Blast Effects and Mitigation

2013 Maryland Engineers Conference

Overview

- Contents

  1.1. Preface

  Introduction to BakerRisk

  1.2. Introduction to Blast Resistant Design

  Types/sources of blast loads

  How blast design differs from conventional design

  Specifying response/damage criteria

  Client/consultant roles and responsibilities

  1.3. Blast Load and Effects

  Introduce key parameters and types of explosions, and their effects

  1.4. Blast Analysis and Mitigation Techniques

  Overview of methods for evaluating blast resistance and mitigation

1.1. Preface

BakerRisk Company Overview

- Established 1984
- Current company profile
  - *Headquartered in San Antonio, TX with 7 offices in US, Canada and UK*
  - *160 employees*
    - > 80% technical
    - > 70% of technical staff with advanced degrees (MS or PhD)
- Mission statement
  - *To provide integrated engineering, research, and risk assessment to aid our clients in managing hazards associated with explosive, flammable, reactive and toxic materials*

Market Sectors

- Oil & gas
  - *Exploration & production*
  - *Refining*
- Industrial
  - *Chemical processing*
  - *Pharmaceuticals*
- U.S. and Canadian federal governments
  - *Anti-terrorist design and research*
  - *Explosive Safety*
  - *Weapons effects research*
- Insurance risk companies
- Litigation support

BakerRisk Key Distinctives

1.2. Introduction to Blast Resistant Design

BakerRisk

Sources of Explosions

- Condensed phase explosions (high explosives)
- Vapor cloud explosions
- Combustible dust explosions
- Bursting pressure vessels
- Boiling liquid expanding vapor explosion
- Rapid phase transition

Who Is Interested in Explosions?

- Military
  - *Design facilities to resist hostile weapons, terrorist threats*
  - *Targeting/weaponeering of hostile facilities*
  - *Munitions storage and handling*
- Industry
  - *Oil refining*
  - *Chemical processing*
  - *Explosives manufacturing*
- High-profile buildings
  - *National, local governments*
  - *Developers, owners of high rise or office buildings*

How Often Do Accidental Explosions Occur?

- ~1/day somewhere in the world
- Explosive loading should be considered a rare event for design purposes, but not an impossible one

BAKERRISK

Some Concepts To Get Used To

- "Blast resistant" can be a misleading term
  - *Better: "Able to resist blast loads of a given intensity"*
- Blast loads are low probability, high consequence
  - *Always more difficult to accommodate in design process*
- Blast typically governs structure over conventional design
  - *Adds some cost depending on level of threat*
- Components may undergo significant deformation and damage even at its design level
- Building owner may determine design load and level of acceptable damage
  - *Performance based design similar to current seismic design approach*
- No single authoritative, binding code

BakerRisk

Differences between Conventional and Blast Design

Conventional	Blast
High frequency event	Low frequency event
Always compulsory	Often voluntary
Governed by building code	Design specification often selected by owner
Loads prescribed by code	Design load related to owner decision
Enforced by building officials	Exempt from building official review; often not subjected to peer review
Loads are static	Loads are dynamic (time dependent)
Response is elastic	Response exceeds elastic limit, can accept significant permanent deformations
Analysis is static	Dynamic analysis methods are needed
Material properties are conservative (reduced from nominal)	Material properties are realistic (increased from nominal)
Relatively precise	Very high degree of uncertainty

BAKERRISK

Steps in the Design Process

- Identify critical assets
  - *Occupied buildings*
  - *Business interruption*
  - *Safe havens*
- Select hazard or threat
- Determine applicable loads on the assets
- Select allowable damage level (or level of protection)
  - *Light, moderate, severe damage (response criteria)*
- Conduct analyses
  - *Determine structural response of each component*
  - *Correlate to project mandated response criteria*
- Correlate component damage to building damage
- Determine acceptability, iterate as necessary

BAKERRISK

Asset Identification

- What are you trying to protect?
  - *Your facility/buildings*
  - *Your employees*
  - *Off-site personnel and property*
  - *Your reputation*
- What are they worth?
  - *Business interruption cost*
  - *Replacement cost (of buildings)*
  - *Liability and damages*

