BLAST CAPACITY ASSESSMENT AND TESTING

A-60 OFFSHORE FIRE DOOR

Final Report
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EXECUTIVE SUMMARY

Baker Engineering and Risk Consultants, Inc. (BakerRisk) was tasked by JRJ Alum Fab, Inc. (JRJ) to evaluate its A-60 O/S Fire Door design through analysis and testing. The effort included a dynamic structural analysis of the single opening fire door design, recommendations on design modifications based on the analytical analysis, and the testing of the door system using the BakerRisk shock tube to simulate blast loads from high explosives and industrial explosions.

BakerRisk evaluated the basic design of the single opening A-60 O/S Fire Door. Single-degree-of-freedom (SDOF) models of the door panel were developed using the structural and geometrical properties of the door panel system. Once the door panel capacity was determined, the remaining components of the door system were also evaluated. Initially, the door panel was found to be the weakest or limiting component of the single door system. Based on the findings of this initial analysis, BakerRisk then worked with JRJ to develop design modifications that would increase the structural resistance of the door panel while not adversely impacting the fire resistance of the door system. The analytical analysis of the redesigned A-60 O/S door formed the basis of the selection of blast loads used in the shock tube testing of the door system.

The study included the testing of three single opening A-60 O/S doors. Test results were used to develop a more accurate SDOF model for the door panel. Based on the test data, the analytical model was modified to align with observed test results. The resulting SDOF model was used to develop a pressure-impulse (P-i) diagram of the door response for each of the three categorized ASTM descriptions of door response.

The P-i diagrams developed in this study can be used to predict the inbound response of the A-60 O/S fire door to a wide range of blast loads. Note that to ensure damage does not occur in the rebound phase of response, a three-point latch will be required.

Baker Engineering & Risk Consultants, Inc. (BakerRisk) certifies that all information contained in this document is accurate to the best of our knowledge, and that the analysis approach used follows general engineering principles commonly used for blast resistant design and evaluation.

Signed:

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2.0 PERFORMANCE CRITERIA

The acceptable level of response of doors under applied blast loads varies greatly depending on the intended use of the door. Historically, five categories of blast door response have been defined for use in industry. The categories range from no damage to the door, to complete failure of the door, and have been used in ASTM F2247-03 "Standard Test Method for Metal Doors Used in Blast Resistant Applications (Equivalent Static Method)." Although the category for door failure is omitted by ASTM, the four categories of performance that are defined in the ASTM document are similar to the categories previously used in industry. These categories, defined in Table 1, are intended for the evaluation of a door tested under an increasing applied static pressure. Note that these categories apply to loadings on a door in the seated direction and do not address rebound in the actual descriptions; however, they do address testing a door in both the seated and unseated direction in separate tests with potentially different capacities. The ASTM document addresses rebound response of a door by recommending selection of a required rebound resistance based on door use. Levels of 100%, 50%, or 0% of the inbound capacity are recommended as potential rebound capacities of a door, depending on the intended use. The ASTM document does not recommend when a particular level should be specified, leaving that decision to the authority requesting the door performance evaluation.

Table 1. Four Categories of Door Performance Defined in the ASTM Document

Category I	The specimen is unchanged (no permanent deformation) after the loading incident and the door is fully operable. The specimen remains intact and responds elastically. In field tests, a tolerance of 2 mm (5/64-inch) difference between pre-test and post-test measurements is allowed for elastic response.
Category II	The door is operable, but measurable, permanent deformation to the door panel exceeding 2 mm (5/64-inch) has been experienced. The specimen remains as an integral system.
Category III	Non-catastrophic failure. No structural failure occurs to the specimen that prevents the specimen from providing a barrier to blast wave propagation. However, the specimen is permanently deformed and the door panel is inoperable.
Category IV	The door panel is severely deformed. For the seating direction, the deformation of the door panel must be limited to a level that does not cause the door panel to be forced through the door frame opening. For the unseating direction, the latching mechanism is permitted to fail, allowing the door to swing open; however, the door panel shall remain supported by the hinges and it is evident that the door panel will not become a flying debris hazard.

