U.S. Army Armament Research and Development Command
Aberdeen Proving Ground, Maryland 21005

ABSTRACT

The work reported here is a part of a study funded by the Federal Emergency Management Agency (FEMA) under Work Unit 1123C to upgrade existing shelters in key worker and host areas. The objective of this portion of the study is to determine closures suitable for shelters in these two areas. Ultimate failure of closures (breakout) was determined by dynamic loading tests performed at the BRL 2.44 m blast simulator. Test results are given for three types of closures. Load ratios of ultimate failure to allowable static design loads were found dynamically to be about four for the wood beam/plywood skin closures. This would make it acceptable for both host and key worker shelter areas.

I. INTRODUCTION

The work described here is a part of a study funded by FEMA under Work Unit 1123C to upgrade existing shelters. The objective of the Interagency Agreement No. EMW-E-0699 with the Ballistic Research Laboratory (BRL) was to design and test a series of closures made from readily available materials that might be suitable for use in host and key worker areas. A major requirement was that the materials could be obtained at local suppliers. Also, the closures should be useable for opening sizes from small pipe vents to entryways for underground shelters.

Previous work sponsored by FEMA at BRL (1), (2) had verified design procedures (3) indicating that plywood panels and plywood stressed-skin panels were satisfactory expedient closures for the low pressure host area. They were also effective closures for small, pipe vent type openings in the higher pressure risk area if used with suitable supporting fixtures. The need, therefore, was to design and test closures intended for entryway-size openings in the risk area.

Accordingly, three types of closures were prepared for testing at the BRL 2.44 m (8 ft) shock tube: commercial steel doors, steel grating/plywood closures, and wood beam/plywood skin closures. The method of testing is described in the next section.

II. TEST PROCEDURE

Details of the test flange, closures, and recording instrumentation are described briefly in this section.

A. TEST FLANGE AND CLOSURES

The test flange and the closures are shown in Figures 1-4. All tests were conducted with the closures mounted in the vertical position. Wooden frames were used to mask each of the closures to give a smooth wall effect for the test. The clearance of about 0.5 cm that separated the closure from the frame was covered with strips of rubber, with a loose edge left on the closure side.

The beam closure shown in Figure 2 was made of 3.81 × 8.89 cm (2 × 4's) joists on edge, sandwiched and nailed, between sheets of 1.27 cm thick plywood. The short ends were supported with a length of 7.62 cm during the tests of this closure. The face grain of the plywood sheets ran in the direction of the 2 × 4's to give the greatest strength.

Figure 3 shows ordinary steel grating, covered on one side with plywood (0.635 or 1.27 cm) to contain the blast pressure. The grating normally is sold in a standard width of 0.91 m, so two widths were attached to cover the end flange opening of 1.219 × 1.676 m. Grating was supported 7.12 cm on all sides.

The third closure tested is shown as Figure 4. The doors were full-flush steel, no cut-outs, and had internal bracing with a filler of rock wool for insulation. The doors were supported on all four edges.

All closures were tested to ultimate failure, where major portions, or all of the closure was blown from the end flange opening (1.219 × 1.676 m).

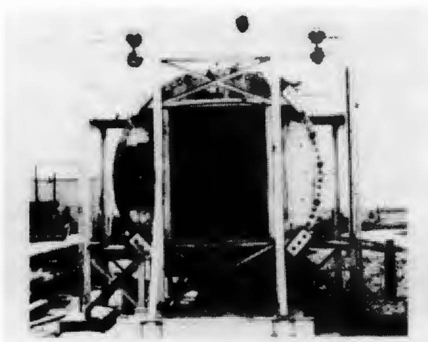

Figure 1. Test fixture, 2.44 m shock tube.

Figure 2. Wood beam closure, Shot 8-82-25.

Figure 3. Grating closure, Shot 8-82-31.

Figure 4. Steel door, Shot 8-82-35.

B. INSTRUMENTATION

The blast pressure load applied to the closure was measured at a point on the wooden masking frame 11.43 cm from the long edge of the flange opening. The transducer was approximately centered vertically along the heighth of the frame. The output from the transducer (PCB Model 113A24) was suitably amplified and recorded by an CEC FM 3300 tape recorder. Records were available for a quick-look from an on-site oscillograph for immediate recording changes for following tests.

The displacement of the closure was tracked with an OPTRON Model 501 Electro Optical Displacement Follower (4). A light cardboard target, painted black was attached with an aluminum holder to the center of the closure. The target was optically tracked and converted to displacement-time records by the recorder.

