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Building Siting Screening Criteria for Structural Failure Hazards to Occupants

Johnny Waclawczyk*, Mark Whitney
ABSG Consulting, Inc
140 Heimer Rd Suite 300 San Antonio, TX 78232
*Presenters E-mails:jwaclawczyk@absconsulting.com

Abstract

Evaluation of occupied buildings for accidental explosion hazards at petrochemical facilities is a vital part of a process safety program and is a key element of facility siting. In some cases, buildings may be screened out prior to performing structural blast evaluations due to minimal exposure to blast loading. Defining a minimum blast load in which a specific type of building may be screened without structural assessment is left to the owners or their engineering consultants. Determining when a structural assessment for blast hazards is necessary is a critical safety decision.

Currently, API-752 does not include a blast load value that can be used for screening out building types without the requirement for structural assessment. Other publications provide pressure-based benchmarks for screening either for buildings in general or for specific types of buildings. This paper reviews industry guidance and makes recommendations for building blast-screening for consideration in the next revision of API-752.

Keywords: Risk Assessment, Quantitative Risk Assessment, Consequence Techniques, Explosions, Building Screening, Blast Assessment, Minimum Blast Load Hazard, API-752

1 Introduction

Ensuring protection of personnel in the event of an accidental explosion is paramount in a blast hazards assessment. Physiologically, humans can withstand higher blast pressures (e.g. 99% survivability with overpressure < ~1.9 Bar and threshold of eardrum damage ~5 psi [[1]]) than many structures. Pressure in these range can cause significant structural damage to conventionally constructed buildings resulting in severe injuries and fatalities due to structural failure and debris. Thus, evaluation of occupied buildings for accidental explosion hazards at petrochemical facilities is a vital part of a process safety program and is a key element of facility siting.

There are three traditional methods of evaluating of buildings for blast hazards; detailed finite element analysis (FEA), basic dynamics (single and multi-degree of freedom systems), and screening based on blast loads. Building screening is sometimes applied and performed by defining a minimum blast load in which a specific type of building(s) may be considered adequate for personnel protection prior to performing structural blast evaluations due to minimal exposure to blast loading. Screening policy and definition of acceptable blast load criteria are left to the owners or their engineering consultants to perform.

Various industries and government agencies have provided varying levels of regulatory requirements, recommended practices, guidance documents and minimum standards regarding blast evaluation of buildings and screening limits.

American Petroleum, Institute (API) API-752 [2] is a recommended practice for accidental explosions in the industrial facilities. Currently, API-752 does not include a blast load value that can be used for screening out building types without the requirement for structural assessment. Other publications provide pressure-based benchmarks for screening either buildings in general or for specific types of buildings. This paper reviews industry guidance, examines difficulties and challenges for screening evaluations, and makes recommendations for building blast-screening for consideration in the next revision of API-752.

2 Building Screening for Blast Hazards

Screening level analysis is intended to establish the adequacy of a building to perform at or better than a specific level of response without performing structural calculations. In most cases, a blast pressure value is referenced in which a building would be expected to sustain a particular level of damage. If blast loads on the building are predicted to be at or lower than the screening value no additional structural analyses are necessary, and the building is considered adequate to withstand structural failure hazards. Non-structural hazard screening criteria (e.g., window fragments, falling overhead lights, overturning equipment racks) may still require assessment and are not addressed by this paper. Some screening values for window glass hazards are mentioned below, but the focus of the paper is structural failure hazards.

Establishing screening criteria has been accomplished in many ways. Historical references and industry guides often provide and update screening values for blast hazards. Subject matter experts with extensive experience with structures subjected to blasts have provided information, data, and methods for screening structural systems for blast response. Collection and comparison of damage to buildings affected by accidental explosion is also highly relied upon to set screening levels. Finally, research and blast testing are used to establish, refine, and supplement screening criteria.

Screening criteria have often been established based upon construction type (e.g. masonry buildings, pre-engineered metal buildings, light weight wood trailers, etc.). In an effort to simplify screening and evaluations, a single pressure value is often sought after that could be applied to many types of buildings in a “one size fits all” approach. It should also be pointed out that screening criteria does not typically directly address occupant vulnerability which is a primary intent of blast hazard assessment.

