Facility Siting Challenges and Blast-Resistant Design and Retrofit of Buildings at Refinery and Petrochemical/Chemical Facilities

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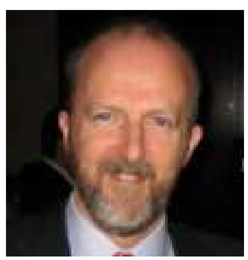
PSRG
Process Safety and Reliability Group



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Engineering of Structures
and Building Enclosures

Contact Details

This PSM Forum topic was originally presented by PSRG and Simpson, Gumpertz & Heger in Houston in April 2016 and in Baton Rouge and Lake Charles in June 2016.

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Agenda

- Overview of Facility Siting
  - Guidance
  - Intentions
  - Hazard Types
- Approaches to Facility Siting
  - Spacing Tables
  - Consequence-based
  - Risk-based
- Issues with Facility Siting Studies
- So you have a study, now what?

Three Guidance Documents

API RP 752
First published 1995
Now 3rd ed., 2009

API RP 753
1st ed., 2007

API RP 756
1st ed., 2014

Intentions of Facility Siting

- Minimize risk to personnel
  - Locate personnel / buildings away from process areas
  - Design, construct, install, modify, and maintain buildings to protect occupants from process hazards
- Facility Siting is mainly concerned with **Occupied Buildings** and **Critical Buildings** in case of an emergency (e.g., Fire Pump House, Emergency Command Centers, etc.)

Types of Hazards

Flammable Hazards

Jet Fires

- May ignite structures
- May block escape routes

Pool Fires

- May ignite structures
- May block escape routes
- May surround a building

Flash Fires

- Main concern is vapor ingress/migration before ignition

Explosive Hazards

Vapor Cloud Explosions (VCE)

- Flammable vapor + congestion
- Congested area (“PES”) may be some distance from leak
- Identification of PES is crucial for any facility siting study
- Primary concern is overpressure blast
  - Peak overpressure, psi
  - Duration, ms
  - Impulse, psi.ms; or psi.s

Explosive Hazards

- Boiling Liquid Expanding Vapor Explosion (BLEVE)
  - Secondary event
  - Prevent through design and spacing
  - Delay through insulation and deluge systems
  - Not typically a building design factor
  - Evacuation is the typical approach

Toxic Hazards

- ERPG-3 or IDLH typically used as the toxic threshold
- If threshold exceeded at building:
  - Shelter in place (needs special design and equipment)
  - Evacuate (may need special PPE)
- Response should be based upon the potential toxic concentration and the expected duration of the event

Approaches to Facility Siting

- Spacing Tables
- Consequence-based Assessment
- Risk-based Assessment

Spacing Tables

- Often used early in a project when lacking sufficient information to conduct a detailed Facility Siting Study
- Aids in initial building and equipment placement
- Several sources for spacing tables, e.g.:
  - CCPS
  - GE GAP
- Do not account for toxic or explosive hazards
- Appropriate spacing can reduce congestion which mitigates explosions

Consequence-based Assessment

- Uses "Maximum Credible Event" (MCE) approach
- MCEs are the scenarios that have a "reasonable probability" of occurrence at a facility
  - No industry RAGAGEP for identifying MCEs
  - General industry practice is a 1" to 2" leak
- Certain level of subjectivity in identifying "MCEs"
  - 2" may not be "maximum" or "credible" in all cases
- What consequence end-point to use?

Risk-based Assessment

- Can use large number of scenarios
- Risk = Consequence * Frequency of occurrence
- Considers variables such as:
  - Leak probability (Initiating Event, Size, Location)
  - Ignition probability
  - Weather conditions
- Issue #1: Frequency source?
- Issue #2: Risk criteria / target?

Issues with Facility Siting

- Modeling
- Consequence vs Risk
- What is "occupied"?
- Shelter-in-place vs evacuation
- Common traps / problems