Threat or Hazard Definition

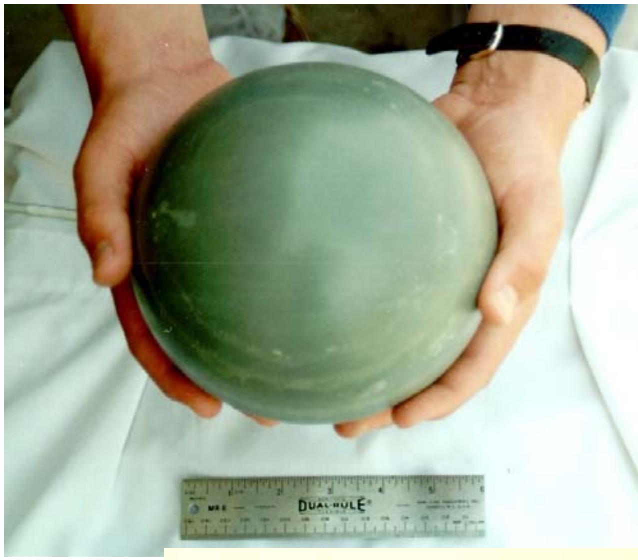
- Typically, need to define the threat
  - *Military*
    - Munition size, type, and standoff
  - *Industry*
    - Assessment of hazards related to processes
  - *Occupied buildings*
    - Assessment of terrorist threats
- Multiple threats may apply

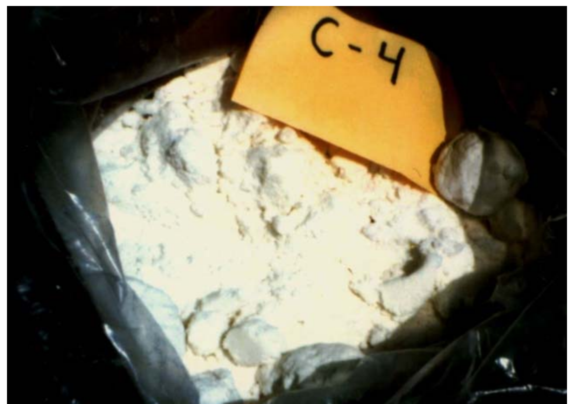
BakerRisk

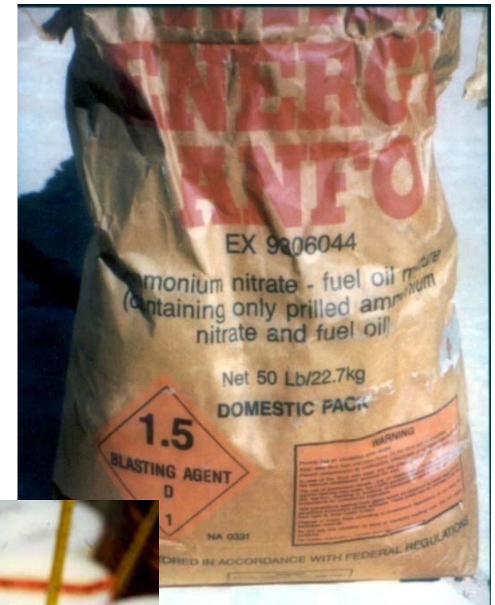
Design Basis Threat (DBT) and Design Criteria

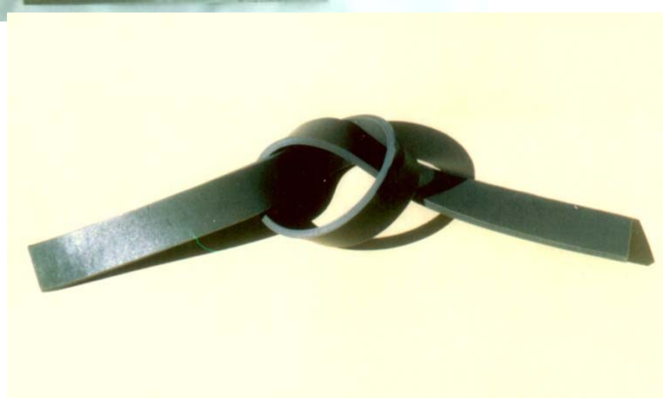
- Design criteria consist of the loads and allowable response
  - *Design Basis Threat – The capabilities and weapons that a potential assailant may possess*
  - *Design pressure and impulse for industrial hazards*
- Response levels based on guidance documents – unlike conventional static design, these vary with the use of the building!
  - *AT/FP guidelines*
  - *DoD manuals*
  - *ASCE guidance*
  - *Industry publications or practice*

Hand-Carried Charges: Bulk Explosives









BAKERRISK

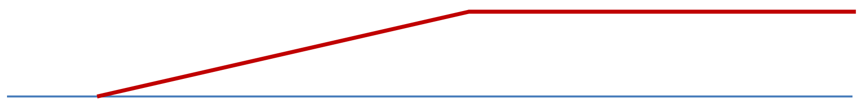
Damage and Crater from Small Vehicle Bomb

The suspected vehicle was estimated to have contained approximately 165 to 220 lb [75-100 kg] of explosives.