Diligent care must be used in order to apply screening criteria properly. A clear understanding of the background of the established screening criteria being used is critical. The industry that the criteria was intended for can dictate the type of blast loads that the information is applicable. For example, criteria established for Department of Defense use would likely assume highly energetic materials and explosives which tend to result in higher pressure shorter duration blast loads. While industrial facilities criteria such a refineries and chemical plants are more likely to criteria based on vapor cloud explosions (VCEs) with lower pressure and longer duration blast waves. It should be known whether the screen values are based on overpressure or free-field blast loading of applied loads to surfaces of a building. It is common to reference screening criteria based on pressure values alone. In such cases, criterion must be based on long duration blast loads such as those from VCEs (hundreds of milliseconds). However, guides and documents often do not always reference the type of explosion or assumed blast duration and present only a pressure value as it relates to a building damage.

3 Published Criteria

A sampling of published screening criteria in a variety of sources was reviewed and included documents and references from institutes and associations related to oil, gas, and chemical industries, government agencies, Department of Defense, and international standards.

3.1 API-752

API-752 and API-753[3] are two of the most recognized documents for recommended practices in the blast hazard evaluation in oil, gas, and chemical processing industries. Table 4 of the 1st [4] and 2nd [5] editions of the API-752 document includes of free-field overpressure values with consequences for various building types (a copy is shown below in Table 1). The document states "In a consequence analysis, it may be assumed that building occupants could incur injuries if the integrity of the building is exceeded.".

Table 1. Overpressure and Consequences on Various Building Types (1st and 2nd Edition of API-752)

Table 4—Overpressure on Various Building Types

Building Type	Peak Side-on Overpressure (psi)	Consequences
Wood-frame trailer or shack	1.0	Isolated buildings overturn. Roofs and walls collapse
	2.0	Complete collapse
	5.0	Total destruction
Steel-frame/metal siding pre-engineered building	1.5	Sheeting ripped off and internal walls damaged. Danger from falling objects
	2.5	Building frame stands, but cladding and internal walls are destroyed as frame distorts
	5.0	Total destruction
Unreinforced masonry bearing wall building	1.0	Partial collapse of walls that have no breakable windows
	1.25	Walls and roof partially collapse
	1.5	Complete collapse
	3.0	Total destruction
Steel or concrete frame w/unreinforced masonry infill or cladding	1.5	Walls blow in
	2.0	Roof slab collapses
	2.5	Complete frame collapse
	5.0	Total destruction
Reinforced concrete or masonry shear wall building	4.0	Roof and wall deflect under loading. Internal walls damaged
	6.0	Building has major damage and collapses
	12.0	Total destruction

Note: Source: *The Effects of Nuclear Weapons*, rev. ed., Samuel Glasstone, Editor
Prepared by the U.S. Department of Defense, published by U.S. Atomic Energy Commission

For the 5 building types included the minimum overpressure listed with a building damage consequence ranged from 1 psi to 1.5 psi. This may give the impression that buildings can be screened for blast damage hazards at about 1 psi. The values were given based on nuclear weapons testing prior to 1964 indicating very long duration blast loads.

Both the 1st and 2nd Editions of API-752 also included pressure effects on various building components (shown in Table 2) based on loads applied as reflected pressures. Assuming a reflection factor of about 2.0 for lower pressures the following values for selected common building components would result the following:

- 0.25-0.5 psi (20-35 mbar) Glass shattering with hazardous velocities
- 0.5-1.5 psi (35-100 mbar) Metal/Cemesto/Brick Cladding
- 0.5-1.5 psi (35-100 mbar) URM wall collapse, possible shattering

Table 2. Overpressure and Effects on Various Building Components (1st and 2nd Edition of API-752)

Table 3—Overpressure Effects on Various Building Components[a]

Building Component	Reflected Overpressure (PSIG)	Component Response
Glass	0.2	Breaking
Glass	0.5 – 1.0	Shattering with body penetrating velocities
Wooden frame	1.0 – 2.0	Structural failure and potential collapse
Steel cladding	1.0 – 2.0	Internal damage to walls, ceilings and furnishings
Concrete-asbestos cladding (Transite)	1.0 – 2.0	Shattering
Brick cladding	2.0 – 3.0	Blown-in
Unreinforced masonry	1.0 – 3.0	Wall collapse, possible shattering

Note: [a]Source: *The Effects of Nuclear Weapons* by Glasstone (1964).

