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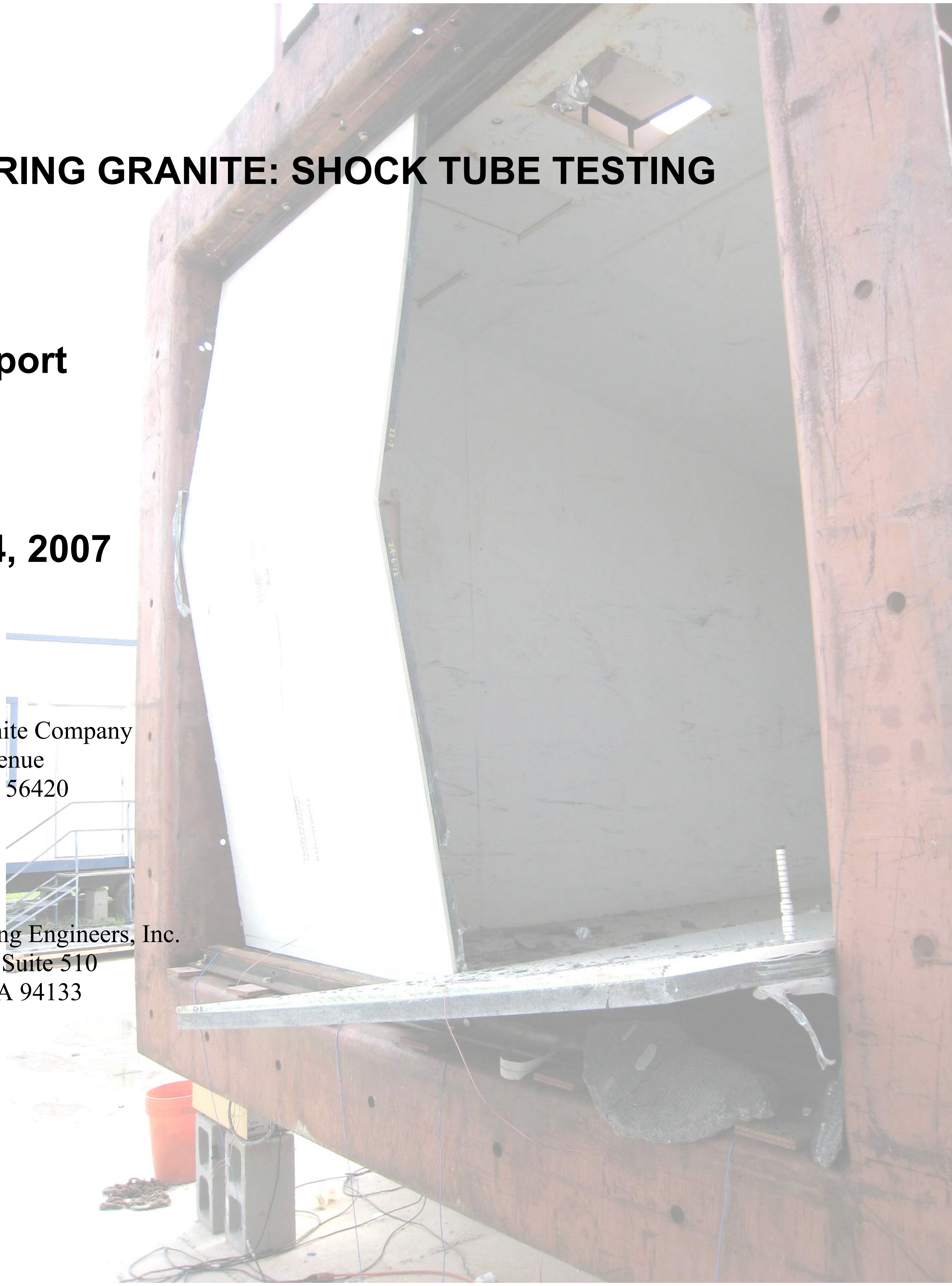

COLD SPRING GRANITE: SHOCK TUBE TESTING

FINAL Report

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1 EXECUTIVE SUMMARY 3
2 INTRODUCTION 4
3 BACKGROUND 4
4 OBJECTIVES 4
5 APPROACH 4
6 PERFORMANCE EVALUATION METHODOLOGY 5
6.1 Performance Evaluation Limits 5
6.2 Pressure-Impulse Diagrams (PI Diagrams) 6
6.3 Charge Size (Weapon) – Standoff Diagrams (WS Diagrams) 8
7 GRANITE PROPERTIES 10
8 TESTING PROGRAM 10
9 TEST RESULTS EVALUATION 11
9.1 Tests 1 through 6: Ideal Support Conditions 12
9.2 Tests 7 and 8: Typical Installation Support Conditions 14
10 PERFORMANCE EVALUATION USING PI DIAGRAMS 16
10.1 Expected Performance of Composite Granite 16
10.2 Supporting Structure Considerations 18
10.3 Rebound Considerations 18
11 CONCLUSIONS AND RECOMMENDATIONS 19
11.1 Conclusions 19
11.2 Recommendations for New Design 19
11.3 Recommendations for Performance Evaluation 19
11.4 Additional Testing Recommendations 20
12 REFERENCES 20
13 APPENDIX I: CALCULATIONS 21
13.1 Granite-Eglass Composite Property Estimate 22
13.2 Test Result Comparison 27
13.3 Mesabi Black: Performance Evaluation 36
14 APPENDIX II: MECHANICAL PROPERTIES 55
14.1 Granite Mechanical Properties 56
14.2 Eglass Mechanical Properties 57

1 EXECUTIVE SUMMARY

Background
Hinman Consulting Engineers, Inc. (Hinman) was contracted by Cold Spring Granite Co., to develop a shock-tube testing program of eglass laminated composite granite assembly to study feasibility of air-blast protection and to determine the performance of the system when subjected to air-blast loading.

This Study
The results of this testing and analyses can be utilized in the development of the design of the new composite granite panels as well as performance evaluation of existing panels when used in air-blast protective capacity. Shock tube testing was performed to validate analytical P-I diagrams which are used to determine levels of protection and anchorage forces.

Conclusions and Recommendations
- Testing of composite granite assembly verified that this system can be used to provide protection for air-blast loads. Furthermore, tested composite granite assembly provided protection level equivalent to GSA High Level of Protection. Testing also revealed that composite granite panels are very brittle and weak in rebound direction. Although it is expected that broken granite pieces will come loose during the rebound, eglass laminate panels are expected to remain anchored and still provide protection to occupied space.
- Composite granite panels should be design to performance condition not to exceed Moderate Damage. Overall performance of composite granite and supporting structure assembly should be verified by constricting corresponding PI diagrams. If damage due to rebound is a considerations, direct time-history analysis should be conducted.
- Performance evaluation of existing composite granite panels should be carried out using PI diagrams if rebound is not a performance consideration.
- Anchorage should be designed to 1.25 times the ultimate capacity of composite granite panels in both positive and rebound directions respectively, while supporting structure (backup-framing) should be designed to full static capacity of the panels.

This Report
This report provides general background on the work accomplished, a brief description of the testing program, descriptions of the preliminary performance evaluation theories, results of the testing, comparison of analysis results and actual tested system responses, conclusions and recommendations, and supporting calculations.