BAKERRISK

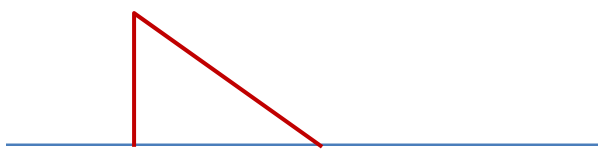
Types of Blast Load Specifications

- Static

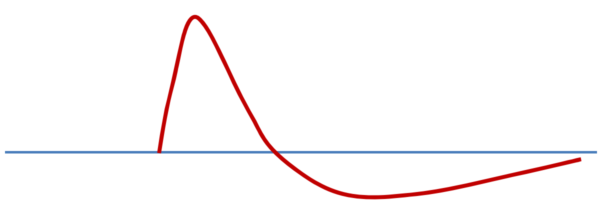


- Quasi-static

- Pressure and duration (triangular)



- More complex



Damage Levels

- Two types of damage levels
  - *Component*
  - *Building*
- Allowable damage level depends on criticality of asset being protected
  - ***Low** damage: high-priority buildings with critical function (e.g., central control room)*
  - ***Medium** damage: low-priority buildings with non-critical function, but significant populations*
  - ***High** damage: sparsely populated or unoccupied buildings*

BAKERRISK

Alternative to Damage Levels: Levels of Protection

Level of Protection	Potential Building Damage/Performance [2]	Potential Door and Glazing Hazards[3,4]	Potential Injury
Below AT standards[1]	Severe damage. Progressive collapse likely. Space in and around damaged area will be unusable.	Doors and windows will fail catastrophically and result in lethal hazards. *(High hazard rating)*	Majority of personnel in collapse region suffer fatalities. Potential fatalities in areas outside of collapsed area likely.
Very Low	Heavy damage - Onset of structural collapse, but progressive collapse is unlikely. Space in and around damaged area will be unusable.	* Glazing will fracture, come out of the frame, and is likely to be propelled into the building, with potential to cause serious injuries. *(Low hazard rating)* * Doors will be severely deformed but will not become a flying debris hazard. *(Category IV)*	Majority of personnel in damaged area suffer serious injuries with a potential for fatalities. Personnel in areas outside damaged area will experience minor to moderate injuries.
Low	Moderate damage – Building damage will not be economically repairable. Progressive collapse will not occur. Space in and around damaged area will be unusable.	* Glazing will fracture, potentially come out of the frame, but at reduced velocity, does not present a significant injury hazard. *(Very low hazard rating)* * Doors will experience non-catastrophic failure, but will have permanent deformation and will be inoperable. *(Category III)*	Majority of personnel in damaged area suffer minor to moderate injuries with the potential for a few serious injuries, but fatalities are unlikely. Personnel in areas outside damaged areas will potentially experience minor to moderate injuries.
Medium[5]	Minor damage – Building damage will be economically repairable. Space in and around damaged area can be used and will be fully functional after cleanup and repairs.	* Glazing will fracture, remain in the frame and results in a minimal hazard consisting of glass dust and slivers. *(Minimal hazard rating)* * Doors will be operable but will have permanent deformation. *(Category II)*	Personnel in damaged area potentially suffer minor to moderate injuries, but fatalities are unlikely. Personnel in areas outside damaged areas will potentially experience superficial injuries.
High[5]	Minimal damage. No permanent deformations. The facility will be immediately operable.	* Glazing will not break.(No hazard rating) * Doors will remain intact and show no permanent deformation. *(Category I)*	Only superficial injuries are likely.

1. This is not a level of protection and should never be a design goal. It only defines a realm of more severe structural response, and may provide useful information in some cases.

2. For damage / performance descriptions for primary, secondary, and non-structural members, refer to PDC Technical Report 06-08.

3. Glazing hazard levels are from ASTM F 1642.

4. Door hazard levels are from ASTM F 2247.

5. Beyond minimum standards.

- Can think of LOP ≈ 1/Damage
  - *High damage ≈ low LOP*
  - *Low damage ≈ high LOP*
- Used in AT/FP guidelines

Ref: UFC 4-010-01, Table 2-1, p. 26

BAKERRISK

Response Analysis

- Apply design loads to structure
- Analysis can be performed in various ways
  - *Look-up curves*
  - *Engineering models (SDOF)*
  - *High-fidelity models (finite element)*
- Determine response
  - *Typically interested in peak response*
  - *For high-fidelity modeling, more interested in material stresses and strains*

ASCE Component Response Levels

Typical design objective

Increased construction cost

Damage Level	Description
Low	Component has none to slight visible permanent damage.
Medium	Component has some permanent deflection. It is generally repairable, if necessary, although replacement can be more economical and aesthetic.
High	Component has not failed, but it has significant permanent deflections causing it to be unrepairable.
Collapse	Component has failed completely.