A high speed camera (Red Lakes HYCAM) operated at 1000 pictures per second supplemented the displacement follower when it was over ranged.

III. RESULTS

The results are summarized with a data table and typical loading/deflection-time records.

A. DATA TABLE

Table 1 summarizes the resulting loading pressure, transient center deflection, vibration frequency, and damage to the closures.

TABLE 1. LOADING DATA FOR CLOSURES

SHOT NO.	CLOSURES	LOAD, kpa	DISPL., cm	FREQ., Hz	ULTIMATE FAILURE / ALLOWABLE LOAD	DAMAGE
8-82-25	Wood beam	239	3.14	121/19	-----	2×4 broken.
8-82-26		300	----	------	-----	Half panel out.
8-82-27		278	3.40	102/16	4	Skin broken.
8-82-29	Steel grating	174	----	-----	-----	Walls broken.
8-82-30		215	----	-----	-----	Grating out.
8-82-31		192	----	-----	7	Grating bulged.
8-82-33		53	5.50	75/15	1.2	Bulged.
8-82-34		57	> 5.75	-----	-----	Door bent.
8-82-35		52	8.75	83/15	-----	Bulged.

The wood beam/plywood closures (Shots 8-82-25 to 8-82-27) were tested through a range of loading pressures (reflected) from 239 kPa (34.7 psi) to 300 kPa (43.5 psi). Slight damage by bulging occurred at the low end of the loading range. At 300 kPa (43.5 psi), the closure was in place and effective. Two frequencies of vibration were measured - 102 to 121 Hz and 16-20 Hz. Near ultimate failure the vibrations tend to damp out.

The loading range for the steel grating (Shots 8-82-29 to 8-82-31) varied between 174 kPa (25.2 psi) and 215 kPa (31.2 psi). When the two sections of grating were held together with U-bolts the closure remained together at a load of 174 kPa (25.2 psi). At 215 kPa (31.2 psi), the closure was blown completely away from the shock tube. Successful operation was found at an intermediate load of 192 kPa (27.8 psi).

The third type of closure, the commercial steel door was weak even when supported on all four sides. The doors tested behaved inconsistently but failed at about 57 kPa (8.3 psi). None survived load ranges comparable to either the wood beam or the grating closure.

B. LOADING AND DEFLECTION PLOTS

Figures 5 and 6 show some typical pressure and deflection plots as a function of time during the blast loading period. The pressure record (upper trace) was modified as damage occurred to the closure letting the blast wave vent. When the closure remained intact, the deflection record follows the loading-pressure well. See Shots 8-82-25, 31, and 35 for no venting. Venting is shown by Shots 8-82-26, 29, and 34.

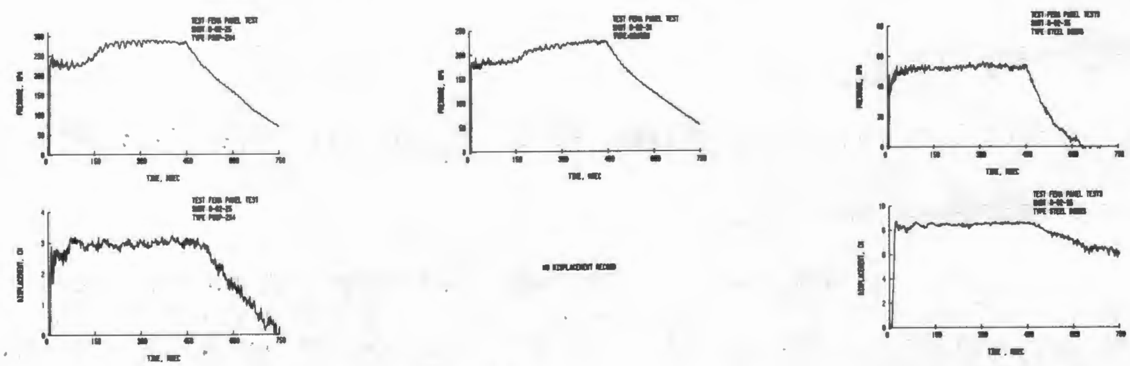

Figure 5. Records for effective closures.