2 INTRODUCTION

Hinman Consulting Engineers, Inc. (Hinman) was contracted by Cold Spring Granite Co., to develop a shock-tube testing program of eglass laminated composite granite assembly to study feasibility of air-blast protection and to determine the performance of the system when subjected to air-blast loading. The results of this testing and analyses can be utilized in the development of the design of the new composite granite panels as well as performance evaluation of existing panels when used in air-blast protective capacity.

3 BACKGROUND

Eglass laminated composite granite panels have already been tested and are used for ballistic protection. However, their blast resistant capabilities are still under the investigation. We were contracted by Cold Spring Granite Co. to perform preliminary evaluation and to determine the feasibility of using composite granite panels to provide air-blast protection.

4 OBJECTIVES

The objectives of this study are to…

1. determine the feasibility of using eglass laminated composite granite assembly to resist air-blast loads
2. determine dynamic capacity of panels and panel systems, to establish range of protection levels
3. determine level of protection afforded by typical configuration
4. provide recommendations for future design and performance evaluation, when subjected to air-blast loads

5 APPROACH

Out technical approach is outlined below:

1. Perform preliminary analytical evaluation of eglass laminated composite granite assembly to verify the feasibility of this system to resist air-blast loads
2. Based on preliminary analysis derive test program to verify preliminary assumptions and derive target air-blast pressures and impulses for testing
3. Perform shock-tube testing and adjust testing to determine maximum dynamic capacity
4. Derive PI diagrams for test specimens and perform evaluation based on observed damage
5. Perform limited parametric studies for various system configurations other then tested
6. Draw preliminary conclusions and provide design recommendations

6 PERFORMANCE EVALUATION METHODOLOGY

This section outlines our performance evaluation methodology. First step in determining performance levels is to describe damage levels. Damage level descriptions follow response limits document published by US Army Corps of Engineers, Protective Design Center [1]. The second step is to estimate PI diagrams that yield result, which are comparable to observed performance during the testing and adjust design parameters as becomes necessary.

6.1 Performance Evaluation Limits

Performance limits adopted for this study are summarized in Table 1.

Table 1. Performance evaluation limits adopted in this study

Component Damage Level	Description of Component Damage	Ductility	Equivalent Level of Protection
Blowout	Panel is overwhelmed by the blast load causing debris with significant velocities	$\mu > 1.5$	Below AT Standards
Hazardous Failure	Panel has failed, and debris velocities range from insignificant to very significant	$1.25 < \mu \leq 1.5$	Very Low
Heavy Damage	Panel has not failed, but it has significant permanent deflections, replacement is required	$1 < \mu \leq 1.25$	Low
Moderate Damage	Panel has some permanent deflection, replacement may be necessary	$0.75 < \mu \leq 1$	Medium
Superficial Damage	Panel has minimally visible damage, some replacement may be necessary	$\mu \leq 0.75$	High

Ref: Adopted from PDC-TR 06-08, 20 October 2006
Note: Performance limits are for far field effects only
Performance limits exclude damage due to rebound
Span shall not exceed 96in

6.2 Pressure-Impulse Diagrams (PI Diagrams)

Pressure-Impulse (PI) diagrams, also known as isodamage curves, allow for rapid assessment of element response over a large spectrum of air-blast load cases. A PI diagram consists of solved responses of an element graphed on a pressure vs. impulse axis. Each point on the curve is a single value of pressure and impulse which will result in the stated response. Sample PI diagram is shown on Figure 1 along with corresponding performance limit zones.

The system performance to air-blast load prescribed as 20psi pressure and 300psi-msec impulse would be Blowout and this load would approximately correspond to 2,000lb bomb at 150ft distance.

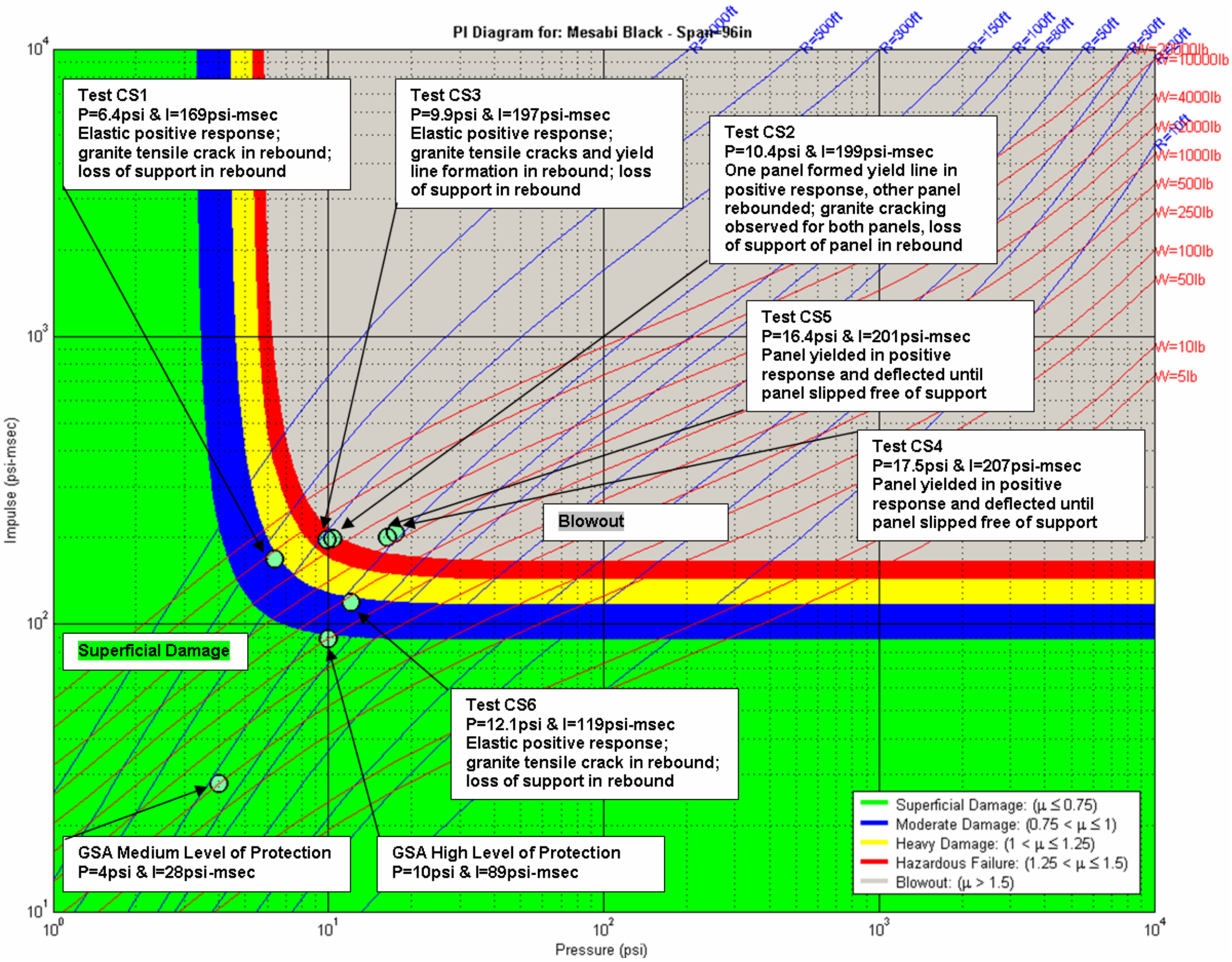

Figure 1. Tests 1 through 6: Damage assessment using PI diagrams
(note: Weapons and standoffs are for reflected pressures and impulses)