As mentioned, Table 1 utilizes free-field overpressure and Table 2 utilizes reflected overpressure. It is important to know which is being used when relying on any source for pressure-based screening.

The most recent version of the API-752 document (3rd Edition) does not include any pressure to building or component damage related information. Rather, it promotes the use of updated technology for prediction of blast damage to buildings, determination of occupant vulnerabilities, and estimates of event frequencies. It also points the evaluators toward building damage level assessments using tools such as charts (or software that automate use of charts) that have been developed based on the assessment of representative buildings or detailed structural analysis. Tables listing the lowest overpressures from the charts that cause specific damage levels (pressure asymptotes) may also be used.

3.2 API 753

API-753 was written to specifically address process plant portable buildings. Table 2 of the document (included in Table 3 below) contains upper bound free-field pressure values two damage level descriptions for lightweight wood trailers. These are generally considered the weakest constructed portable building used in the processing industries. The establishment of the upper bound pressures was based on FEA modeling and compared with empirical damage observed at accident sites involving vapor cloud explosions. The lower limit value of 0.6 psi is regularly used to site temporary light wood trailers for low vulnerability to occupants. Some companies that are less risk-adverse use the 0.9 psi value.

Table 3. Upper Bound Pressure V Damage Level for Lightweight Wood Trailers

Table 2—Overpressure Effects on Light Wood Trailers

Building Damage Level (BDL)	BDL Description	Parameters Used for Light Wood Trailers	Upper Bound Pressure
2A	Trailer is damaged in localized areas. Individual components on walls facing the blast sustain up to major damage. Other walls and the roof sustain up to moderate damage. Window breakage and falling overhead items are expected.	Studs on the reflected wall (the wall facing the explosion) are expected to crack but remain in place.	0.6 psi
2B	Trailer damage is widespread, but structural collapse is not expected. Wall components facing the blast sustain major damage and may fail. Wall and roof components not facing the blast sustain up to major damage. Window breakage and falling overhead items are expected	Studs on the walls that do not face the explosion are expected to crack with more significant damage to the reflected wall.	0.9 psi
Data from *Pressure Levels for Siting Wood Trailers Using the API RP 752 Addendum Simplified Approach*, BakerRisk Paper No. 760-110-06, September 8, 2006.			

3.3 Chemical Industries Association UK

In the United Kingdom, the Chemical Industries Association's (CIA) presents a benchmark value for overpressure and damage threshold for buildings in the 3rd Edition of "Guidance for the location and design of occupied buildings on chemical manufacturing sites" [6]. Table 4.1 of the CIA guidance (shown in Table 4) cites a value of 0.4 psi (30 mbar) below which overpressure are insufficient to cause structural damage or significant glass hazards. The guide states "Where hazard criteria are not exceeded no specific building design features or upgrades are required." Therefore, the overpressure value is intended as encompassing screening value. Reviewing the source [7] for this value illustrates that it is a lower bound selected from a listing of a variety of construction components and qualitative damage descriptions over a range of overpressures. Although not explicitly noted, it is presumed that the 0.4 psi is based on free-field overpressure at the building location.

Table 4. Chemical Industry Association (UK) Benchmark

Table 4.1 Often applied Benchmarks for the hazard based approach.

Hazardous effect	Benchmark value below which no specific building safety measures are required	Basis
Explosion overpressure	30mbar	Overpressures below 30mbars are insufficient to cause structural damage or significant window glass hazards[28a]
Thermal radiation[19]	6.3 kW/m^2	Radiation levels below 6.3kW/m^2 are taken as "safe escape" (1% fatality 90 seconds exposure)
Flammable gas	LFL	Buildings outside LFL will not experience ingress of flammable gas above flammable concentrations
Toxic gas concentration	EPRG 3	Buildings outside EPRG 3 will not experience concentrations of concern from toxic gas ingress

28 a. *Derivation of Fatality Probability Functions for Occupants of Buildings Subject to Blast Loads, Phases 1, 2 & 3.* W S Atkins Science and Technology, Contract Research Report 147, ISBN 0 7176 1434 4.