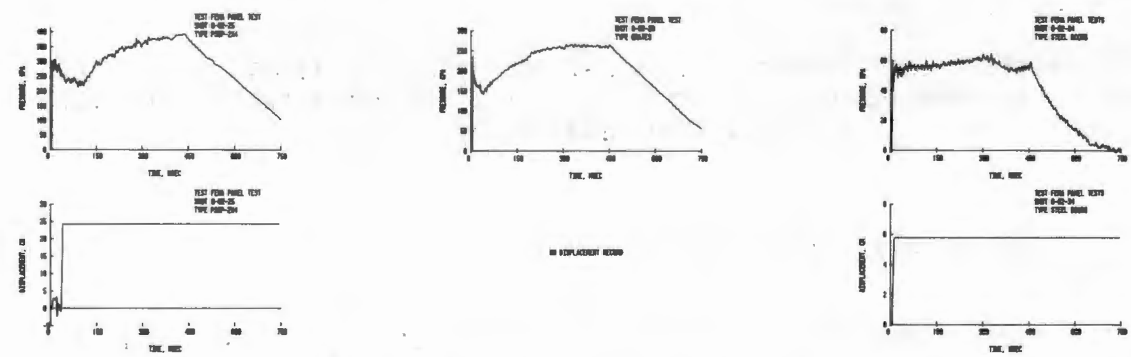

Figure 6. Records for vented closures.

IV. ANALYSIS

The analysis will follow the methods given in the design procedures of (3). This procedure was used for predicting the ultimate failure of the wood beam/plywood closures and also for the steel doors. Table values from (5) were used for the allowable static load for the steel grating/plywood closure.

A. WOOD BEAM/PLYWOOD CLOSURES

The horizontal shear mode was judged to be weakest for the wood beam/plywood closures. Accordingly, the total load-horizontal shear, P_v, was calculated following the procedures given in (3).

$$P_v = (2(\Sigma F_v t)/(\ell\ell' Q_v))(EI_g/E_{stringer}), \quad (1)$$

where F_v = allowable stress (6) in stringers horizontal shear (655 kPa), t = sum of stringer width (167.6 cm), EIg = stiffness factor (17.46×10^{10} kPa -cm^4), E_{skin} = modulus of elasticity for plywood skins (7) (13.64×10^6 kPa). $E_{stringer}$ = modulus of elasticity for stringer (12.77×10^6 kPa), ℓ = clear span of stringers (121.9 cm), ℓ' = clear width of closure (167.9 cm), and Q_v = the statical moment (2029.07 cm^3). The allowable load, P_v, is 72.42 kPa (10.5 psi).

The dynamic load, P_{dm}, needed to cause ultimate failure is found from Equation 2.

$$P_{dm} = 4P_v \left(1 - \frac{1}{2\mu}\right), \quad (2)$$

where the ductility ratio, μ, is taken as 2. P_{dm} is 217.3 kPa (31.5 psi).

B. STEEL GRATING/PLYWOOD CLOSURES

The allowable load was taken as the safe load given (5) for the steel grating (27.8 kPa, 4.03 psi). The plywood sheet (0.635 cm) cover for the grating was neglected. The dynamic load for ultimate failure was calculated from Equation 2 with a μ of 10 used for steel. P_{dm} = 105.6 kPa (15.31 psi).

C. COMMERCIAL STEEL DOORS

Calculations were made for the steel door assuming it would act like a stressed skin panel under deflection (3). The allowable static load for panel deflection, P_d, is found from Equation 3.

$$P_d = 1/\left[C\ell\ell'\left(\frac{5}{384}\frac{\ell^2}{(EIg)} + \frac{0.15}{AG}\right)\right] + DL, \quad (3)$$

where C = factor (360), EIg = stiffness factor (5.07×10^{10} kPa-cm^4), A = cross section of internal braces (15.58 cm^2), G = modulus of rigidity of stringers (79.57×10^6 kPa), ℓ = clear span of panel in direction of stringers

(167.64 cm), and ℓ' = clear width of panel (109.4 cm). The dead weight (DL) was set to zero since the doors were tested as upright wall panels. P_d = 21.0 kPa (3.04 psi). For support on all four sides, P_d is modified by a factor of 2.139 times. The allowable load is 44.92 kPa (6.52 psi). No attempt was made to calculate ultimate failure.

IV. SUMMARY AND CONCLUSIONS

Three types of closures were tested to ultimate failure at the BRL 2.44 m blast simulator: (1) wood beam/plywood skin panels, (2) steel grating/plywood closures, and (3) commercial steel doors. Compared to allowable safe static loads, the grating closures were about seven times stronger, the wood beam panels about four times stronger, and the steel doors only about twenty percent above the allowable static loads. The wood beam closures and grating closures withstood loads that would probably allow both to be used in the key worker areas. The commercial doors tested withstood loads which would make them suitable only for host areas.

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