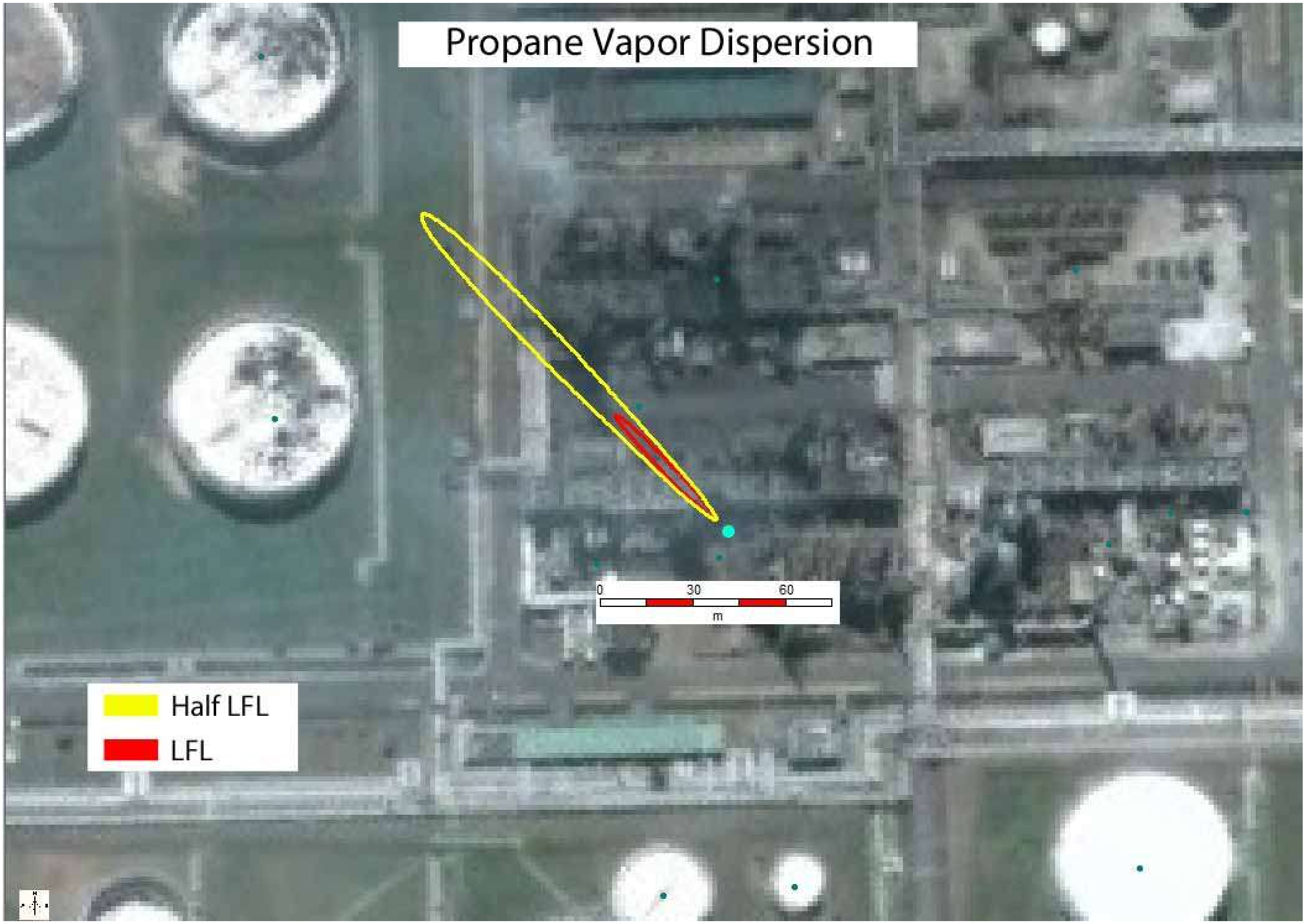
Issues: Modeling Input

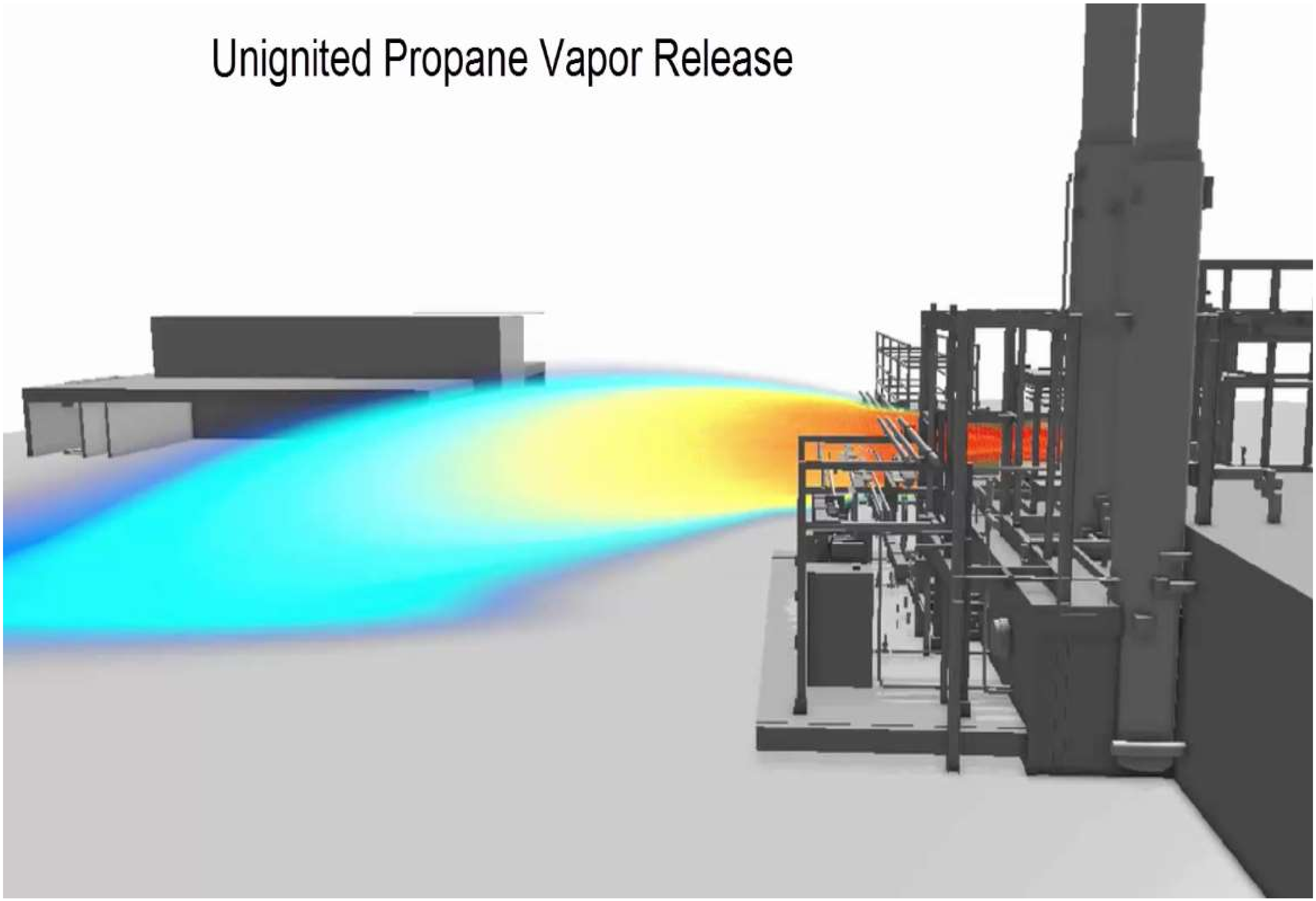
- MCE selection (consequence approach – most common)
  - 1″ or 2″? More?
  - Leak origin? Equipment? Valves? Welded pipe?
  - Leak orientation?
- Include/exclude VCE? Jet? Pool? F/fire? Toxic? (Why?)
- What's leaking?
  - P, T, phase, composition?
- Wind and weather assumptions?
- PES identification? (vs. free-field / unconfined)
- Flammable mass determination?
- Toxic effect? (Dose based? Probit equation?)

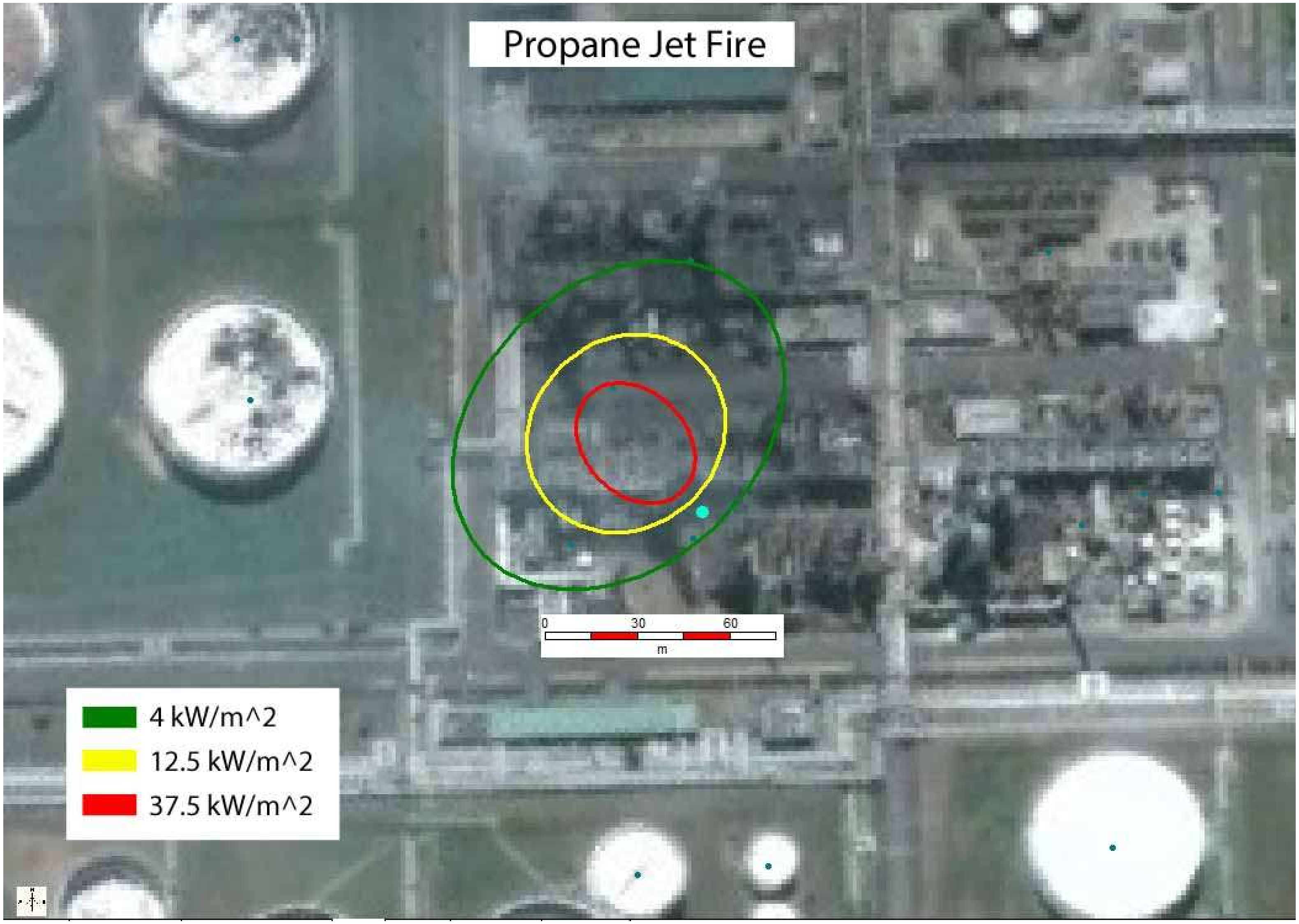
Issue: Modeling Approach

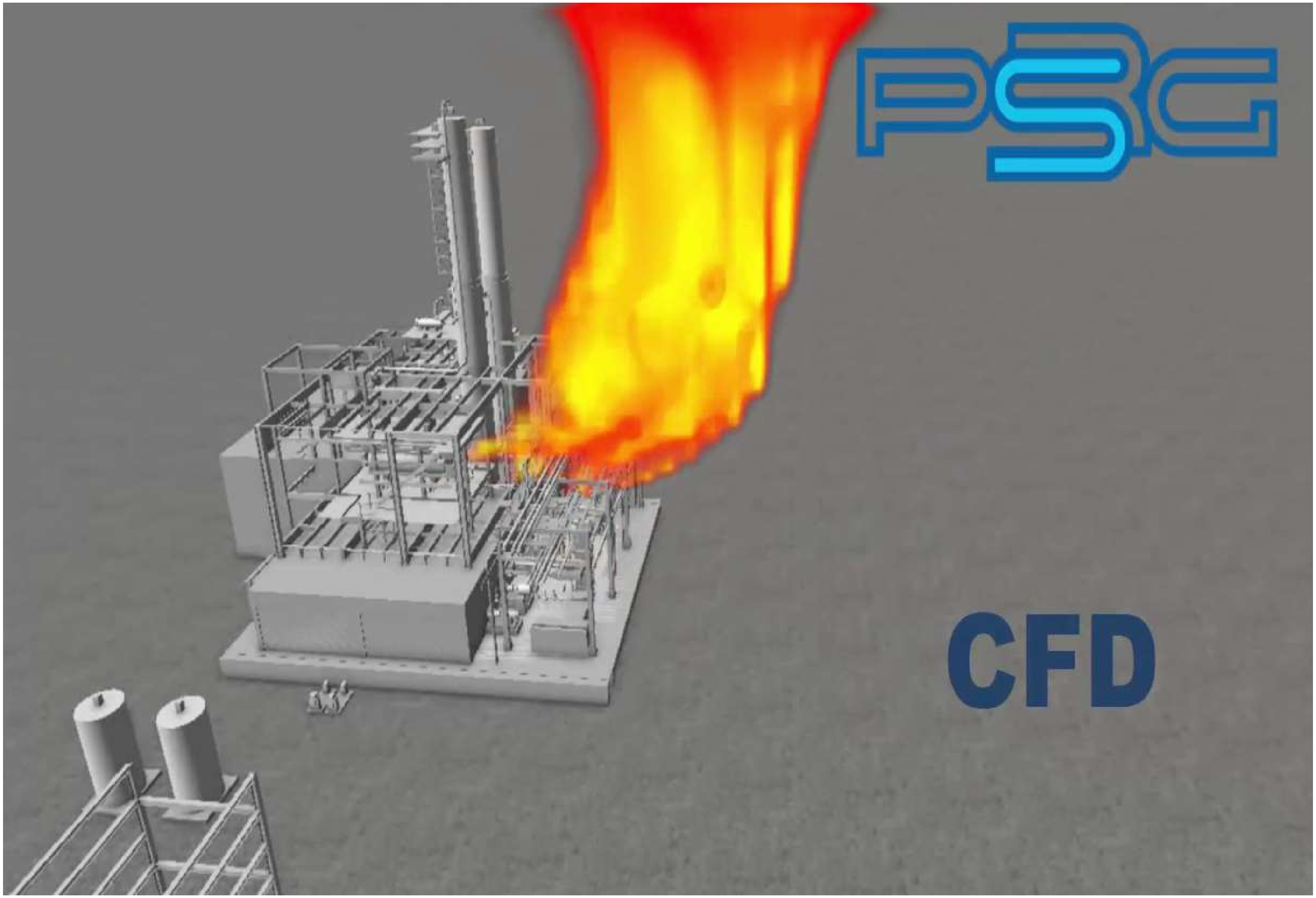
- Gaussian style models:
  - PHAST
  - CANARY
  - DEGADIS

- Computational Fluid Dynamics (CFD)
  - FLACS; EXSIM


Propane Vapor Dispersion
0
30
60
m
Half LFL
LFL


Unignited Propane Vapor Release


Propane Jet Fire
0
30
60
m
4 kW/m^2
12.5 kW/m^2
37.5 kW/m^2


PSRG
CFD

What Model is Appropriate?