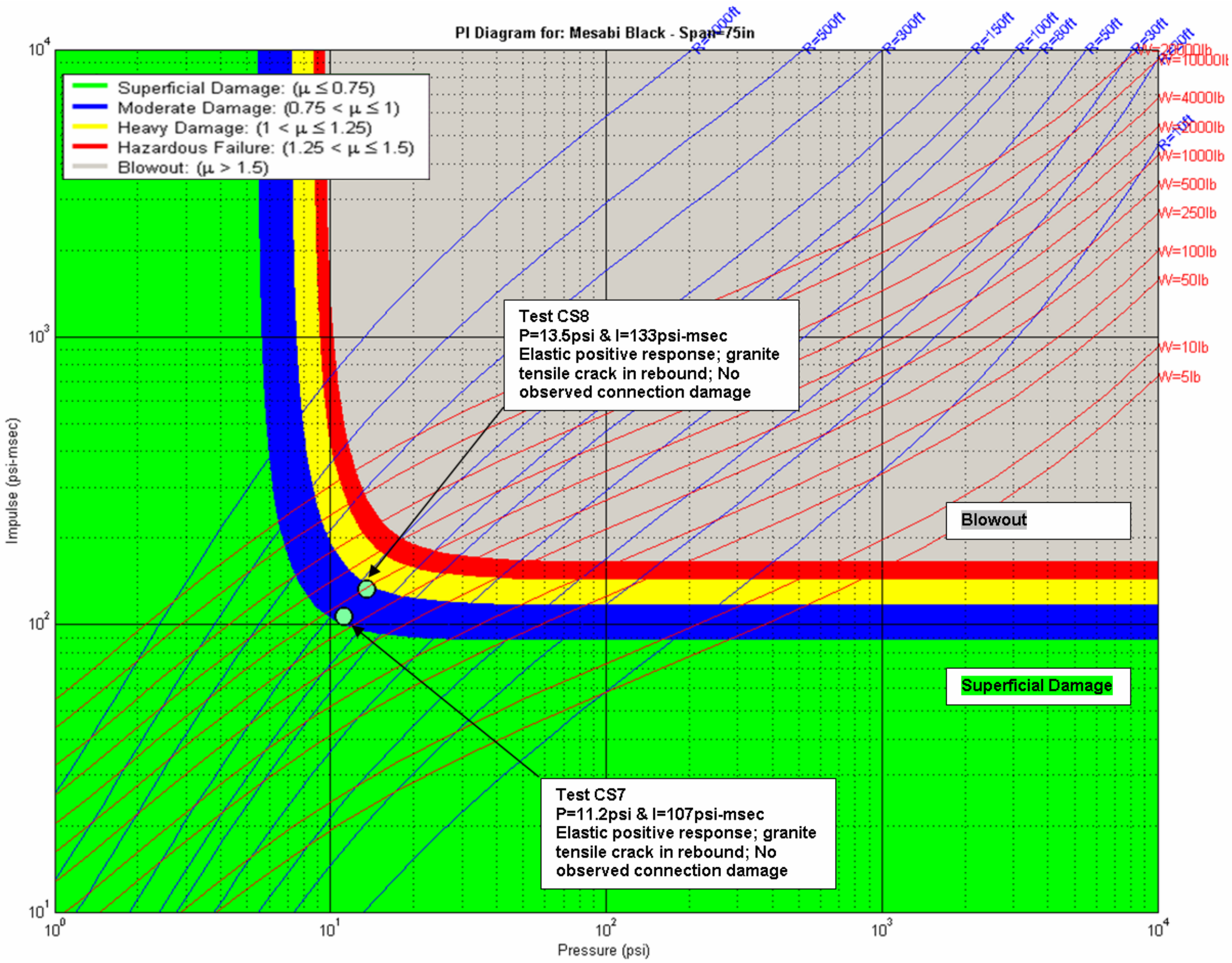

Figure 2. Tests7 and 8: Damage assessment using PI diagrams
(note: Weapons and standoffs are for reflected pressures and impulses)

6.3 Charge Size (Weapon) – Standoff Diagrams (WS Diagrams)

An alternate way of representing PI diagrams is to plot them in standoff weapon format as shown on Figure 3. Advantage of this representation is that structural response could be directly correlated to explosion size and standoff. For example 1,000lb size bomb detonated at distance of 200ft will result in superficial damage, while 1,000lb size bomb detonated at distance of 100ft will cause blowout performance.