3.4 TNO "Green Book"

Another international source, often referred to as the "TNO Green Book"[8], has been commonly used for building damage estimation based on tables of overpressures and damage descriptions. From a sampling of these tables, shown in Table 5, it is seen that in the pressure range of 1 to 2 psi damage is described as Minor to Moderate, partial roof collapse and 25% wall failure, and walls of concrete block have collapsed. Glass hazards are also noted at 0.4 psi (3kPa) with 50% of all window panes will be broken.

Table 5. TNO Green Book Damage Descriptions

70 kPa	: More than 75% of all outer walls have collapsed.
35 kPa	: The damage is not repairable; 50% to 75% of all outer walls are lightly to heavily damaged. The remaining walls are unreliable.
7-15 kPa	: Not habitable without very major repair works. Partial roof failures, 25% of all walls have failed, serious damages to the remaining carrying elements. Damages to window-frames and doors.
3 kPa	: Habitable after relatively easy repairs. Minor structural damage.
1-1.5 kPa	: Damages to roofs, ceilings, minor crackformation in plastering, more than 1% damage to glass-panels.

Table 5. Damages to structures.

Description of Damage	P_s(kPa)
Connections between steel or aluminium ondulated plates have failed	7-14
Walls made of concrete blocks have collapsed	15-20
Brickstone walls, 20 - 30 cm, have collapsed	50
Minor damage to steel frames	8-10
Collapse of steel frames and displacement of foundation	20
Industrial steel self-framing structure collapsed	20-30

3.5 HUD and EPA-RMP

Two government agency documents include minimum pressure values for blast hazards on structures in which mitigation is not required. The U.S. Housing and Urban Development (HUD) and Environmental Protection Agency (EPA). The HUD guidebook[9], "Siting of HUD-assisted Projects near Hazardous Facilities (HUD-1060-CPD, Sept. 1996)" provides the technical guidelines to determine acceptable separation distances. It indicates a minimum pressure of 0.5 psi is acceptable based on the statement in the document. *"Research conducted by military services indicated that 0.5 psi is an acceptable level of blast overpressure for both people and buildings. At this level, people will probably not be injured (especially if located inside a building) and no major structural damage will result to buildings, with the exception of broken windows."*

The EPA requires facilities which store or produce hazardous materials at various minimum quantities to have a Risk Management Plan (RMP). EPA has prepared a separate document, *RMP Offsite Consequence Analysis Guidance*[10], which provides simple methods and reference tables for determining distance to an endpoint for worst-case and alternative release scenarios.

In the document, a 1.0 psi overpressure is given for acceptable exposure for offsite structures. It does not exclude the possibility of severe injuries or death. It does qualify its guidance with the following: *"this overpressure may cause property damage such as partial demolition of houses, which can result in injuries to people, and shattering of glass windows, which may cause skin laceration from flying glass"*.

3.6 High Explosive Related Regulations

Department of Defense (DoD) Explosives Safety Manual 6055.9 [[11]] contains published maximum overpressure exposure limits for inhabited building and public property lines. This document requires that without detailed analysis inhabited buildings may not be exposed to more than1.2 psi and 0.9 psi for small explosion and large explosions, respectively. Above these thresholds mitigation measures are required or detailed analysis is needed to show structural damage is limited to acceptable levels.

NATO's AASTP-1[[12]] is a similar document to the DoD 6055.9. In the AASTP-1, 0.72 psi (50 mbar) is given as the limit for exposure for inhabited buildings. This is reduced to 0.3 psi (20 mbar) for high importance buildings (e.g. schools, hospitals, and glass clad buildings). The 0.72 psi limit is qualified with, *"The distances are intended to prevent serious structural damage by blast, flame or projections to ordinary types of inhabited buildings (23 cm brick or equivalent) or caravans and consequent death or serious injuries to their occupants."* It is further added that the limits are "not sufficiently large to prevent breakage of glass and other frangible panels or cladding used in … buildings of vulnerable construction.".