- Simple models usually sufficient
- The additional detail provided by CFD does not usually warrant the time and expense

- However, CFD may be justified for:
  - Extremely complex facility geometries, such as offshore platforms
  - Large elevation or terrain changes; large obstacles
  - Assessing mitigation measures (e.g., blast/fire walls)

Risk- or Consequence-based?

- Consequence-based assessment will typically result in greater safety margins, but it is not always practical
- Consequence-based assessments are best used on new facilities, as the costs of reinforcement/relocation are lower
- Risk-based assessments can help existing facilities identify what changes have the most impact

Issues: Defining “Occupied”

Per API RP 752: A building is intended for occupancy if it has personnel assigned or it is used for a recurring group function

- Change Houses
- Control Rooms
- Guard Houses
- Laboratories
- Lunchrooms

Rule of Thumb: If the building has a chair and a table in it, it should be considered as an occupied building

Issues: “Portable” and API 752/753

- What is “portable”?
- When should building be assessed as “permanent”?

- API 753 definition: “Any rigid structure that can be easily moved to another location within the facility…
  “regardless of the length of time it is kept at the site.
- Examples: wood-framed trailers; containers; semi-trailers; portable blast resistant structures
- Excludes tents (see API 756)

- Pre-engineered/prefabricated modular building?

Issues: Shelter vs Evacuation (toxic)

- Shelter In Place:
  - HVAC System capable of being shutdown or placed in recirculation
  - System to notify occupants
  - Emergency communications equipment
  - Appropriate building design to minimize infiltration
  - Appropriate PPE

- Evacuation:
  - Emergency action plan and procedures
  - Marked emergency exits and evacuation routes
  - Means to notify occupants of toxic release
  - Designated muster locations and shelters
  - Plan to account for occupants
  - Appropriate PPE

Issues / Traps

- Invalid assumptions
  - All assumptions should be explicitly stated and justified
  - Should be conservative
- "MCE" selection
- Modeling errors
  - Wrong model for the situation
  - Incorrect / inappropriate inputs
  - Poor interpretation of raw results
- Consequence end-points
- Risk targets

So you have a FSS; now what?

- Buildings either "pass" or "fail"
  - Spacing tables: too close = fail
  - Consequence basis: too high = fail
  - Risk basis: too high = fail
- If pass, all good
- If fail?
  - Relocate?
  - Strengthen?

Risk Mitigation – “Simple”

- Relocation of control rooms
  - Last resort on existing facilities
- Relocation of occupied buildings to areas of lesser risk
  - Move to a location outside of blast zone
  - Move admin, maintenance, warehouse facilities
- Relocation is technical simple, but may have high cost

Risk Mitigation - Detailed

- Structural Engineering Analysis and Response
- Structural Retrofit of Existing Facility
- Building hardening/reinforcement
- Blast Walls
- Structural Retrofit - Enclosure Structure
- Encases existing facility - reduces downtime, less disruption to facility
- Structural Design of New Facility
- Blast Resistant Modules (BRMs)

Overview

- Blast-Resistant Design
  - Rationale
  - Typical Buildings Found in Refineries and Petrochemical Facilities
  - Typical Strengthening Approaches
  - Design of Blast-Resistant Structures
    - New Buildings
    - Evaluation and Retrofit of Existing Buildings
    - Performance Criteria
    - Analytical Methods for Blast Response Analysis
- Case Studies for Different Blast Design Projects
- Questions & Discussion
- Note: The materials presented in this portion of the presentation have largely been drawn from a paper presented at the 11th Global Congress on Process Safety, April 2015, titled, 'Blast-Resistant Design and Retrofit of Buildings at Petrochemical Facilities', by Paul Summers, Guzhao Li and Zonglei Mu, now with SGH

Rationale for Blast-Resistant Structural Design

- One of the measures an owner can employ to minimize the risk from accidental explosions to personnel, facilities and business interruption
- Other mitigation measures include:
  - Siting (adequate spacing from explosion hazards)
  - Hazard reduction (inventory and process controls, occupancy limitations)
  - Thorough risk assessment and quantification
- Applicable to both design of new buildings and structural evaluation of existing buildings, followed by strengthening as necessary

Typical Buildings Found in Refineries and Petrochemical Facilities

Reinforced Concrete Shearwall Building with Steel Gravity System

Reinforced Concrete Shearwall Building

Reinforced Masonry Building with Steel Gravity Frame

Reinforced Masonry Building

Reinforced Masonry Control Building with Prestressed Concrete Roof

Steel Moment Frame (Transverse) and Braced Frame (Longitudinal) Maintenance Shop

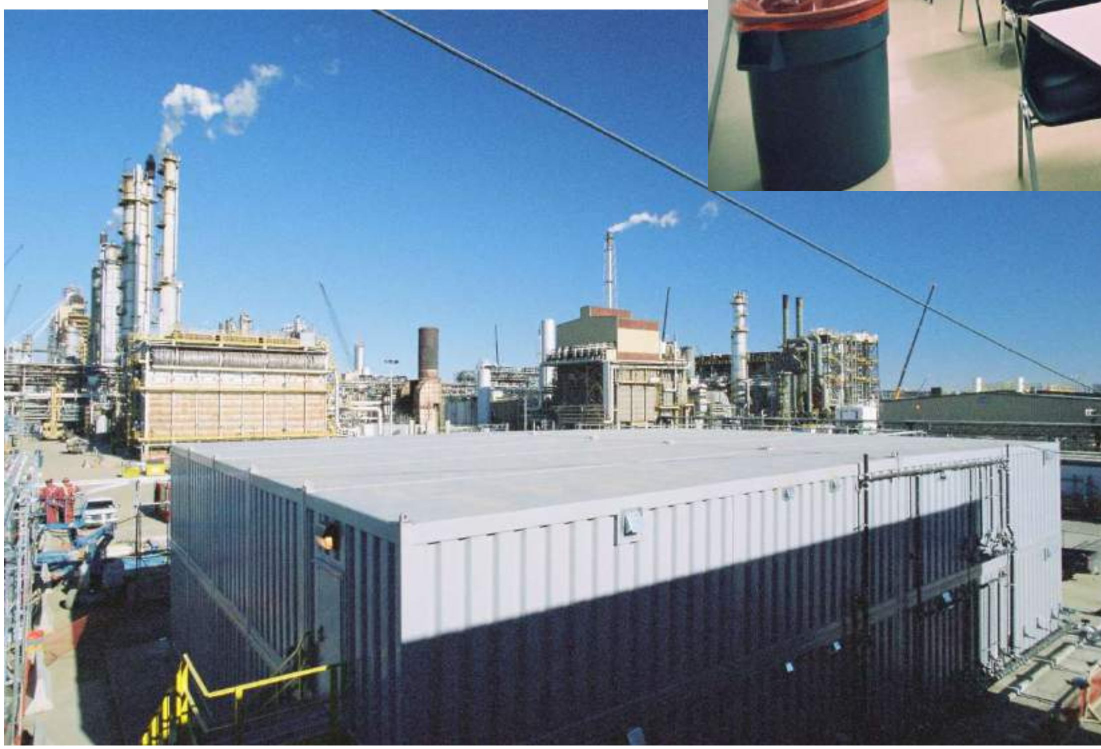
Modular Steel Buildings

Single Module Building, 12 ft. x 40 ft., 500 sq. ft.

Typical Single-Story Refinery Control Building (Five Individual Modular Buildings Welded Together, 2,500 sq. ft.)