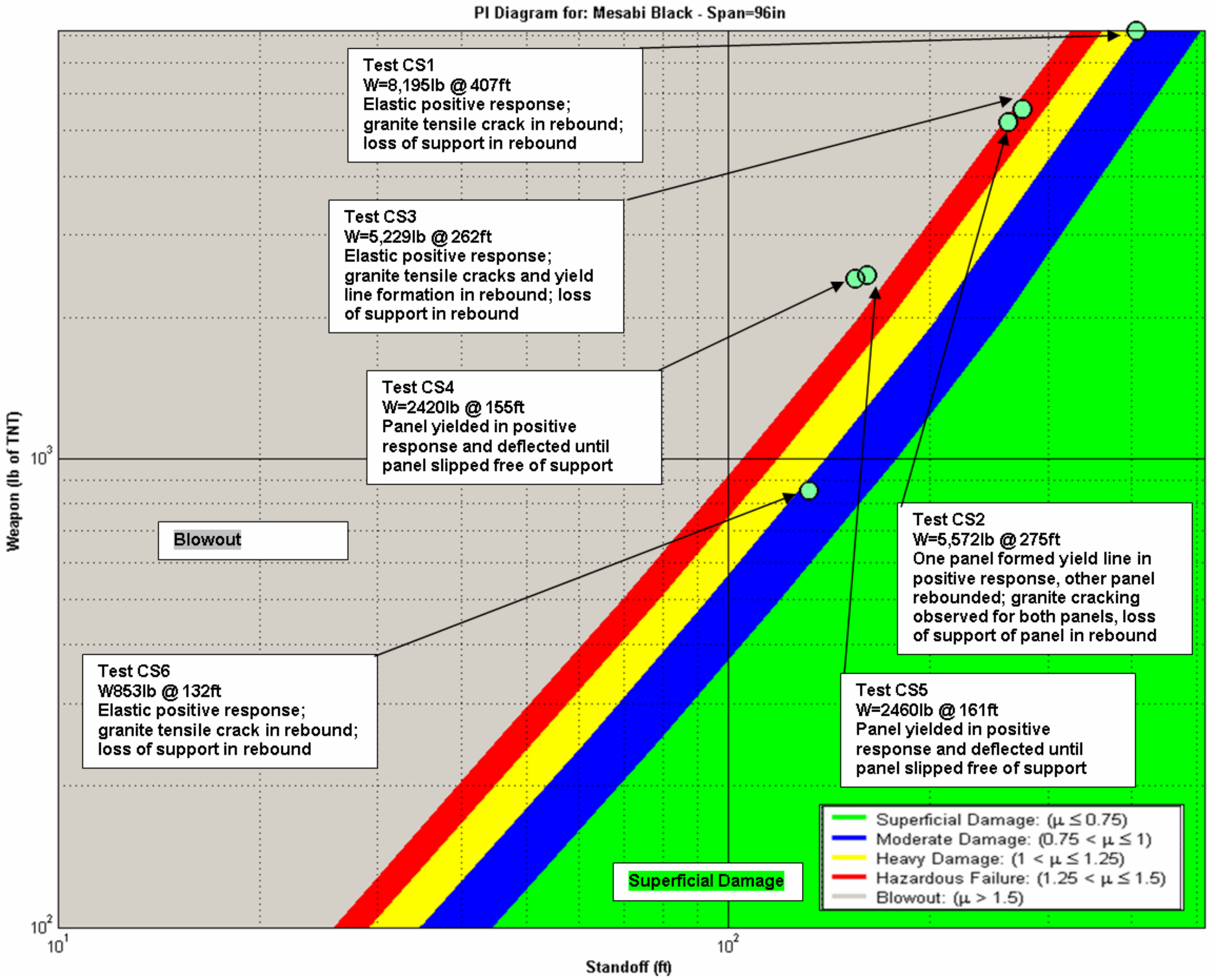

Figure 3. Tests 1thriugh 6: Damage assessment using WS diagrams
(note: Weapons and standoffs are for reflected pressures and impulses)

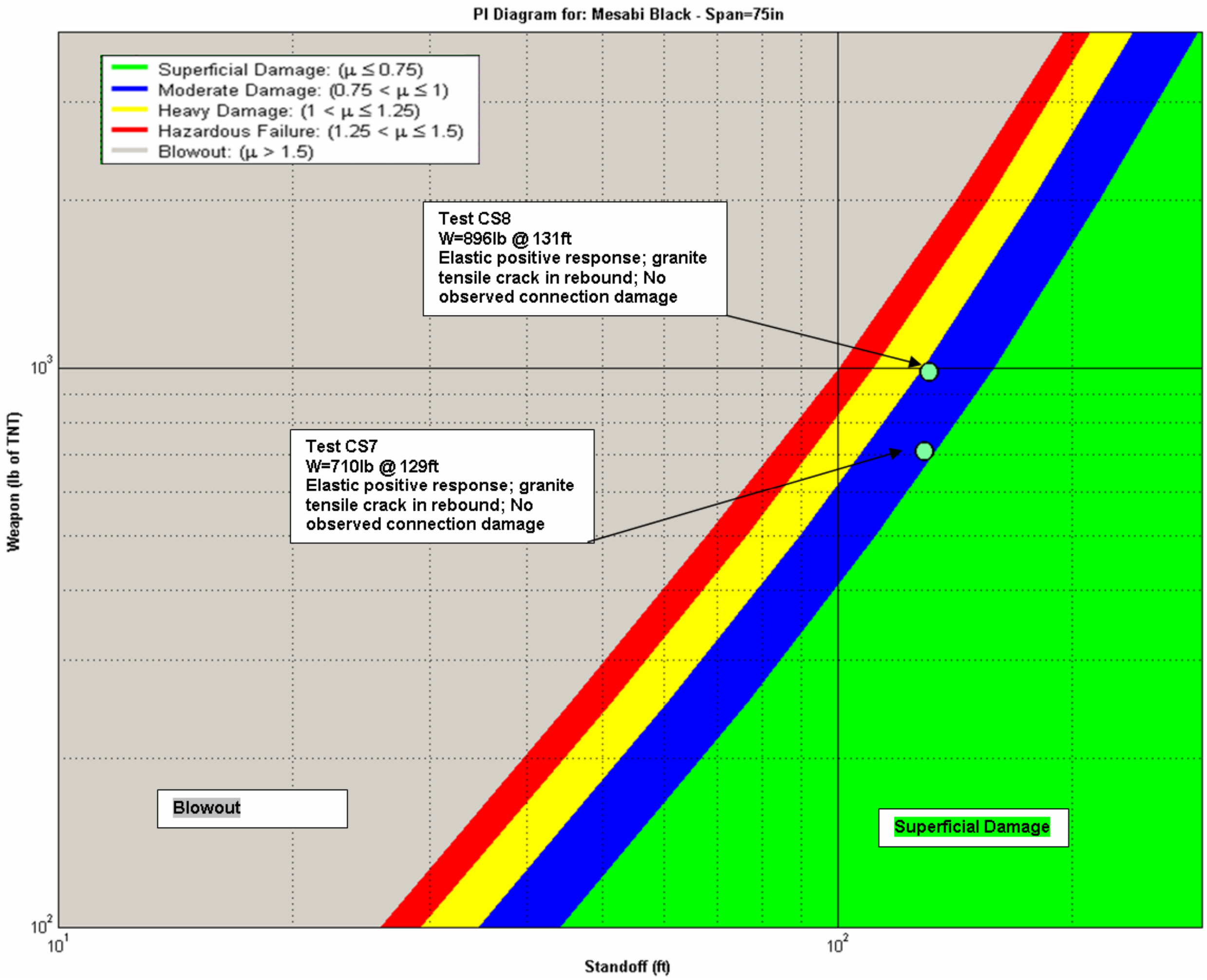

Figure 4. Tests 7 and 8: Damage assessment using WS diagrams
(note: Weapons and standoffs are for reflected pressures and impulses)

7 GRANITE PROPERTIES

Granite mechanical properties were supplied by Cold Spring Granite. Assumed mechanical properties of granite in this study is summarized in Table 2

Table 2. Assumed mechanical properties of granite

Granite	Density lb/ft^3	Modulus of Rupture lb/in^2	Compressive Strength lb/in^2	Flexural Strength lb/in^2	Flexural Modulus of Elasticity lb/in^2
Carnelian	168	1,820	20,800	1,480	9,000,000
Mesabi Black	173	1,830	18,500	1,550	9,000,000
Rockville White	169	1,840	21,000	1,530	9,000,000
Average	170	1,830	20,100	1,520	9,000,000

Ultimate compressive strain = 0.3%
Tensile capacity = 0psi

Eglass mechanical properties were obtained from Hardwire, Inc. (see APPENDIX II: MECHANICAL PROPERTIES)

8 TESTING PROGRAM

This section provides a brief summary of the testing program. More detailed information is provided in the testing lab report by Backer Engineering and Risk Consultants, Inc Report dated August 2, 2007 [4]

The testing program consisted of eight shock tube tests, performed on June 18 2007 through June 22, 2007 at the Baker Engineering and Risk Consultants shock tube testing facility in San Antonio, Texas. Six of the tests (1-6) were conducted with ideal simple support conditions to better understand eglass composite granite behavior under air-blast loads and two of the tests (7 and 8) were conducted for granite panels supported with steel framing, which approximately represent typical installation assembly. Main purpose of testing of typical installation assembly was to determine the performance and anchorage.

Composite granite panels were approximately 8ft x 4ft in size and two panels were tested side-by side, which allowed us to test two specimens at a time.