Increased casualties

Ref: ASCE, "Blast Resistant Buildings in Petrochemical Facilities," Table 5.B.1.B, p. 69

BakerRisk

Response Criteria

- Typically applicable to engineering models
- Typically defined in two parallel ways
  - *Ductility = measure of extent of plasticity*
  - *Support rotation = related to deflection and span*
  - *Must satisfy both criteria (if both apply)*
- Example

Component	Low Damage		Medium Damage		High Damage	
	μ	Θ	μ	θ	μ	θ
Steel beams, girts, purlins	3	2°	10	6°	20	12°

Ref: ASCE, "Design of Blast-Resistant Buildings in Petrochemical Facilities," Table 5.B.2, p. 70

BakerRisk

ASCE Building Damage Levels

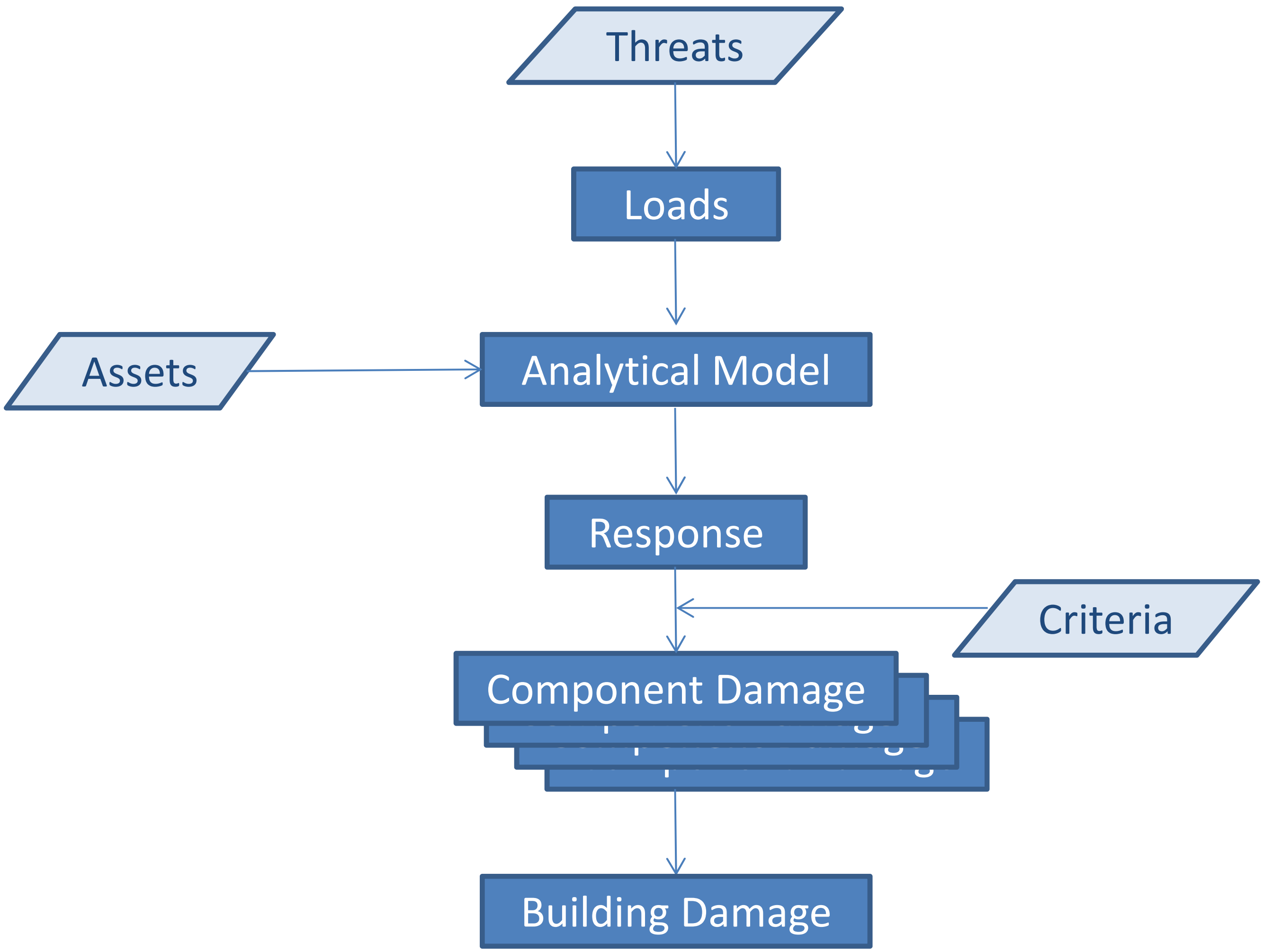
Damage Level	Description
Low	Localized component damage. Building can be used, however repairs are required to restore integrity of structural envelope. Total cost of repairs is moderate.
Medium	Widespread component damage. Building should not be occupied until repaired. Total cost of repairs is significant.
High	Key components may have lost structural integrity and building collapse due to environmental conditions (i.e. wind, snow, rain) may occur. Building should not be occupied. Total cost of repairs approaches replacement cost of building.
Collapse	Building fails completely. Repair is not feasible.