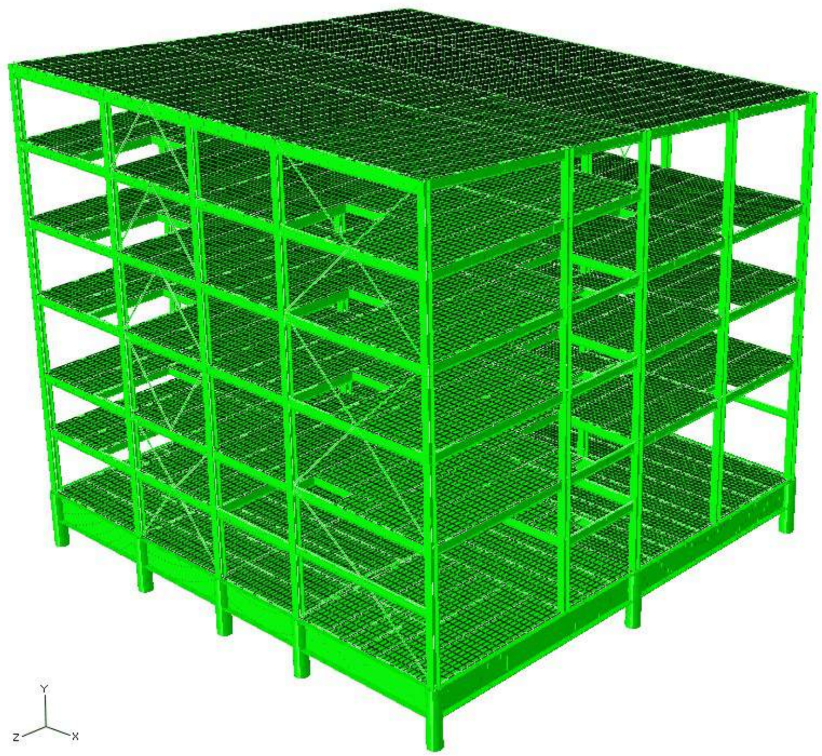
Two-Story 20-Module Building

(10,000 sq. ft.)



Stackable Bolted Blast-Resistant Modular Buildings

Six-Story Single-Module Building (45,000 sf.)

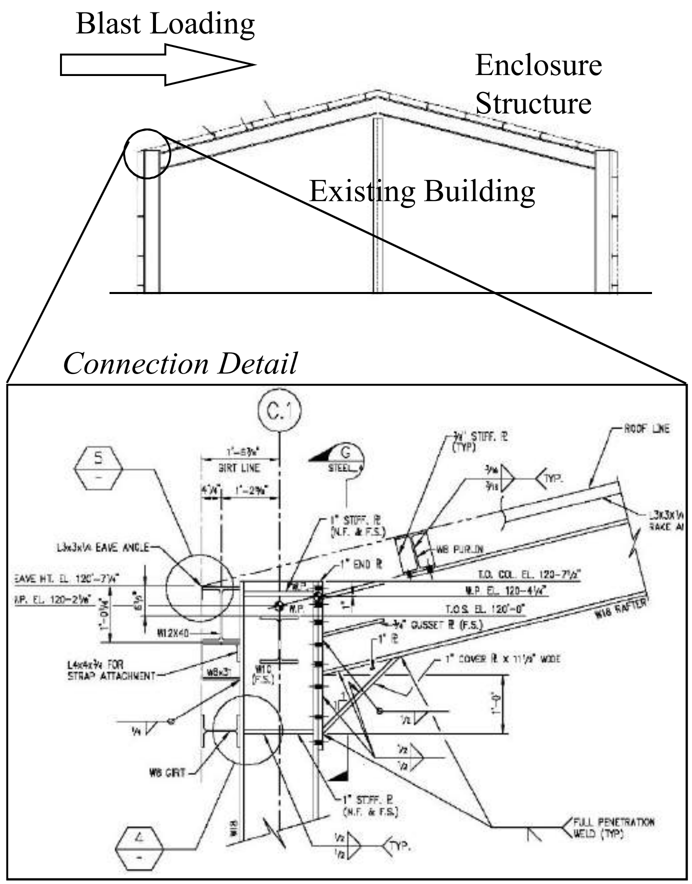


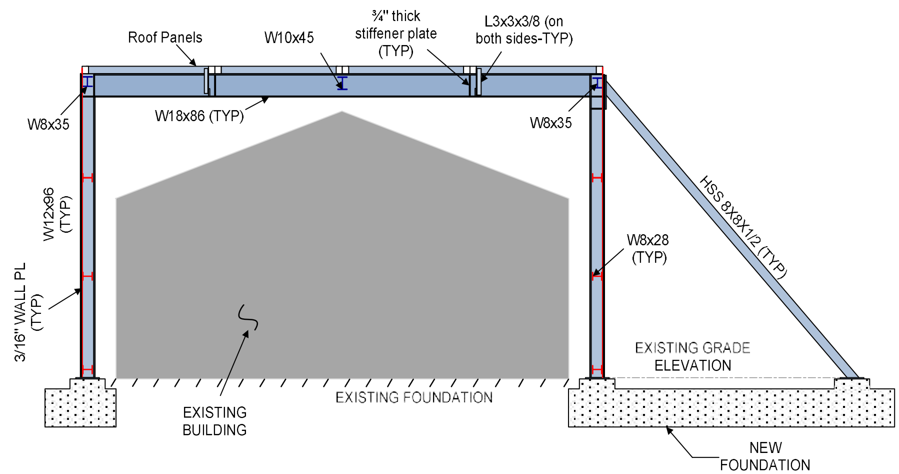
Typical Strengthening Approaches

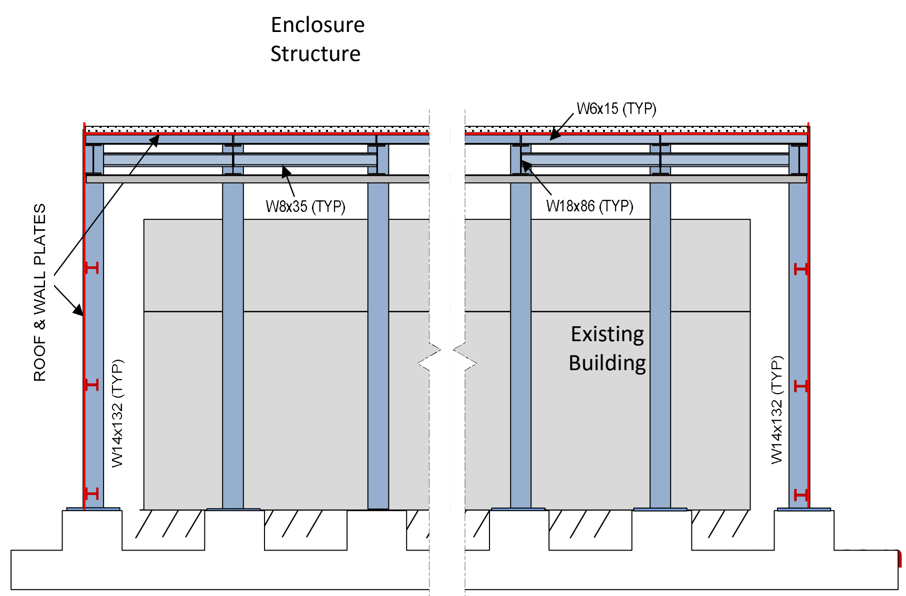
Retrofit Design Options – Strengthening using Shotcrete Walls & New Shield Roof

Retrofit Design Options – Strengthening Using Exterior Posts

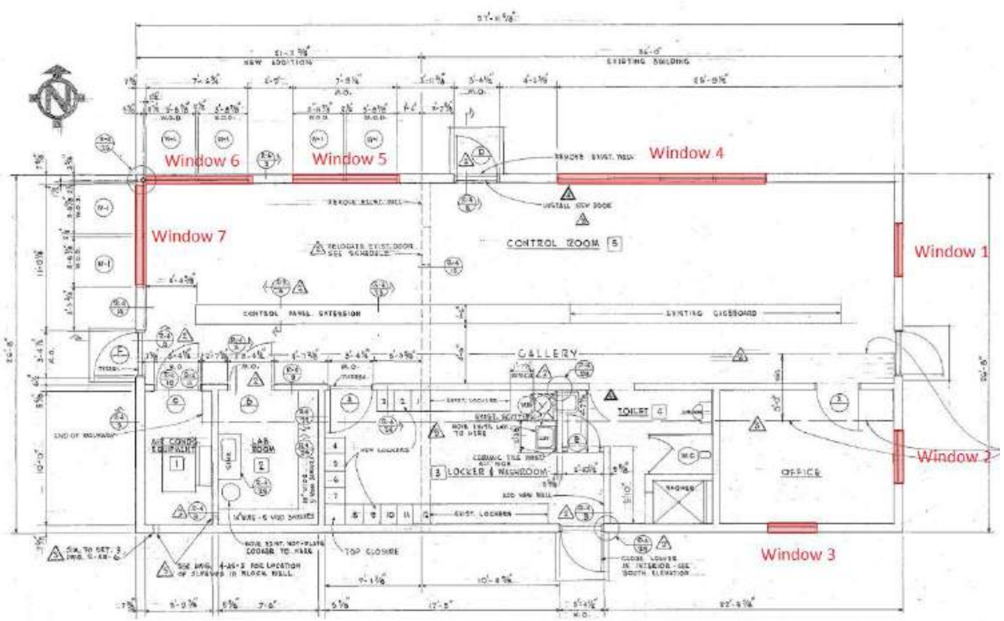
Retrofit Design Options – Enclosure Structures