9 TEST RESULTS EVALUATION

This section presents results of analysis and actual tests and compares them

Table 3. Test results summary [4]

Test No.	Support conditions	Pressure (psi)	Impulse (psi-msec)	Duration (msec)	Response Description	Approximate Corresponding Threat	Performance evaluation
CS1	Ideal simple supports	6.4	169	65	Elastic positive response; granite tensile cracks in rebound; loss of support in rebound	W = 8,195lb Standoff = 407ft	Moderate Damage
CS2	Ideal simple supports	10.4	199	55	One panel formed yield line in positive response, other panel rebounded; granite cracking observed for both panels, loss of support for panel in rebound.	W = 5,572lb Standoff = 275ft	Hazardous Failure
CS3	Ideal simple supports	9.9	197	57	Elastic positive response; granite tensile cracks in rebound; loss of support in rebound	W = 5,229lb Standoff = 262ft	Hazardous Failure
CS4	Ideal simple supports	17.5	207	45	Panels yielded in positive response and deflected until panel slipped free of support	W = 2,460lb Standoff = 161ft	Blowout
CS5	Ideal simple supports	16.4	201	46	Panels yielded in positive response and deflected until panel slipped free of support	W = 2,420lb Standoff = 155ft	Blowout
CS6	Ideal simple supports	12.1	119	45	Elastic positive response; granite tensile cracks in rebound; loss of support in rebound	W = 853lb Standoff = 132ft	Moderate Damage
CS7	Typical installation	11.1	107	43	Elastic positive response; granite tensile cracks in rebound; no observed connection damage	W = 710lb Standoff = 129ft	Moderate Damage
CS8	Typical installation	13.5	133	25.3	Elastic positive response; granite tensile cracks in rebound; no observed connection damage	W = 896lb Standoff = 131ft	Moderate Damage

Performance evaluation of the test results is carried out using PI and WS diagrams as shown below.

9.1 Tests 1 through 6: Ideal Support Conditions

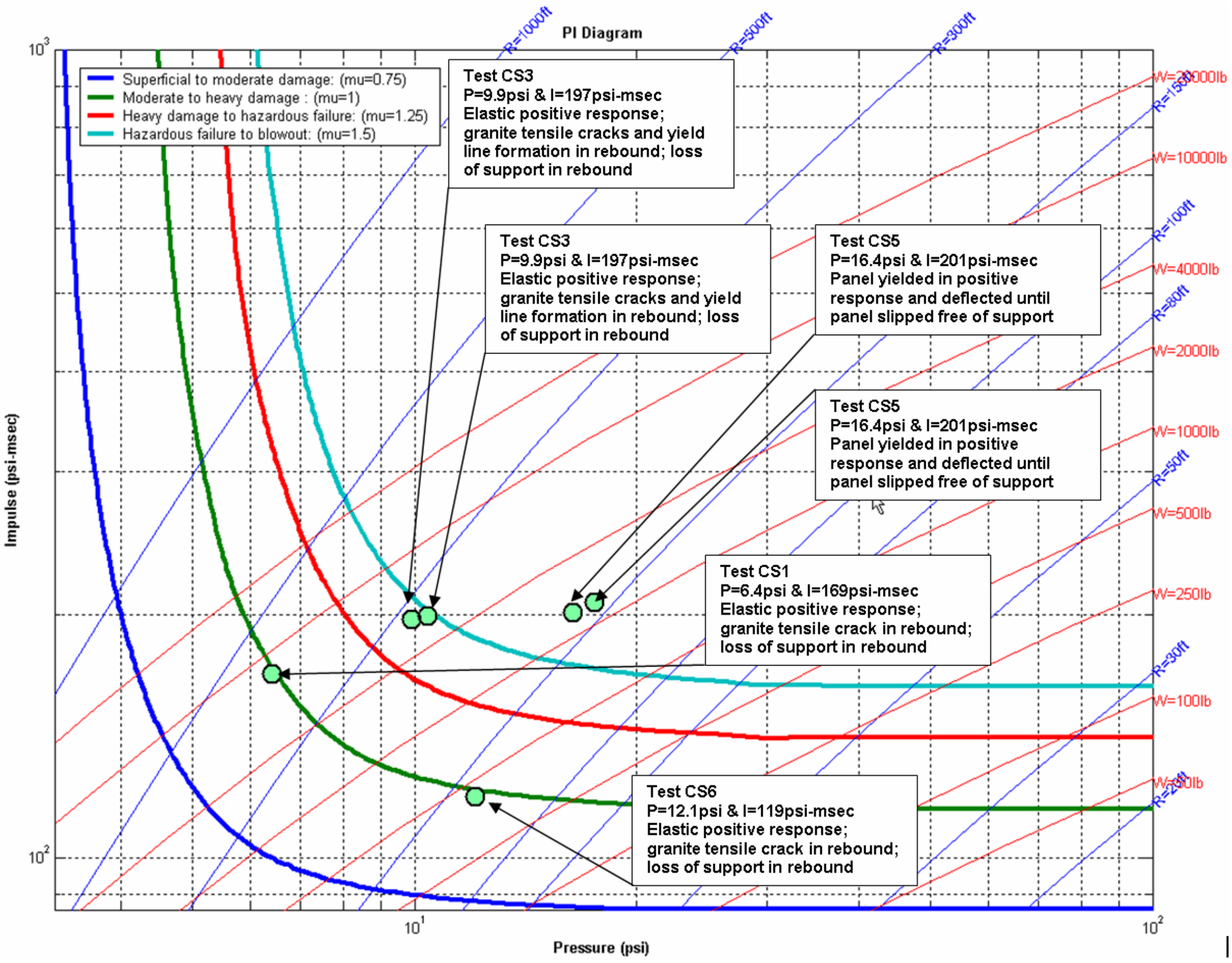

Figure 5. PI diagrams for test 1 though 6
(note: Weapons and standoffs are for reflected pressures and impulses)