Acceptable risk threshold (owner-specific)

Ref: ASCE, "Blast-Resistant Buildings in Petrochemical Facilities," Table 5.B.1.A, p. 69

BakerRisk

Overview of Assessment/Design Process



What is the Blast Consultant's Role?

- Need to be involved in the early stages of the project
  - *Incorporate blast resistance in the structural system from the start*
  - *Far more efficient than upgrading a building after it is built*
- Assist in developing the system, not just the structure
  - *Value of trade-offs*
    - E.g., longer distance from operator shelter to process unit
    - Lower blast loads
    - More time spent walking to/from shelter
  - *Assist client in prioritizing objectives*
  - *Assist in selecting design threat, acceptable damage level*

BAKERRISK

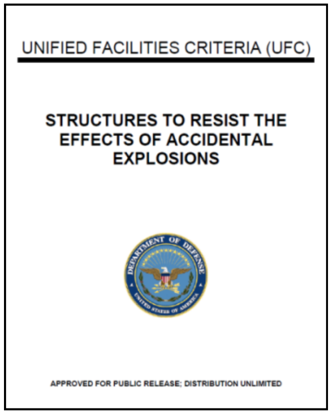
What is the Client's Role?

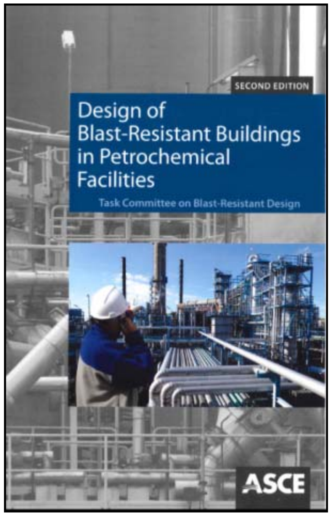
- Set budgets
- Assign priorities to buildings
- Determine damage level for design
- Maintain realistic expectations
  - *Understand roles of each discipline*
- Define operational constraints
  - *E.g., retrofits to be applied externally only or building must remain operational*

BAKERRISK

References

- UFC 3-340-02: Structures to Resist the Effects of Accidental Explosions
  - *AKA "Explosive Safety Manual," replaced TM 5-1300*
- UFC 3-340-01: Design and Analysis of Hardened Structures to Conventional Weapons Effects
  - *AKA "DAHS CWE Manual," TM 5-855*
  - *Limited distribution*
- ASCE, *Design of Blast Resistant Buildings in Petrochemical Facilities,* 2nd edition, 2010
- ASCE 59-11, Blast Protection of Buildings.
  - *Currently under review by BakerRisk and Stone for the US Government*

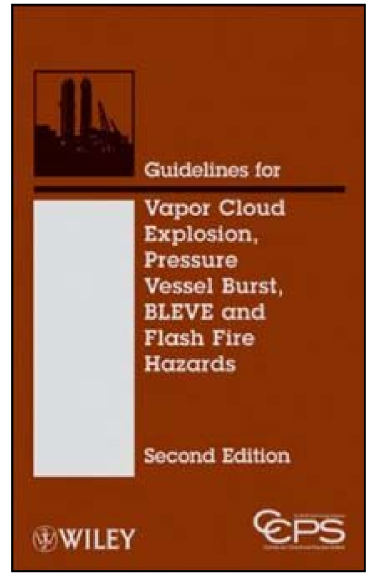


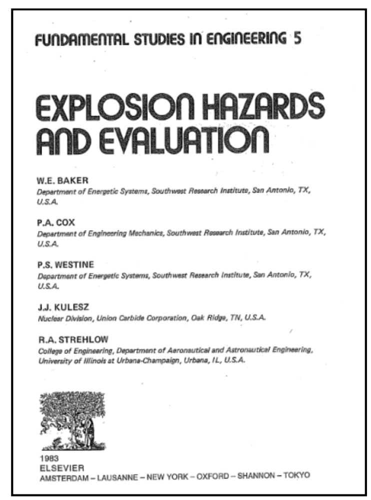


BAKERRISK

References (cont'd)