To utilize the defined ASTM performance categories in an analytical evaluation of doors, it is necessary to expand the definition of some categories to include explicit limits to door panel deformation and design limits that can be directly compared to analytical response predictions. BakerRisk has expanded these definitions and the assumptions used to arrive at the design response limits set for each response category, as described in Table 2.

Table 2. BakerRisk Recommended Door Performance Categories

Category I: No Damage	The door panel and all other components of the door must remain in the elastic response range. Analytical design limits for this response category are a ductility ratio of 1. Additionally, the analysis must include an evaluation that demonstrates that all parts of the door can support the door panel to its maximum capacity.
Category II: Limited Damage	The door panel may experience limited plastic deformation, but must be shown to remain in the frame in both the inbound blast direction and in rebound. All hardware must be evaluated and proven capable of supporting the door panel to its ultimate capacity. An evaluation of door shortening must be performed to ensure that shortening of the door panel due to deflection does not cause loss of bearing on the door stop or pullout of the lock bolt from the frame. The design limit on the door panel is 5 degrees of support rotation. The panel shortening evaluation includes effects of door post deformation, if applicable, and rounded corners of bent plate frames and door skins. The total loss of panel/stop or latch bolt/plate engagement is limited to one-half of that provided under normal installation tolerances.
Category III: Non-Catastrophic Failure	The door panel must remain in the frame and remain a barrier to prevent blast load propagation through the door opening. The door panel may be severely deformed and may be inoperable. The design limit on the door panel is 8 degrees of support rotation. An evaluation related to loss of support due to door panel and post deformation must show that the total loss of engagement is less than the engagement provided, minus the dimensions of any corner radii.
Category IV: Failure without Debris Hazard	The door panel may be severely deformed with openings between the panel and door frame allowed, but the door panel must remain affixed to the door frame. This level of response is difficult to predict analytically, due to the many influencing factors of response once a door panel deflects to the point where bearing supports or latchbolt engagement is lost. Also, simple analytical methods such as single-degree-of-freedom models assuming elastic/perfectly-plastic response do not predict large deformation well. Testing is the best methodology to predict this level of response.

5.0 TEST RESULTS

An analytical analysis of the revised door system was completed prior to testing the A-60 O/S doors and provided a basis for the selection of blast loads in the testing series. The analytical analysis also determined that the door panel would control the response of the door system up to a long duration load of approximately 6 psi. For long duration loads above 6 psi, the door frame would control the response of the door system.

Six tests were conducted on three A-60 O/S door specimens. The test results demonstrate that the door design has significant blast resistant capacity. Details of each test are provided in Appendix A. The applied blast loads and door responses are summarized in Table 3. Note that the door specimen used in Test 2 and Test 3 was the same specimen used for Test 1 and that the door specimen used in Test 5 was the same specimen used for Test 4. In these cases, the test specimen had pre-existing permanent damage from the previous test; thus, the initial conditions of the door specimen were reflected in the final conditions of the subsequent door test.

Table 3. Test Result Summary

Test Number	Applied Blast Load			Total Permanent Panel Deflection (inches)	Maximum Support Rotation (degrees)	Net Panel Deflection from Associated Test (inches)	Performance Category
	Peak Pressure (psi)	Applied Impulse (psi-ms)	Duration (msec)				
1	3.5	164	93.7	1/16	2.9	1/16	I
2*	3.8	186	98.1	5/16	3.7	1/4	II
3*	5.2	236	90.6	3/8	3.9	1/16	II
4	6.7	274	82.6	1/4	3.7	1/4	II
5*	7.0	352	101.3	5/8	4.2	3/8	II
6	11.2	123	21.6	7/16	4.5	7/16	II

** Panel Deflection is Total Deflection, Test 2,3 and 5 were conducted with door specimens with pre-existing permanent deflection*

6.0 POST-TEST ANALYSIS

Based on the observed results from the test program certain conclusions have been formed:

- The analytical model that formed the basis for the selected test load conditions was overly conservative in predicting the post-elastic response of the door. However, the analytical model is extremely accurate in predicting the behavior of the door system prior to yielding the door panel.
- The door panel responded beyond 4 degrees of rotation in Test 5 and 6 without losing significant bearing at the door frame. Thus, a response criteria limit of 5 degrees support rotation was determined as a reasonable upper bound of Category II response.
- Significant deformation of the strike side of the frame was noted in Test 5 and Test 6. The level of frame deformation substantiates the analytical analysis door frame results. More significantly, at a long duration load of 6 psi, the response of the door frame begins to govern the response of the door system.
- All doors in the test series sustained damage at Performance Category II and lower. Therefore, while a basis for the modification to the Performance Category II curve could be established, the test series provides no justification for the behavior of the door system beyond the Performance Category II response level. The previously established response criteria limit of 8 degrees of support rotation will therefore define the upper bound of a Category III response.