3.7 American Society of Civil Engineers

The American Society of Civil Engineers (ASCE) "Design of Blast Resistant Buildings in Petrochemical Facilities" [[13]] was written with a specific audience of design engineers supported the petrochemical industry. It includes recommendations and methodologies for development of blast loads, dynamic analysis of structures, responses criteria, and damage limits specifically related to hazards associated with petrochemical facilities. While focused on design, the document does address siting buildings, designed for conventional loads only, at an overpressure of 1 psi or less. It goes on to state that *"…unstrengthened buildings can sustain damage less than five percent of the replacement cost and personnel are provided a high degree of protection from death or serious injury."* The basis selection of this value is provisions of DoD 6055.9 limits for inhabited buildings (see Section 3.6 for discussion of DoD 6055.9). It should be noted that the ASCE committee is currently considering a reduction of this over pressure in future editions of the guide.

As can be seen from the sampling of literature regarding blast hazard assessments on building, there is a range of minimum values that are presented or may be interpreted as overpressure screening data. A summary of those examined here is shown in Table 6.

Table 6. Summary of Building "Screening" Values

Source	**Building/Component Type**	**Screening Pressure (psi)**
API 752 2nd Edition (2003)[1]	Glass shattering with hazardous velocities	0.25 - 0.5
	Metal/Cemesto/Brick Cladding	0.5 - 1.5
	URM wall collapse, possible shattering	0.5 - 1.5
API 753	Level 2A Damage	0.6
	Level 2B Damage	0.9
Chemical Industries Association	No structural damage or significant glass hazard	0.44
TNO Green Book	Minor to Moderate Damage Partial roof collapse and 25% wall failure	1 - 2
HUD	No major structural damage with the exception of broken windows. Low probability of injury.	0.5
EPA-RMP	Partial demolition of houses, shattering of glass windows Some injuries to people and possible skin laceration from flying glass	1.0
DoD 6055.9	Inhabited Buildings and Property Boundaries – small explosions	1.2
	Inhabited Buildings and Property Boundaries – small explosions	0.9

Source	Building/Component Type	Screening Pressure (psi)
NATO AASTP-1	Schools, hospitals, and glass clad buildings	0.3
	Ordinary inhabited buildings Prevent serious structural damage by blast, flame or projections to ordinary buildings and consequent death or serious injuries to their occupants."	0.72
ASCE – Design of Blast-Resistant Buildings in Petrochemical Facilities	Based on DoD 6055.9 Unstrengthened buildings can sustain damage less than five percent of the replacement cost and personnel are provided a high degree of protection from death or serious injury	1.0[2]
[1]3rd Edition removed the values and no new minimums were established [2]Committee currently considering a reduction in this value		

4 Reasons for Caution

Selection of a single value for screening buildings of different construction is without a doubt challenging. Determination of a screening overpressure for a single type of construction can also be difficult. Two buildings with the same basic construction can have significantly different load carrying capacities due to differences in details and intended structural response.

Lack of ductility in a structural component dramatically reduces its blast resistance and allowable response levels. As an example, a common construction type in many facilities utilizes concrete masonry units (CMU) or block walls. In locations with very low or no seismic loading requirements, many CMU walls were constructed without steel reinforcement for out of plane loads. A comparison of applied pressure and impulse capacities of unreinforced CMU walls with a similar wall with minimal reinforcement included is illustrated in the Figure 1. Figure 1 is a traditional Pressure-impulse (P-i) diagram. These P-i diagrams are for applied loading as are all of the diagrams shown in the paper. As can be seen in the diagrams, the minimal amount of reinforcement more than doubles its pressure asymptote. For a building evaluator, the visual difference between these two walls can be negligible. It is stressed that these diagrams are applied loads to the wall surface; hence, if the wall is facing the blast a reflection factor would apply to the loading.