- CCPS, *Guidelines for Vapor Cloud Explosion, Pressure Vessel Burst, BLEVE and Flash Fire Hazards*, 2nd Edition, 2010
- Baker et al., *Explosion Hazards and Evaluation*, 1983
- Biggs, *Introduction to Structural Dynamics*, 1964
- PDC TR-06-08: SDOF Structural Response Limits for Antiterrorism Design





BAKERRISK

Government Guidelines

- Project specification ideally includes:
  - *Applicable guideline, including publication date*
  - *Design threat*
  - *Required level of protection (or similar language)*
- If not specified, determine applicable guideline by Government department requesting job
- If not specified, applicable guideline provides necessary information to select blast load and response criteria for analysis

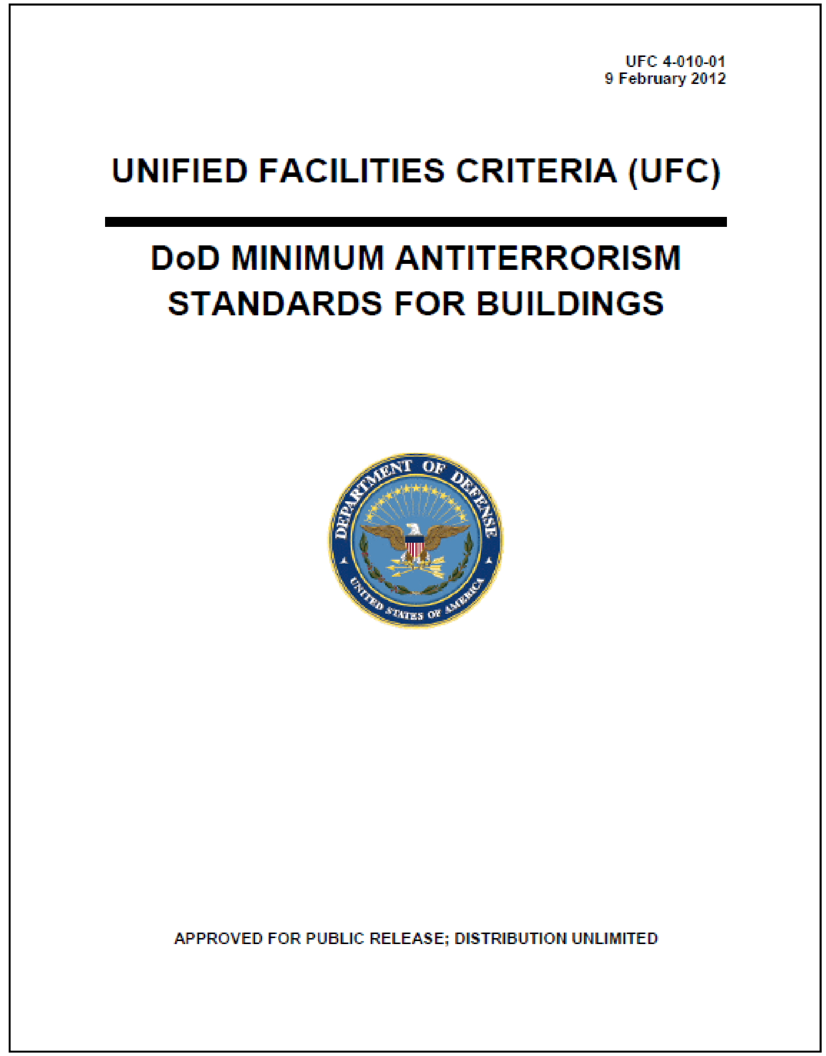
Government Guidelines (cont'd)

- 3 Major Guidelines
  - *UFC*
    - DoD Minimum Antiterrorism Standards for Buildings UFC 4-010-01
    - Any DoD building with anti-terrorism requirements
  - *ISC*
    - Physical Security Criteria for Federal Facilities, An Integrated Security Committee Standard
    - Any federal building that is not DoD or VA, mainly GSA
  - *VA*
    - Physical Security Design Manual for VA facilities:
      - Life-Safety
      - Mission Critical Facilities

BAKERRISK

UFC Guidelines

- UFC Design Threat
  - *Conventional construction standoff distance (CCSD) based on wall type*
  - *When standoffs cannot be met, charge weights specified in UFC 4-010-02 (FOUO) must be considered*



UFC 4-010-01
9 February 2012

UNIFIED FACILITIES CRITERIA (UFC)