Based on the observed test results, a revised single-degree-of-freedom (SDOF) model was required to more accurately predict the response of the door panel.

In order to develop the analytical model, the measured door response was compared to the applied blast load for each test. This comparison provides an understanding of the door behavior in response to a variety of blast loads and the results provided the basis for the development of a revised analytical model. In order to ensure an accurate comparison of the pressure traces captured during an individual test and the idealized pressure-time profile (Figure 3) used in the development of the analytical model, an equivalent blast load was also calculated for each pressure trace. The discrepancy between the pressure traces and the idealized load profile is due to an initial spike in the long duration (Test 1-5) shock tube tests. This equivalent pressure-time profile was then developed using the following procedure:

- Select an equivalent triangular load profile peak pressure, the equivalent peak pressure is selected as the pressure magnitude at the base of the initial pressure spike from each pressure trace. The pressure spike may be neglected in this calculation due to the short duration of the spike (<< 1 ms) in comparison with the natural period of the door system.
- Based on the peak impulse and calculated by integrating the pressure trace, an equivalent triangular load profile duration is determined for each test ($t_d = 2I/p_{eq}$)

Figure 10 provides a graphical representation of this procedure.

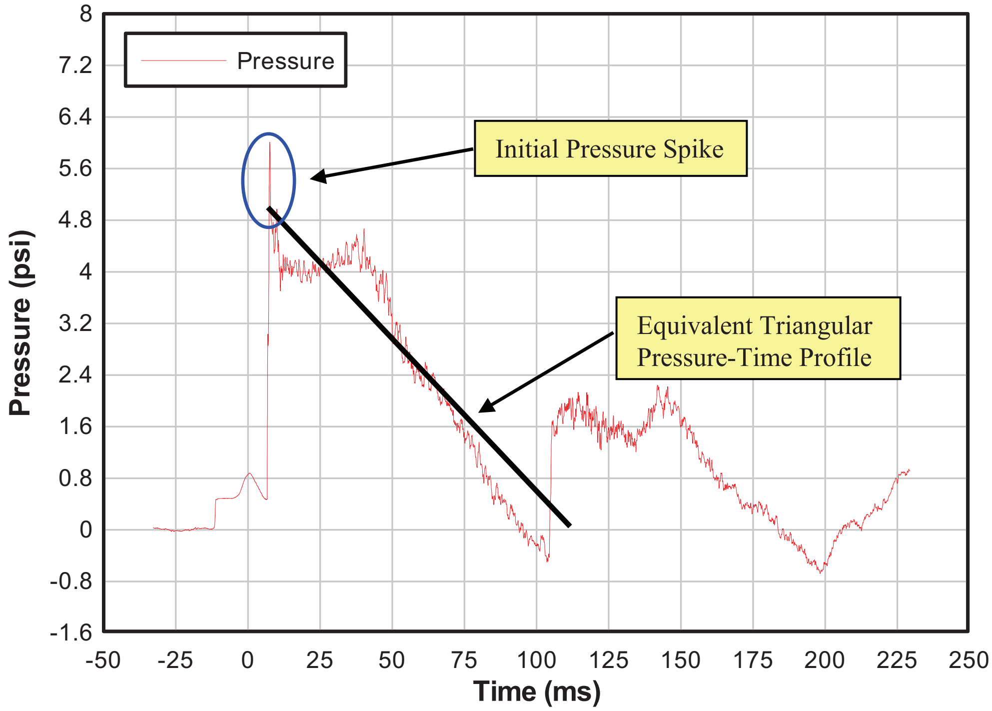

Figure 10. Development of Equivalent Triangular Profile Load

Table 4 provides a tabular summary of the equivalent triangular pressure-time history loads.