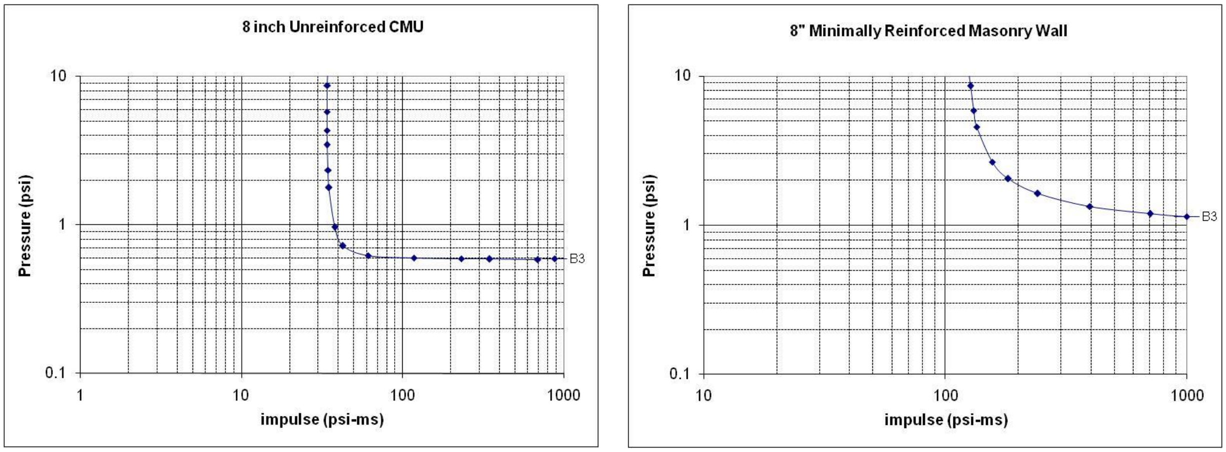

Figure 1. P-I Diagram for Unreinforced and Minimally Reinforced CMU Wall

Another common structural item which can have large differences in blast capacity with seemingly little differences in construction are open web steel joists (OWSJ). When designed for conventional loading, the OWSJ is a very efficient load transferring element. Depending on the design, the load carrying limits may be shear or flexure controlled. A shear-controlled joist will over load its web bracing axially when pushed beyond its full ultimate capacity. Buckling of the bracing ensues and the joist loses its geometric section and load carrying ability rapidly. A flexural-controlled joist will yield in its tension chord first allowing for some limited plastic deformation and energy absorption prior to failure. A comparison of P-i diagrams for shear-controlled and flexural-controlled OWSJ is shown in Figure 2. Again, the pressure capacity increases by a about a factor of 2.

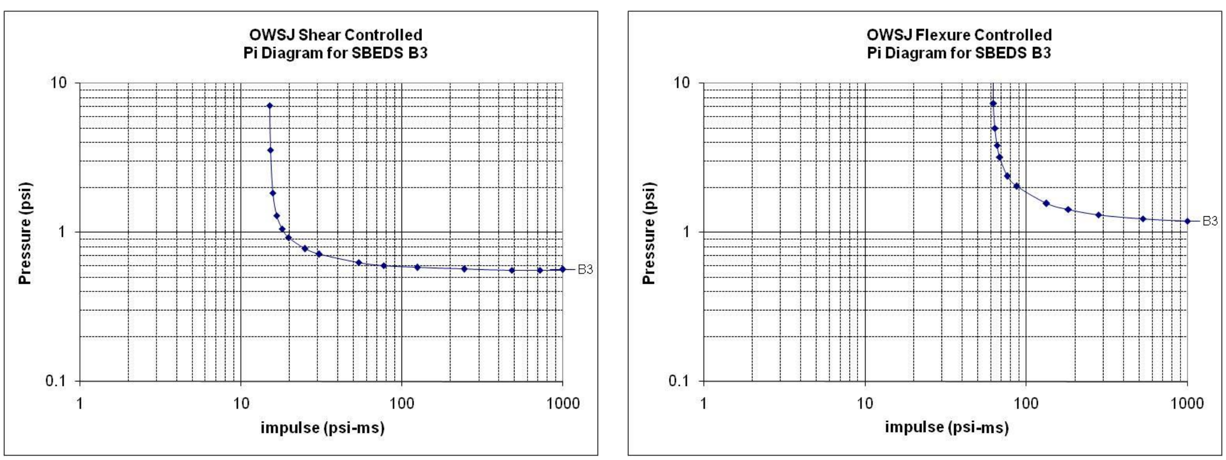

Figure 2. P-I Diagram for Shear and Flexural Controlled OWSJ

Connection detailing in a pre-engineered metal buildings can also make a considerable difference in blast capacity. For a cold-formed girt constructed with a bypass connection (continuous over the outside flange of a column) can exhibit an applied load pressure asymptote about twice the magnitude versus a simply connected member spanning between the columns as seen in Figure 3. Both members are ductile responding and it is the change in support condition for the bypass connection that increases the capacity.