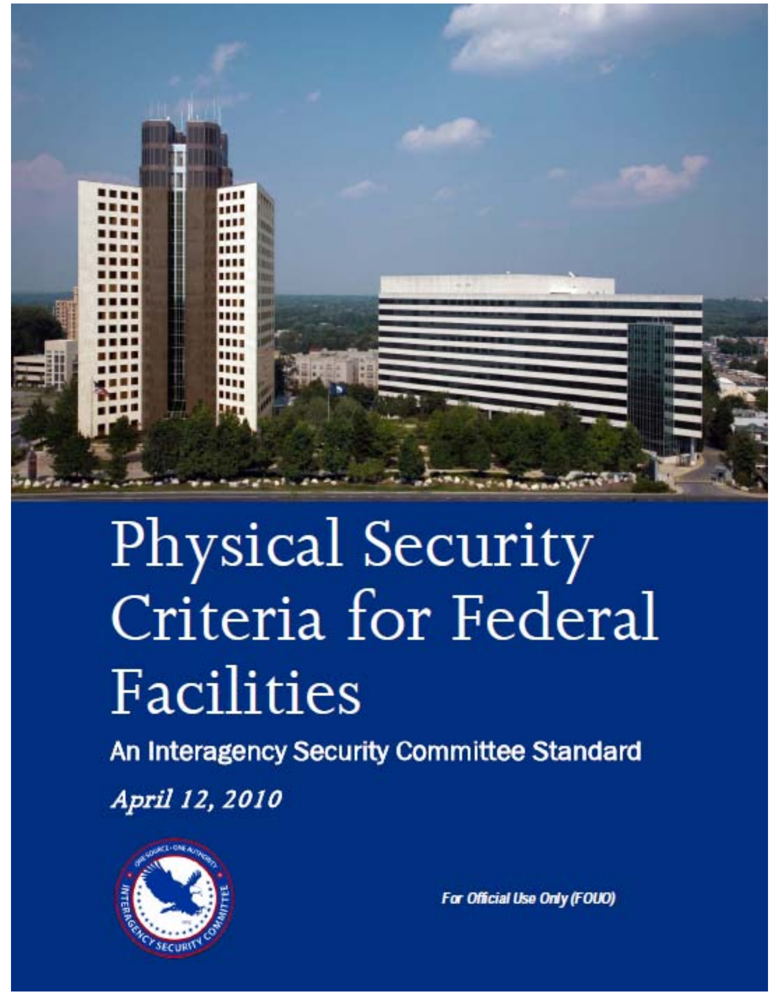
DoD MINIMUM ANTITERRORISM STANDARDS FOR BUILDINGS

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

BAKERRISK

ISC Guidelines

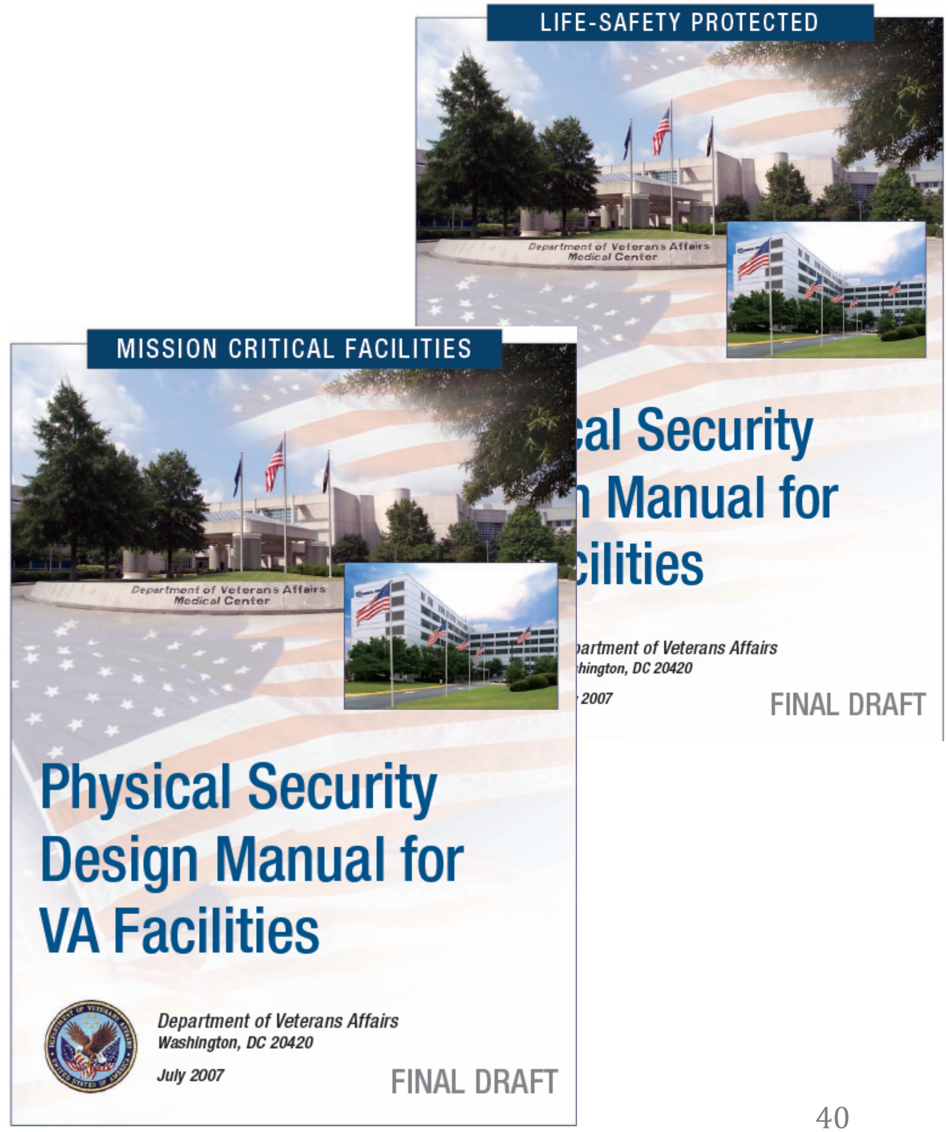
- ISC Design Threat
  - *Approach based on specified Facility Security Level (FSL)*
  - *FSL provided in specification or determined based on document "Facility Securities Level Determinations for Federal Facilities" (FOUO)*
  - *For FSL I and II, prescriptive requirements*
  - *For FSL III or higher, refer to "The Design Basis Threat" (FOUO) to determine applicable threat charge weight and apply specific standoff distance*