Table 4. Equivalent Triangular Profile Test Loads

Test Number	Equivalent Peak Pressure (psi)	Applied Impulse (psi-ms)
1	3.4	164
2	3.8	186
3	4.8	236
4	6.2	275
5	7.0	352
6	11.2	123

The initial SDOF model was based on the assumption that the door would behave perfectly plastic after reaching a deflection equal to the yield limit, therefore, assuming that deflections exceeding 0.6-inches would not exhibit an increase in door panel resistance. The assumed load-deflection of the door panel is shown graphically in Figure 11. Test results, however, showed this assumption to be inaccurate.

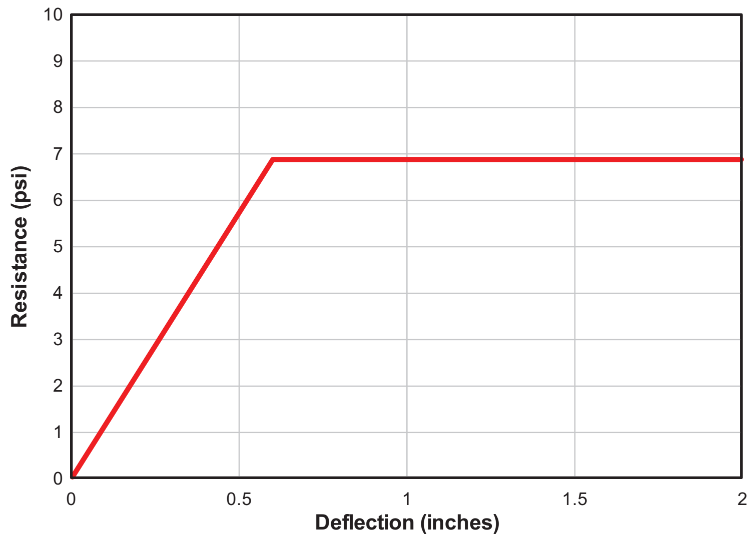

Figure 11. Assumed Resistance versus Deflection Behavior of Door Panel

Since the analytical model accurately predicts the elastic limit of the door (Performance Category I), the inaccuracy of the model lies in predicting the post-yield behavior of the door panel. The door exhibits a degree of increased resistance even after reaching its yield limit. In order to develop a more accurate model of the door panel, the post-yield behavior of the door was modified to more closely correspond with the test results. The revised model thus assumes an elasto-plastic behavior of the door panel. The deflections and corresponding blast loads from the test data were used to develop the revised model of the door panel. Thereby, the loads summarized in Table 4 were used in the redevelopment of the SDOF model. The revised load-deflection behavior of the door is shown in Figure 12, which shows a second yield point of 1.7 times the initial yield at a stiffness of 25 percent less than the elastic stiffness.

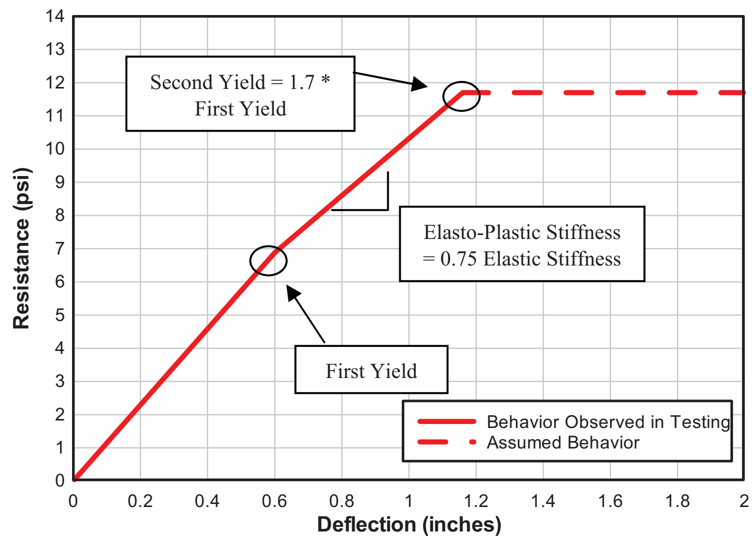

Figure 12. Revised Resistance versus Deflection Behavior of Door Panel

In order to validate the revised model, the equivalent triangular profile test load developed was applied to the model. A comparison of the calculated permanent deflection and the observed net permanent deflection from each test was made to determine the validity of the new model. The observed deflection, for this comparison, was defined as the elastic deflection of the panel plus the observed net deflection of the panel (Table 3). A summary of this comparison is provided in Table 5.