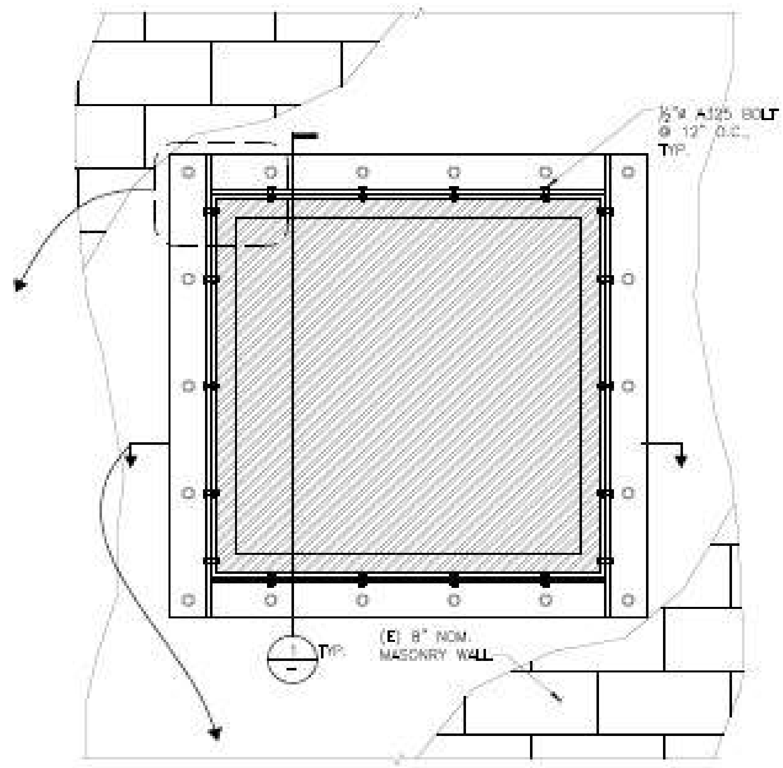






Retrofit Design Options – Doors and Windows





Retrofit Design Constraints (Such as Electrical Penetrations)

Electrical penetrations present significant challenges

Design of Blast-Resistant Structures for the Oil & Gas Industry

Design for Blast & Explosion at Petrochemical Facilities

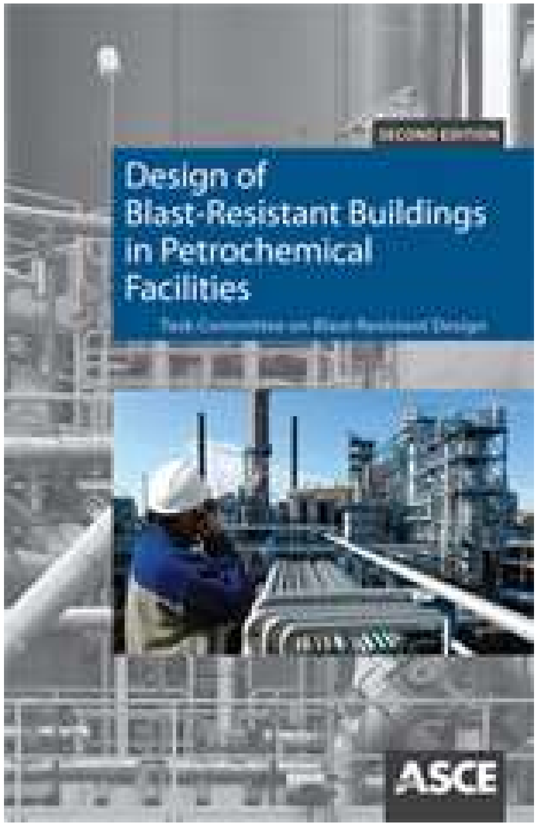
ASCE design guidelines

ASCE Task Committee on Blast Resistant Design

- 1995-1997 and 2006-2010
- Structural engineers, designers, fabricators, owners/operators

'Design of Blast Resistant Buildings in Petrochemical Facilities'

- Used throughout industry primarily for design of structures to resist vapor cloud explosions both offshore and onshore
- Control rooms, operator shelters, walls, accommodations, electrical buildings
- SGH staff members sat on committee

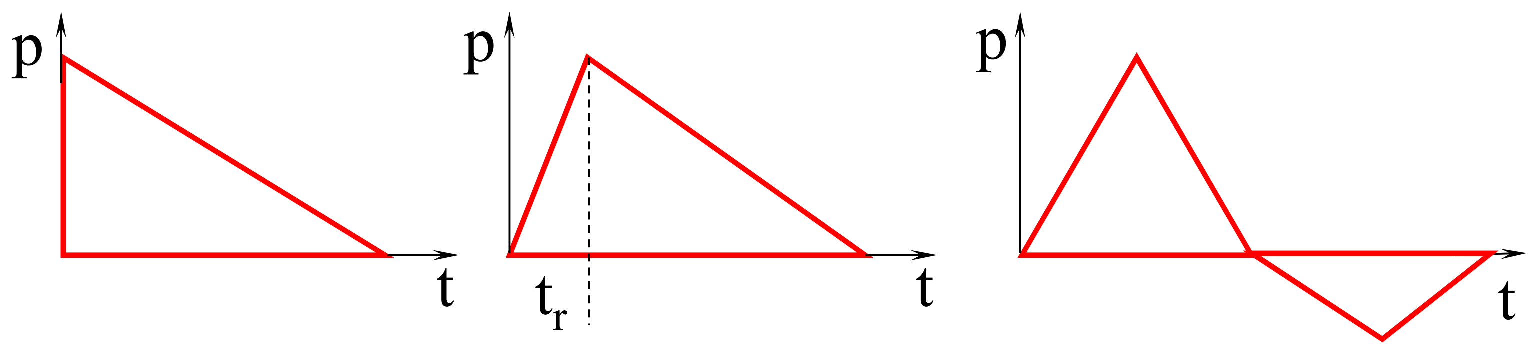


Design Approach

- Blast load prediction
- Selection of appropriate response/performance criteria
- Blast loading analysis
- Design of structural components and connections
- Design of foundations

Blast Load Prediction

- Empirical simplified method (such as TNO multi energy approach) or use of computational fluid dynamics (CFD) analysis
- Blast load cited as free field overpressure with specified duration
- Form of time history is also given, but usually no rise time
- Negative phase is sometimes specified (often 30% of positive phase) with similar overall duration
- Reflected pressure on front wall vs. free field overpressure on roof and side walls



Response/Performance Criteria

Low Damage – Localized component damage. However, repairs are required to restore integrity of structural envelope. Total cost of repairs is moderate.

Medium Damage - Widespread component damage. Building should not be occupied until repaired. Total cost of repairs is significant.

High Damage – Key components may have lost structural integrity and building collapse due to severe environmental conditions (e.g., severe hurricane, earthquake) may subsequently occur. Building should not be occupied. Total cost of repairs approaches replacement cost of building.

Response/Performance Criteria (cont'd)

Factors affecting choice of response criteria:

- Building/component importance
- Building occupancy and function
- Consequences of downtime
- Requirement for continued operation
- Other factors – new or existing construction

Different allowable levels of ductility and rotation for each performance criterion

Response/Performance Criteria (cont'd)

TABLE 5.B.2: Response Limits for Steel Components (as an Example)

Component	Low Response		Medium Response		High Response	
	μ_a	θ_a	μ_a	θ_a	μ_a	θ_a
Hot Rolled Steel Compact Secondary Members (Beams, Girts, Purlins)[2]	3	2	10	6	20	12
Steel Primary Frame Members (with significant compression)[2, 3, 4]	1.5	1	2	1.5	3	2
Steel Primary Frame Members (without significant compression)[2,3,4]	1.5	1	3	2	6	4
Steel Plates [7]	5	3	10	6	20	12
Open-Web Steel Joists	1	1	2	3	4	6
Cold-Formed Light Gage Steel Panels (with secured ends)[5, 8]	1.75	1.25	3	2	6	4
Cold-Formed Light Gage Steel Panels (with unsecured ends)[6, 8]	1.0	-	1.8	1.3	3	2
Cold-Formed Light Gage Steel Beams, Girts, Purlins and Non-Compact Secondary Hot Rolled Members[8]	2	1.5	3	3	12	10

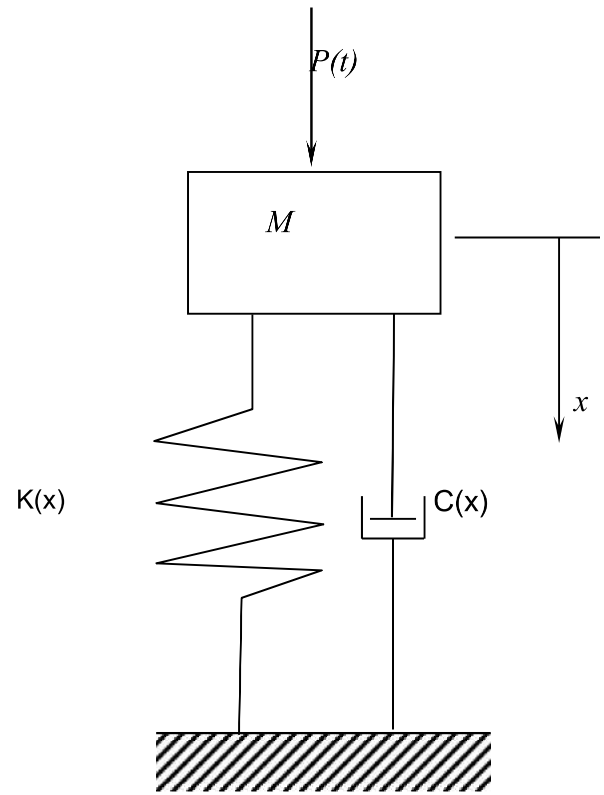
Blast Response Analysis

Analysis Methods:

- Single degree of freedom (SDOF) analysis
- Finite element methods

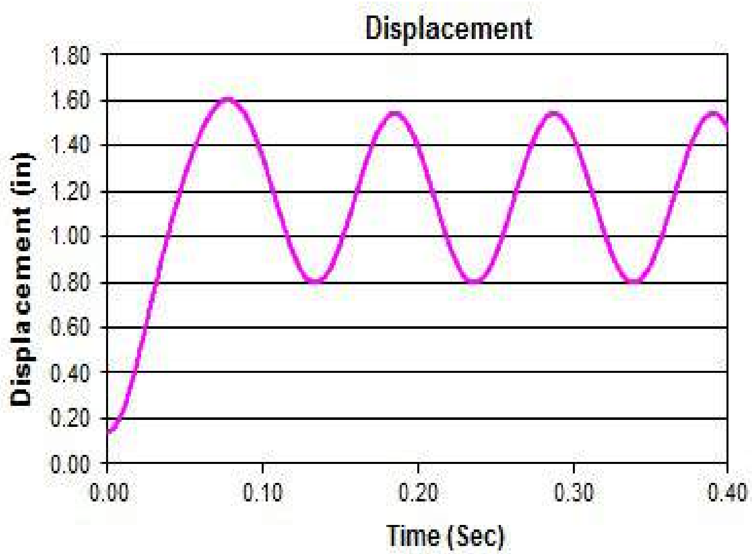
Single Degree of Freedom Analysis

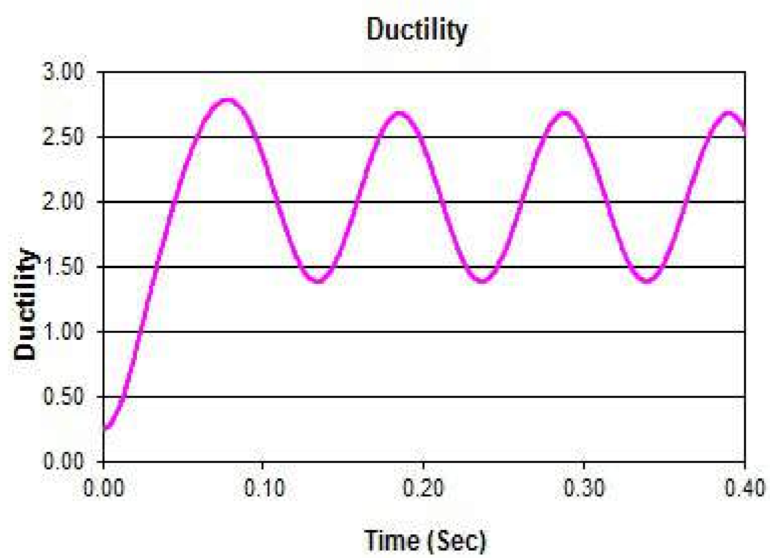
- Sequential component design
- Each component is an equivalent single degree of freedom system
- Forcing function, mass, stiffness and damping
- Generally conservative relative to whole building finite element modeling
- Does not capture overall building response



Blast Response Analysis

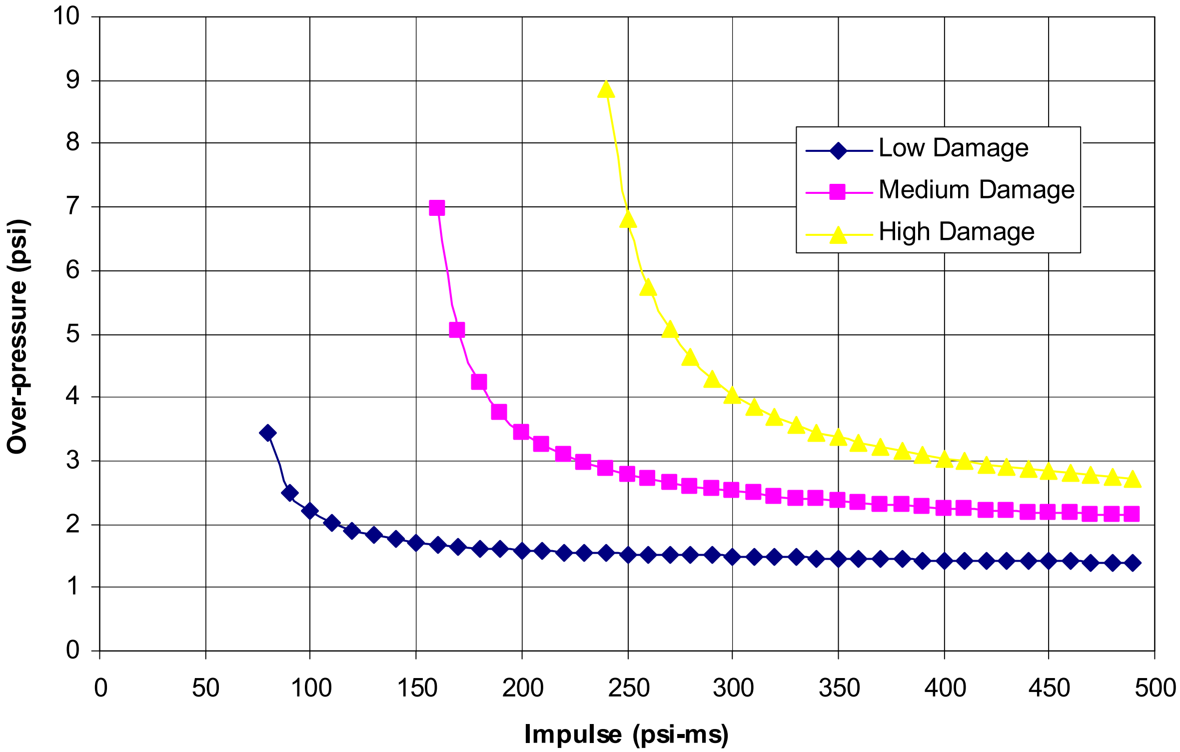
SDOF analysis example





Pressure-Impulse (P-I) Curves

SDOF analysis - Extension to pressure-impulse (P-I) curves to incorporate variation in load profile; lines of 'constant damage'



Nonlinear Finite Element Analysis

- Detailed structural models
- Phased front wall, side wall, and roof loading (rear wall loading sometimes neglected)
- Large displacements (membrane effects) and nonlinear material response
- Beam and shell models
- Use of nonlinear finite element analysis programs, such as ABAQUS

Case Studies in Blast-Resistant Design

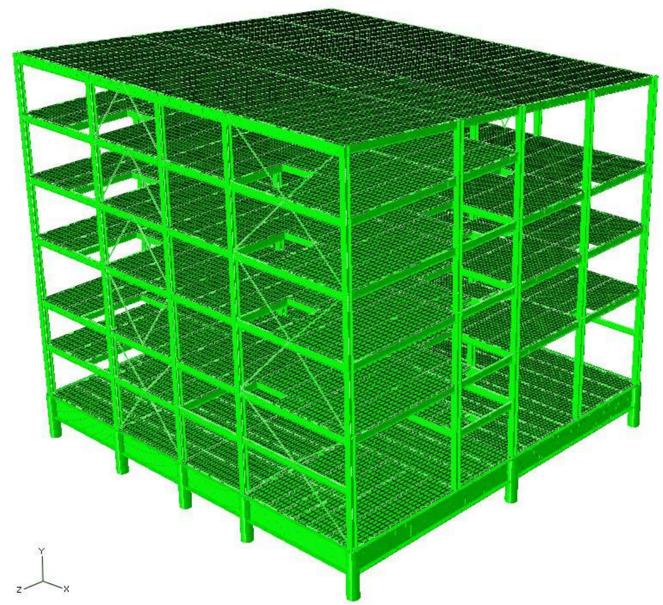
Offshore Operations Center

- Operations center for 50 people
- Six-story steel structure with 90′ by 92′ footprint, 75′ tall, 45,000 sq. ft.
- Designed to provide protection in the event of fire & explosion.
- Building fabricated in the Gulf of Mexico and delivered offshore Alaska via barge
- Building weight 3,500 tons

Blast & Fire Loads

Blast loads:

- Blast load overpressure varies by wall location
- Different for the evaluation of structural components and overall building response
- Phasing effect accounting for different time of arrival considered when the blast loads are applied in the model
- Negative phase considered