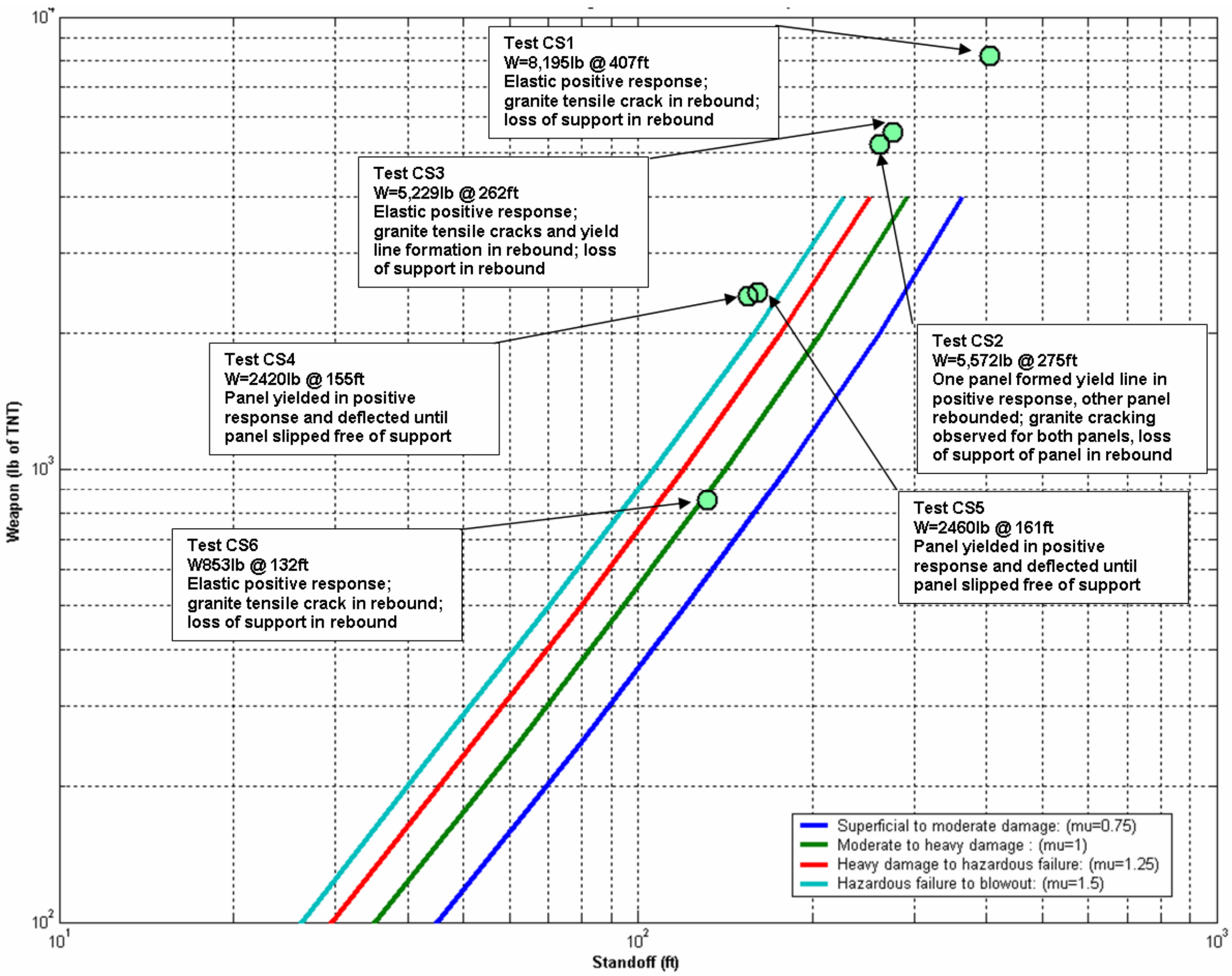

Figure 6. WS diagrams for test 1 though 6
(note: Weapons and standoffs are for reflected pressures and impulses)

9.2 Tests 7 and 8: Typical Installation Support Conditions

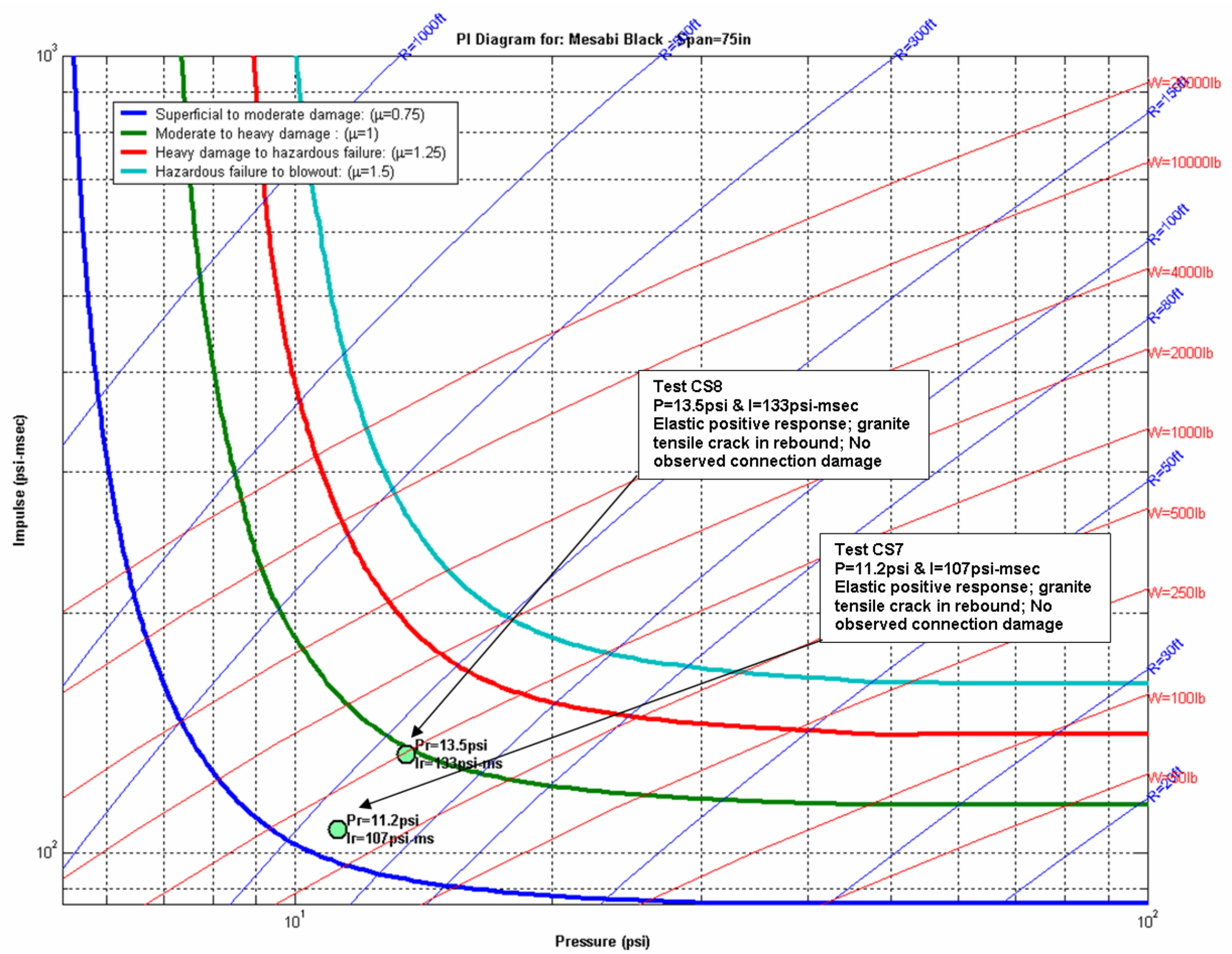

Figure 7. PI diagrams for test 7 and 8
(note: Weapons and standoffs are for reflected pressures and impulses)