Table 5. Summary of Predicted Response Based on Revised Model

Test Number	Observed Deflection (inches)	Revised Model Calculated Deflection (inches)	Calculated / Observed Deflection
1	0.66	0.56	0.85
2	0.85	0.62	0.73
3	0.92	0.78	0.85
4	0.85	0.98	1.15
5	0.98	1.12	1.14
6	1.04	1.47	1.41

Note that the revised model predicts the response of the door to within 15% for Test 1, 3, 4 and 5. The model is more conservative in predicting the door behavior in response to short duration loads (i.e. Test 6).

Based on the revised SDOF model of the door panel, a P-i diagram was developed. The P-i diagram provides upper-bound curves for Performance Category I (elastic-limit) and Category II (support rotation of 5 degrees). The P-i diagram is provided in Figure 13 and the pressure and impulse pairings from all six tests are also shown for reference. This P-i diagram includes the upper bounds for performance categories that were achieved or exceeded in the test series (Performance Category I and II). This diagram may be used to predict the inbound response of the single opening JRJ A-60 O/S door to a wide range of applied blast loads having a pressure-time history profile of the idealized load shown in Figure 3.

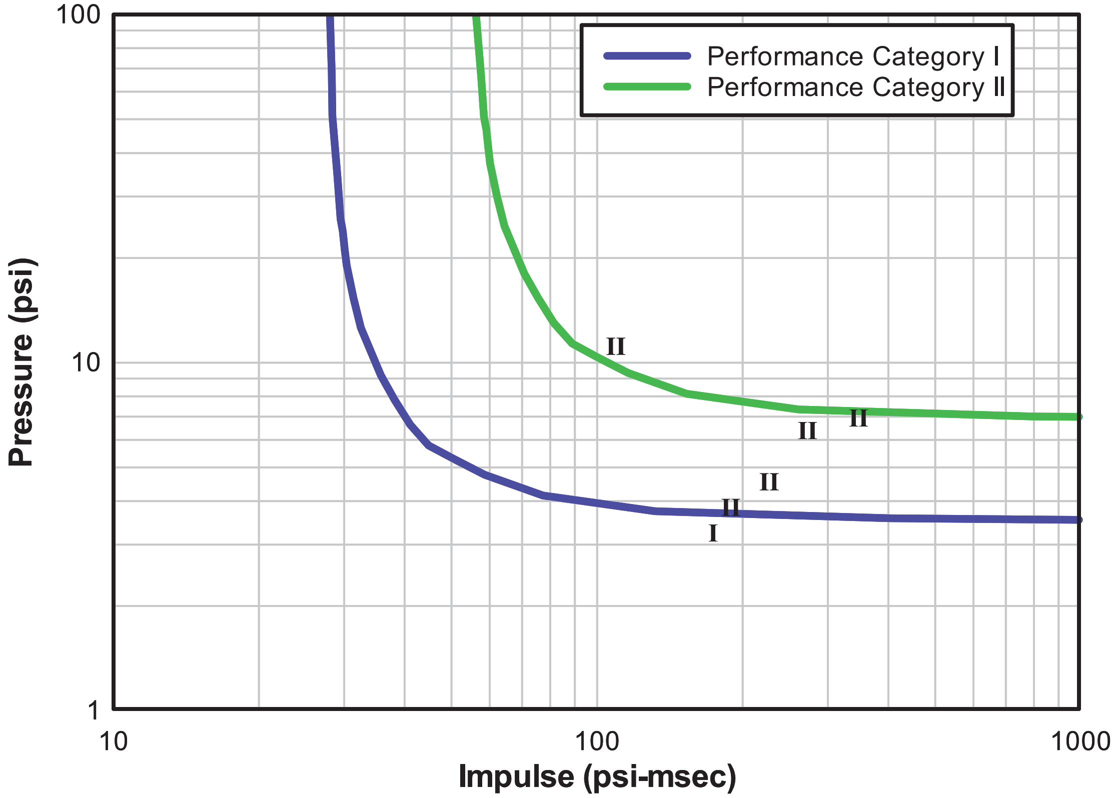