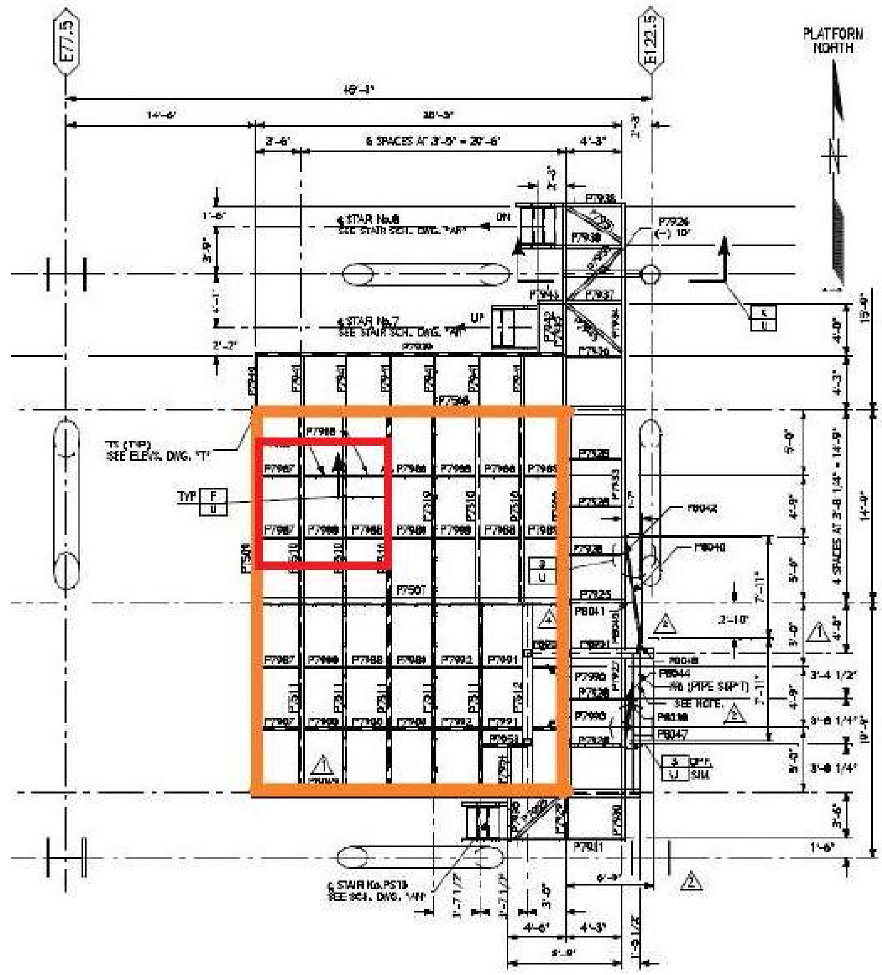
Fire design criterion

- Both jet and pool fires
- Maintain “H60” fire rating after heat flux exposure from a pool fire in addition to an initial heat flux from the impinging of a jet fire.

Deepwater Offshore Platform

Emergency Command Center Building

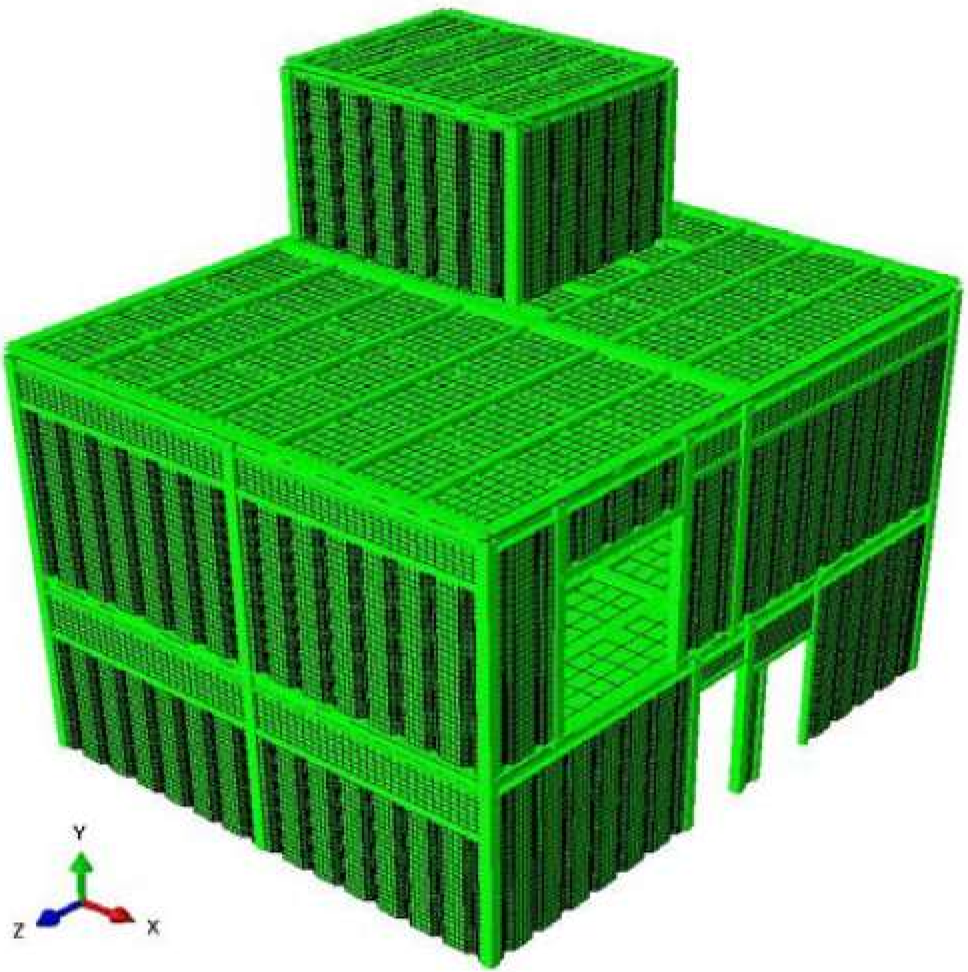
- Two-story steel structure
- Battery room forms partial third story
- Building weight approximately 55 tons



Blast Loads

- Nearly two thousand computational fluid dynamics (CFD) explosion simulations were performed by owner
- A frequency of exceedance was considered when determining the Ductility Level Blast (DLB)
- Blast load overpressure varies by wall locations
- A rise time of zero was assumed for all blast loads
- Phasing effect accounting for different time of arrival not considered due to small size of building

Final FE Model for Blast Analysis



Blast-Resistant Walls Don't Have to be Ugly and Don't Have to be Expensive

www.sgh.com

Cold Formed Steel Wall w/ Composite Sheathing

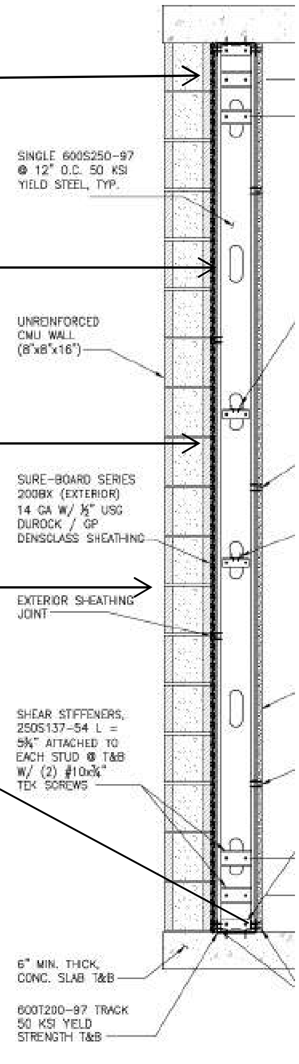
Strategically located stiffeners

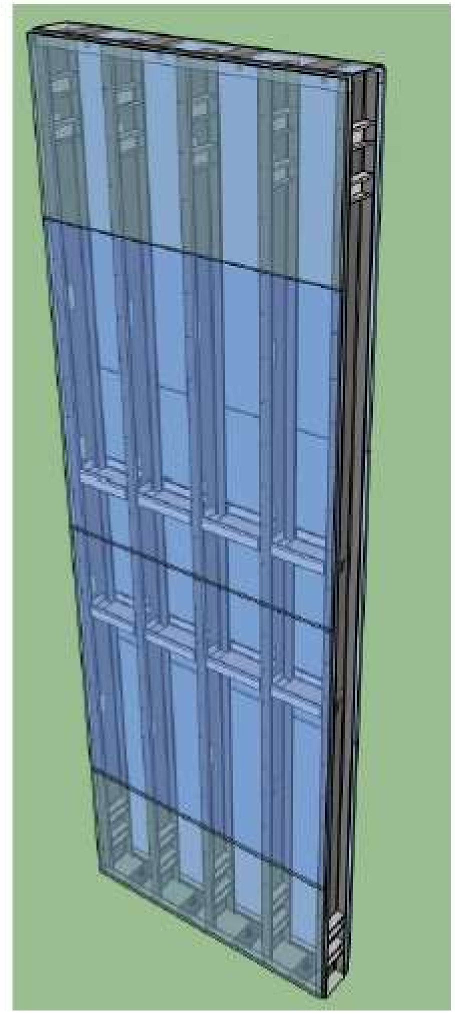
Standard CFS studs

Composite, gypsum board/ light gauge steel sheet (both faces)