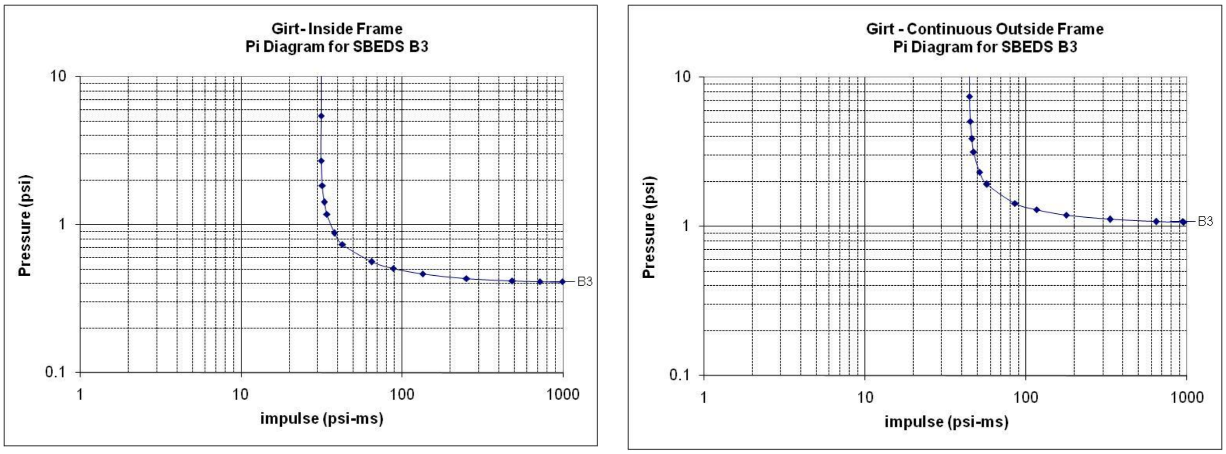

Figure 3. P-I Diagram for Shear and Flexural Controlled OWSJ

Even seemingly robust structural members may have lower blast capacities than intuitively thought. Precast reinforced concrete can have substantial blast resistance due to its strength and mass. However, connections for these members may not always be capable of resisting large reaction associated with a large blast rating. Some of these are intended to only hold members in place and the member itself either bears on another member or connection pocket with gravity being the primary uplift resistance.

Blast capacity rating differences should be identified and addressed before a screening process can be performed to evaluate the building for blast load hazards.

5 Summary and Recommendations

Building screening based on a single pressure value can be an attractive and efficient tool for rapid evaluation of blast hazards. The evaluator or screener should be careful to ensure that screening criteria is properly applied. A clear understanding of the background, industry, and even specific building construction are critical to using an established screening criterion.

A sampling of industry documents and guides demonstrates a broad range of minimal pressure values and damage relationships under which buildings can be considered “safe” or “screened” without further evaluation. This range, of as low as 0.3 psi to as high as 2.0 psi, complicates the ability to select a single value for screening. A rule of thumb of 1.0 psi for building screening has been used in some instances and would appear to be too high to cover the wide range of constructions.

Considerable conservatism is required to select a single value pressure for building screening. This being the case, it is likely that low value must be selected. A conservative value may be so low that only a few buildings will be screened out and further analysis will be required. Essentially, making the screening process ineffective.

The end goal of building evaluation in facility siting processes is typically to determine the risk to occupants. Many of the values presented do not address occupant vulnerability associated with them.

As the API committees move forward to the next editions of recommended practices, the following recommendations are presented for consideration:

- Clearly discuss if there is a need for a single screening value for all building construction types
- Provide understanding that both pressure and impulse should be considered in screening and distinguish between reflected loads and free-field loads in any tables or curves.
- Evaluate and address variability of screening values on similar construction and the need to fully understand considerations such as reinforcement ratios, shear controlled situations, and quality of connections.
- Consider the effectiveness of the screening process for proposed values
- Assess and include occupant vulnerability levels associated with any screening pressure or impulses proposed

6 References

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