Figure 13. Pressure-Impulse Diagrams For Performance Categories I and II

7.0 CONCLUSIONS

BakerRisk has completed an evaluation of the JRJ A-60 O/S single opening door. To determine the panel response to a wide range of applied blast loads, BakerRisk developed an analytical model of the door panel using the structural and geometrical properties of the door panel system. This analytical model provided the basis for the blast load selection and validation program based on three door specimens. Test data from this series is attached in Appendix A. BakerRisk concluded that the initial analytical model was conservative in predicting higher levels of door response. The analytical model was then refined based on the observed test results. The final product of this study is a P-i diagram that may be used to predict the inbound response of the single opening JRJ A-60 O/S door to a wide range of blast loads. The final P-i diagram is provided in Figure 14 and includes the upper bound of the Performance Category III, which was not substantiated during this test series but was based solely on analytical assumptions.

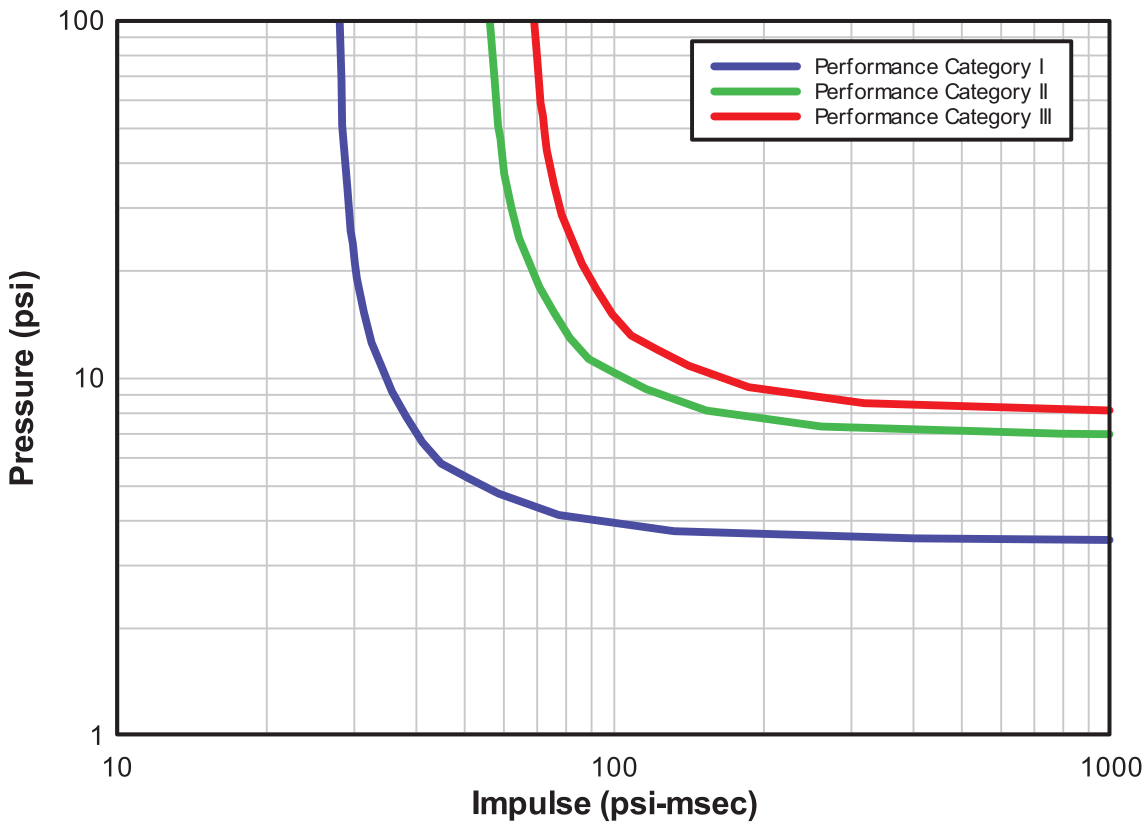

Figure 14. Recommended Pressure-Impulse Performance Diagrams