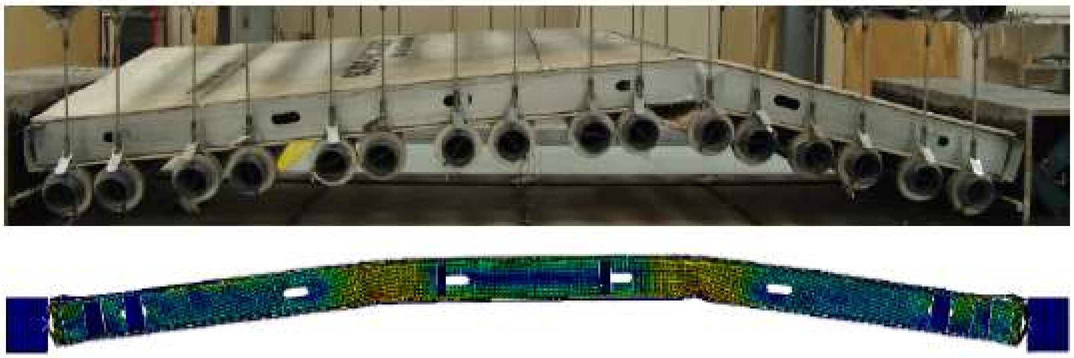
Can be faced with any material

Improved connections



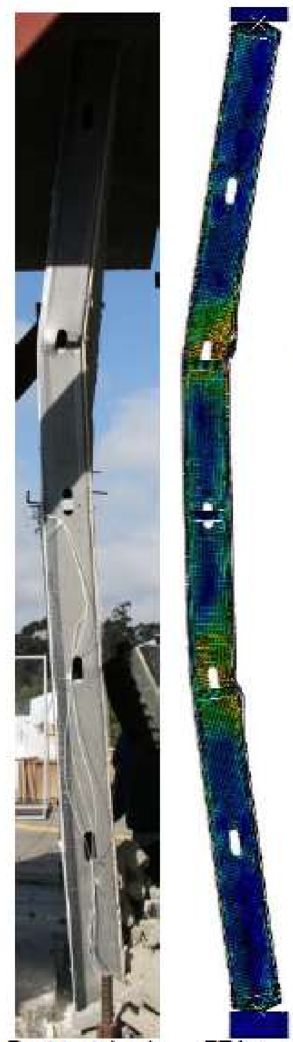


Verified through FEM Analysis, Static and Dynamic Testing



Static Testing

Blast Simulator Testing

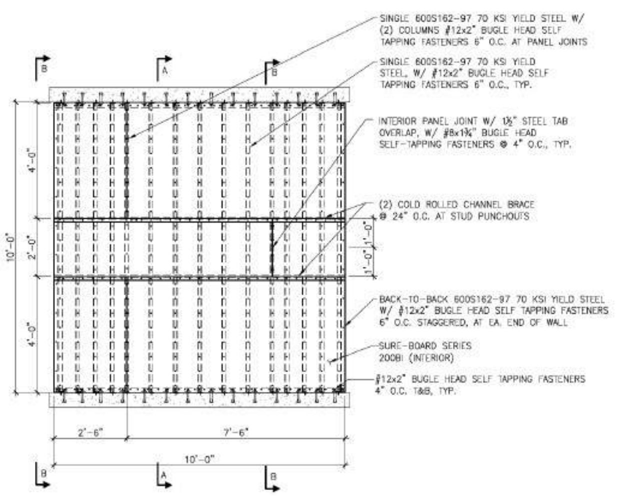


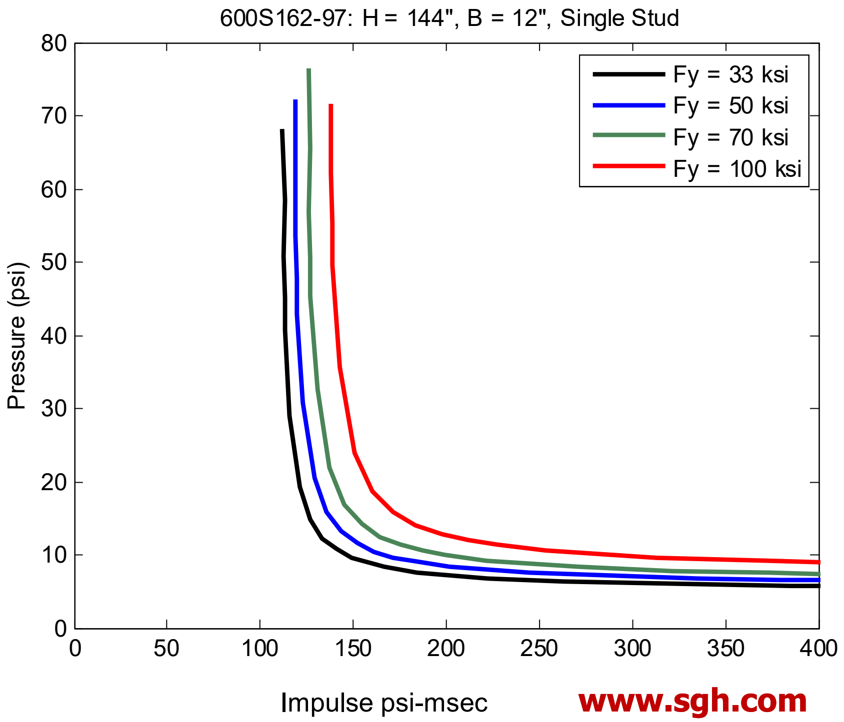
Performance-Based Design Guidelines

- Performance criteria
  - Damage level definition: Superficial, Moderate, Heavy, and Hazardous
  - Peak and residual deflections limits
  - Rotation limits for connections
  - Pressure and impulse limits

- SDOF formulation
  - Resistance functions for different wall configurations
  - Example p-I diagrams for select wall configurations

- Construction details
  - Stud and sheathing layout
  - Lateral bracing system
  - Connections, fasteners, and attachments





System Application

Provides standard architectural wall appearance

High-performance

- Comparable to:
  - Precast concrete panels,
  - Reinforced-concrete walls,
  - Advanced composite systems.

Cost-effectiveness

- $25/SF construction cost vs. $35/SF for precast concrete panel wall (source: Jacobs Technology).
- 30% savings with respect to most cost-effective system.

Construction

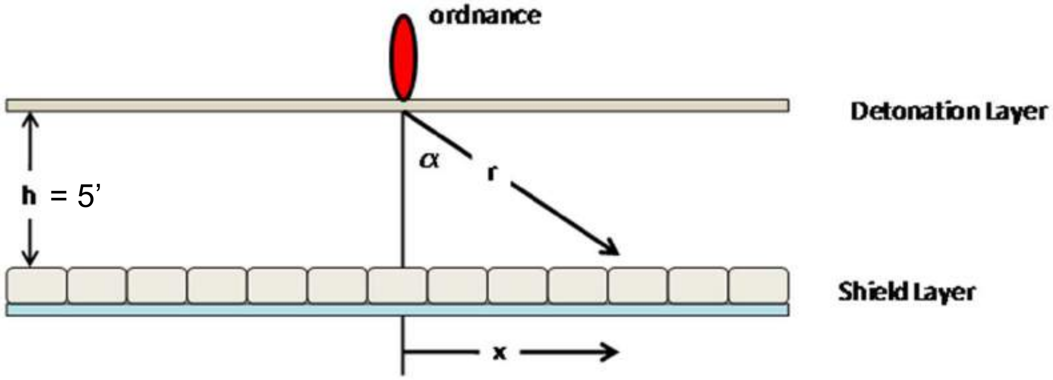
- Practical and easy installation procedures
- Light-weight, mobile, modular wall system
- Retrofit of existing buildings or new stand-alone construction
- Exterior and interior walls
- Multiple spans, bearing/non-bearing

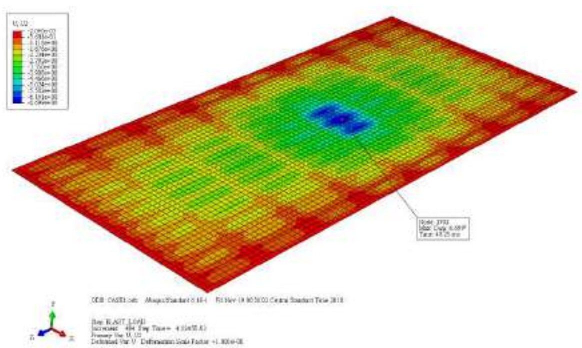
Terrorist-Resistant Structures for Oil Fields

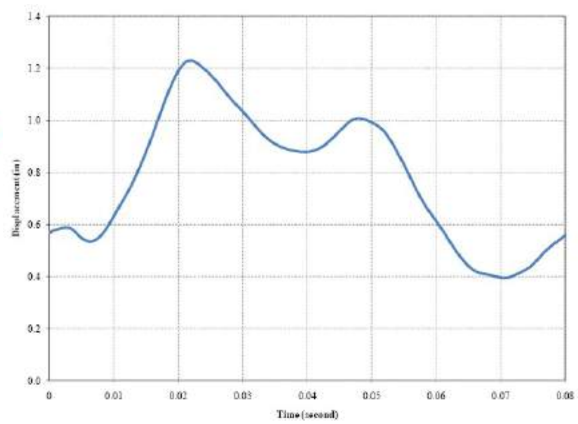
Design of Overhead Protection Structures, Iraq

Hazard: 120 mm Rockets/Mortars

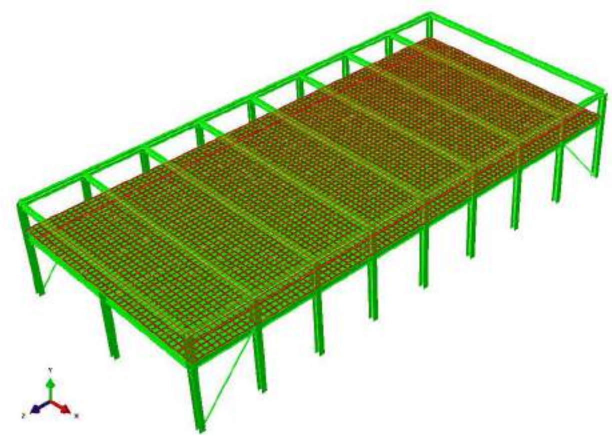
Evaluation of Shielding Layer







Relative Vertical Displacement Time-history at Node 2702



OHP Structures Under Construction

Questions & Discussion