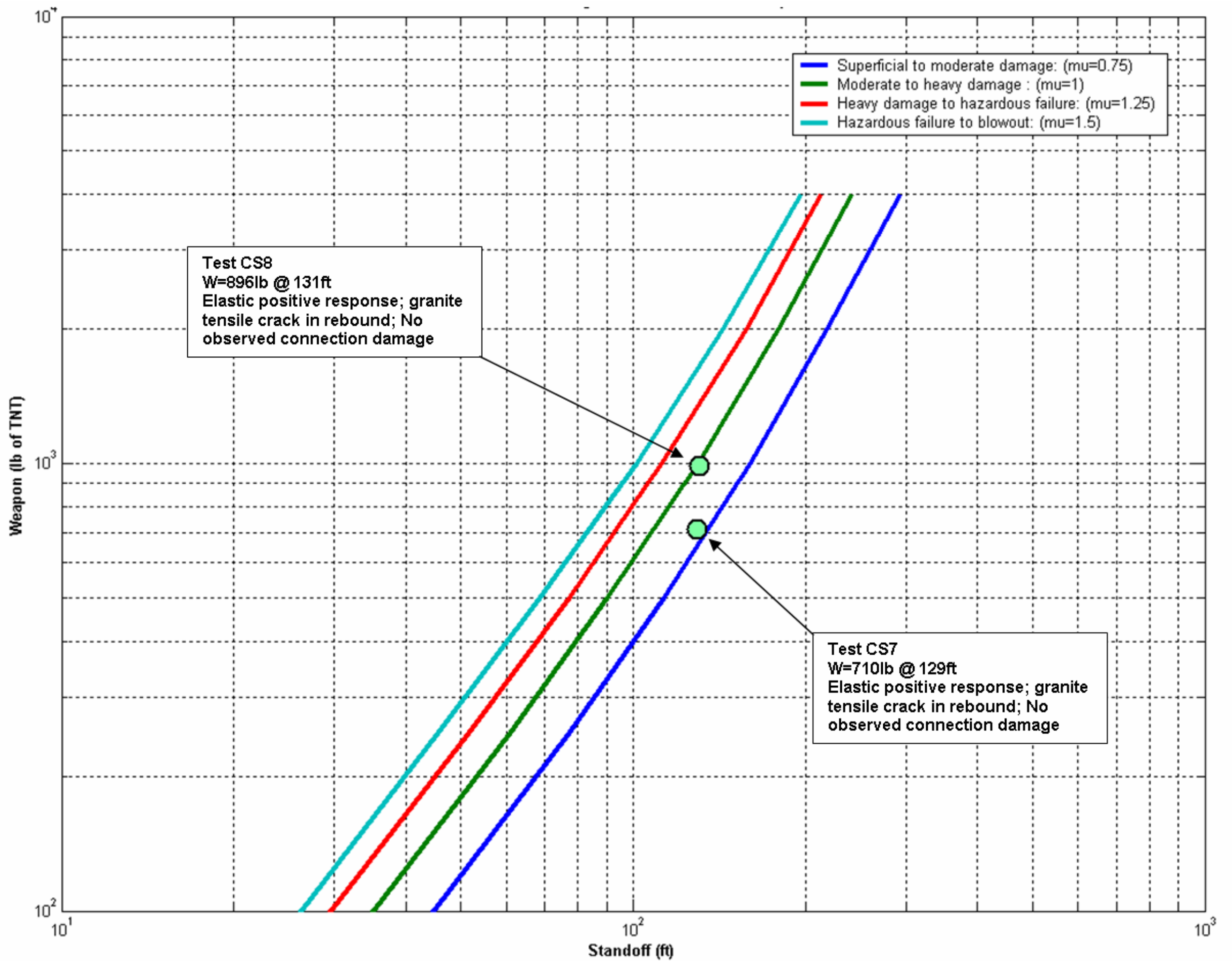

Figure 8.WS diagrams for test 7 and 8
(note: Weapons and standoffs are for reflected pressures and impulses)

10 PERFORMANCE EVALUATION USING PI DIAGRAMS

We have used PI diagrams to perform rapid performance evaluation of composite granite assembly. This section provides summary of our assessment. We have assumed "Mesabi Black" granite properties for this study.

10.1 Expected Performance of Composite Granite

Tables 4 and 5 provide expected performance of composite granite assembly with various eglass and granite thickness and span configuration when subjected to following threats:

1. 500lb of TNT located at 80ft and 100ft distances
2. 1,000lb of TNT located at 80ft and 100ft distances

Table 4. Expected performance of granite-eglass composite system to threat of 500lb at 80ft

Span= 96 in   Threat = 500lb @ 100ft

Granite \ Eglass	0.5in	0.75in	1 in
3cm	Moderate damage	Moderate damage	Moderate damage
4cm	Superficial damage	Superficial damage	Superficial damage
5cm	Superficial damage	Superficial damage	Superficial damage

Span= 75 in

Granite \ Eglass	0.5in	0.75in	1 in
3cm	Moderate damage	Moderate damage	Superficial damage
4cm	Superficial damage	Superficial damage	Superficial damage
5cm	Superficial damage	Superficial damage	Superficial damage

Span= 60 in

Granite \ Eglass	0.5in	0.75in	1 in
3cm	Moderate damage	Superficial damage	Superficial damage
4cm	Superficial damage	Superficial damage	Superficial damage
5cm	Superficial damage	Superficial damage	Superficial damage

Span= 48 in

Granite \ Eglass	0.5in	0.75in	1 in
3cm	Superficial damage	Superficial damage	Superficial damage
4cm	Superficial damage	Superficial damage	Superficial damage
5cm	Superficial damage	Superficial damage	Superficial damage

1 in = 2.54 cm
1 cm = 0.394in

Span= 96 in   Threat = 500lb @ 80ft

Granite \ Eglass	0.5in	0.75in	1 in
3cm	Heavy damage	Heavy damage	Heavy damage
4cm	Moderate damage	Moderate damage	Moderate damage
5cm	Moderate damage	Superficial damage	Superficial damage

Span= 75 in

Granite \ Eglass	0.5in	0.75in	1 in
3cm	Heavy damage	Heavy damage	Moderate damage
4cm	Moderate damage	Moderate damage	Moderate damage
5cm	Moderate damage	Superficial damage	Superficial damage

Span= 60 in

Granite \ Eglass	0.5in	0.75in	1 in
3cm	Heavy damage	Moderate damage	Moderate damage
4cm	Moderate damage	Superficial damage	Superficial damage
5cm	Superficial damage	Superficial damage	Superficial damage

Span= 48 in

Granite \ Eglass	0.5in	0.75in	1 in
3cm	Moderate damage	Moderate damage	Superficial damage
4cm	Superficial damage	Superficial damage	Superficial damage
5cm	Superficial damage	Superficial damage	Superficial damage

1 in = 2.54 cm
1 cm = 0.394in

Table 5. Expected performance of granite-eglass composite system to threat of 1,000lb at 100ft

Span= 96 in   Threat = 1,000lb @ 100ft

Eglass / Granite	0.5in	0.75in	1 in
3cm	Blowout	Hazardous failure	Hazardous failure
4cm	Heavy damage	Heavy damage	Heavy damage
5cm	Moderate damage	Moderate damage	Moderate damage

Span= 75 in

Eglass / Granite	0.5in	0.75in	1 in
3cm	Blowout	Hazardous failure	Heavy damage
4cm	Heavy damage	Moderate damage	Moderate damage
5cm	Moderate damage	Moderate damage	Superficial damage

Span= 60 in

Eglass / Granite	0.5in	0.75in	1 in
3cm	Hazardous failure	Heavy damage	Moderate damage
4cm	Moderate damage	Moderate damage	Superficial damage
5cm	Superficial damage	Superficial damage	Superficial damage

Span= 48 in

Eglass / Granite	0.5in	0.75in	1 in
3cm	Heavy damage	Moderate damage	Superficial damage
4cm	Superficial damage	Superficial damage	Superficial damage
5cm	Superficial damage	Superficial damage	Superficial damage

1 in = 2.54 cm
1 cm = 0.394in

Span= 96 in   Threat = 1,000lb @ 80ft

Eglass / Granite	0.5in	0.75in	1 in
3cm	Blowout	Blowout	Blowout
4cm	Blowout	Blowout	Hazardous failure
5cm	Hazardous failure	Heavy damage	Heavy damage

Span= 75 in

Eglass / Granite	0.5in	0.75in	1 in
3cm	Blowout	Blowout	Blowout
4cm	Blowout	Hazardous failure	Hazardous failure
5cm	Heavy damage	Heavy damage	Heavy damage

Span= 60 in

Eglass / Granite	0.5in	0.75in	1 in
3cm	Blowout	Blowout	Hazardous failure
4cm	Hazardous failure	Heavy damage	Heavy damage
5cm	Heavy damage	Moderate damage	Moderate damage

Span= 48 in

Eglass / Granite	0.5in	0.75in	1 in
3cm	Blowout	Hazardous failure	Heavy damage
4cm	Heavy damage	Moderate damage	Moderate damage
5cm	Moderate damage	Superficial damage	Superficial damage

1 in = 2.54 cm
1 cm = 0.394in

10.2 Supporting Structure Considerations

Composite granite panels are relatively heavy elements and if dislodged from supported structure could generate potentially lethal fragments. Therefore we recommend that supporting structure be able to resist loads up to the ultimate capacity of composite granite. Table 6 list calculated ultimate capacities of eglass laminated composite granite with various spans.

Table 6. Summary of static ultimate capacities of granite-glass composite assembly

Span= 96 in   Positive phase static resistance

Granite \ Eglass	0.5in	0.75in	1 in
3cm	Ru= 8.39 psi	Ru= 11.03 psi	Ru= 13.85 psi
4cm	Ru= 12.15 psi	Ru= 15.55 psi	Ru= 19.02 psi
5cm	Ru= 16.42 psi	Ru= 20.68 psi	Ru= 24.88 psi

Span= 75 in

Granite \ Eglass	0.5in	0.75in	1 in
3cm	Ru= 13.74 psi	Ru= 18.07 psi	Ru= 22.69 psi
4cm	Ru= 19.90 psi	Ru= 25.48 psi	Ru= 31.17 psi
5cm	Ru= 26.90 psi	Ru= 33.88 psi	Ru= 40.76 psi

Span= 60 in

Granite \ Eglass	0.5in	0.75in	1 in
3cm	Ru= 21.47 psi	Ru= 28.24 psi	Ru= 22.22 psi
4cm	Ru= 31.09 psi	Ru= 39.81 psi	Ru= 48.70 psi
5cm	Ru= 42.02 psi	Ru= 52.94 psi	Ru= 63.68 psi

Span= 48 in

Granite \ Eglass	0.5in	0.75in	1 in
3cm	Ru= 33.55 psi	Ru= 44.12 psi	Ru= 55.41 psi
4cm	Ru= 48.58 psi	Ru= 62.21 psi	Ru= 76.09 psi
5cm	Ru= 65.66 psi	Ru= 82.72 psi	Ru= 99.50 psi

1 in = 2.54 cm
1 cm = 0.394in

Span= 96 in   Static resistance in rebound

Granite \ Eglass	0.5in	0.75in	1 in
3cm	Ru= 0.56 psi	Ru= 0.74 psi	Ru= 0.92 psi
4cm	Ru= 0.81 psi	Ru= 1.04 psi	Ru= 1.27 psi
5cm	Ru= 1.09 psi	Ru= 1.38 psi	Ru= 1.66 psi

Span= 75 in

Granite \ Eglass	0.5in	0.75in	1 in
3cm	Ru= 0.92 psi	Ru= 1.20 psi	Ru= 1.51 psi
4cm	Ru= 1.33 psi	Ru= 1.70 psi	Ru= 2.08 psi
5cm	Ru= 1.79 psi	Ru= 2.26 psi	Ru= 2.72 psi

Span= 60 in

Granite \ Eglass	0.5in	0.75in	1 in
3cm	Ru= 1.43 psi	Ru= 1.88 psi	Ru= 1.48 psi
4cm	Ru= 2.07 psi	Ru= 2.65 psi	Ru= 3.25 psi
5cm	Ru= 2.80 psi	Ru= 3.53 psi	Ru= 4.25 psi

Span= 48 in

Granite \ Eglass	0.5in	0.75in	1 in
3cm	Ru= 2.24 psi	Ru= 2.94 psi	Ru= 3.69 psi
4cm	Ru= 3.24 psi	Ru= 4.15 psi	Ru= 5.07 psi
5cm	Ru= 4.38 psi	Ru= 5.51 psi	Ru= 6.63 psi

1 in = 2.54 cm
1 cm = 0.394in

Note: Ultimate resistance is based on one way spanning element

10.3 Rebound Considerations

Damage and failure patterns observed throughout the test confirm that eglass laminated granite assembly is highly susceptible to rebound damage in the form of broken granite pieces being delaminated and thrown back toward the threat source. It is expected that eglass panels themselves will not be dislodged due air-blast loads comparable to heiger level of protection since eglass has large tensile strength and therefore protected space will still be sheltered from outside weather. Although this type of response does not pose significant threat to the occupants in the space to be protected, the replacement of granite panels may become necessary.

11 CONCLUSIONS AND RECOMMENDATIONS

Our conclusions and recommendations, for air-blast loads only, are presented below and are based on the underlying assumption that the panel system is already designed to accommodate all service loads including but not limited to dead, live, wind and seismic loads and load combinations

11.1 Conclusions

Based on the study performed, the following conclusions are drawn:

1. Testing of composite granite assembly verified that this system can be effectively used to provide protection against air-blast loads.
2. Tested composite granite assembly provided a protection level equivalent to GSA High Level of Protection.
3. Testing also revealed that composite granite panels are very brittle and weak in rebound direction. Although it is expected that broken granite pieces will come loose during the rebound, eglass laminate panels are expected to remain anchored and still provide protection to occupied space.
4. Design of anchorage and supporting framing system is of great importance, since composite granite panels are very heavy and could generate lethal debris if thrown into the occupied space.

11.2 Recommendations for New Design

Based on the study performed, the following recommendations are made:

1. Composite granite panels should be design to a performance condition not to exceed Moderate Damage.
2. Supporting structure should be designed to full static capacity of the panels as tabulated in Table 6.
3. Anchors should be designed to 1.25 times the ultimate capacity of composite granite panels in both positive and rebound directions respectively.
4. Overall performance of composite granite and supporting structure assembly should be verified by constructing corresponding PI diagrams.
5. If damage due to rebound is a consideration, direct time-history analysis should be conducted.

11.3 Recommendations for Performance Evaluation

Based on the study performed, the following recommendations are made:

1. Performance evaluation should be carried out using PI diagrams if rebound is not a performance consideration.
2. If rebound is a performance consideration, performance evaluation should be carried out using direct time-history analysis methodologies.
3. Ultimate as well as dynamic capacities of supporting structure including anchorage should be taken into consideration.

11.4 Additional Testing Recommendations

While the data presented from this testing series allows the above recommendations to be developed, these tests represent only a limited number of data points. As with all blast resistant systems, the greater the number of validating data points the greater the confidence in the recommended approach. Additionally, it is desirable to perform static or dynamic testing of anchoring system used to secure composite panels. We therefore recommend additional testing series of a similar nature.

12 REFERENCES

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