BAKERRISK

VA Guidelines

- VA Design Threat
  - *Charge weight and standoff specified with generic name in each document*
  - *Generic name defined in "Physical Security Design Standards Data Definitions" (FOUO)*
  - *Convert charge weight to pressure and impulse*



1.3 Blast Loads and Effects

What is an Explosion?

"…an explosion is said to have occurred in the atmosphere if energy is released over a sufficiently small time and in a sufficiently small volume so as to generate a pressure wave of finite amplitude traveling away from the source…. However, the release is not considered to be explosive unless it is rapid enough and concentrated enough to produce a pressure wave that one can hear."

Baker, W.E., Cox, P.A., Westine, P.S., Kulesz, J.J., Strehlow, R.A., *Explosion Hazards and Evaluation*, Fundamental Studies in Engineering, Vol. 5, Elsevier, Amsterdam, 1983.

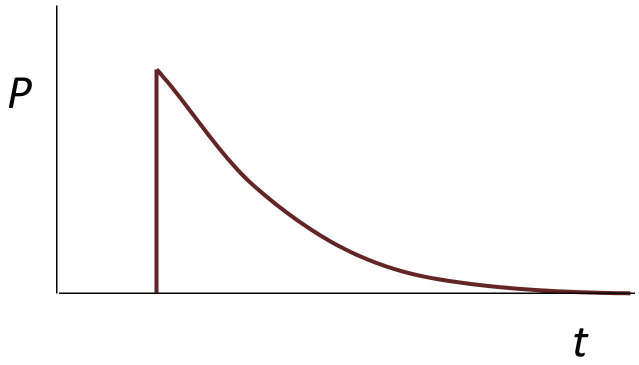
"The sudden conversion of potential energy (chemical, mechanical, or nuclear) into kinetic energy that produces and violently releases gas."

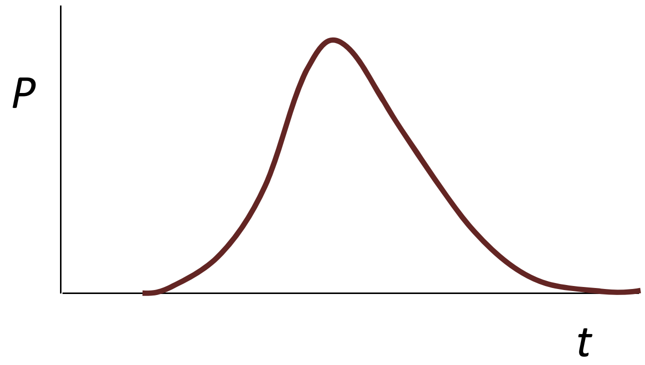
National Fire Protection Association

BAKERRISK

Types of Waves

- Two main classes of pressure waves that can be produced by explosions
  - *Shock wave*
    - Discontinuity in pressure—instant pressure rise
    - More severe loading condition for structures
  - *Pressure wave*
    - Gradual rise and decay of pressure
    - Less severe loading condition for structures





BAKERRISK

Ideal/Non-Ideal Distinction

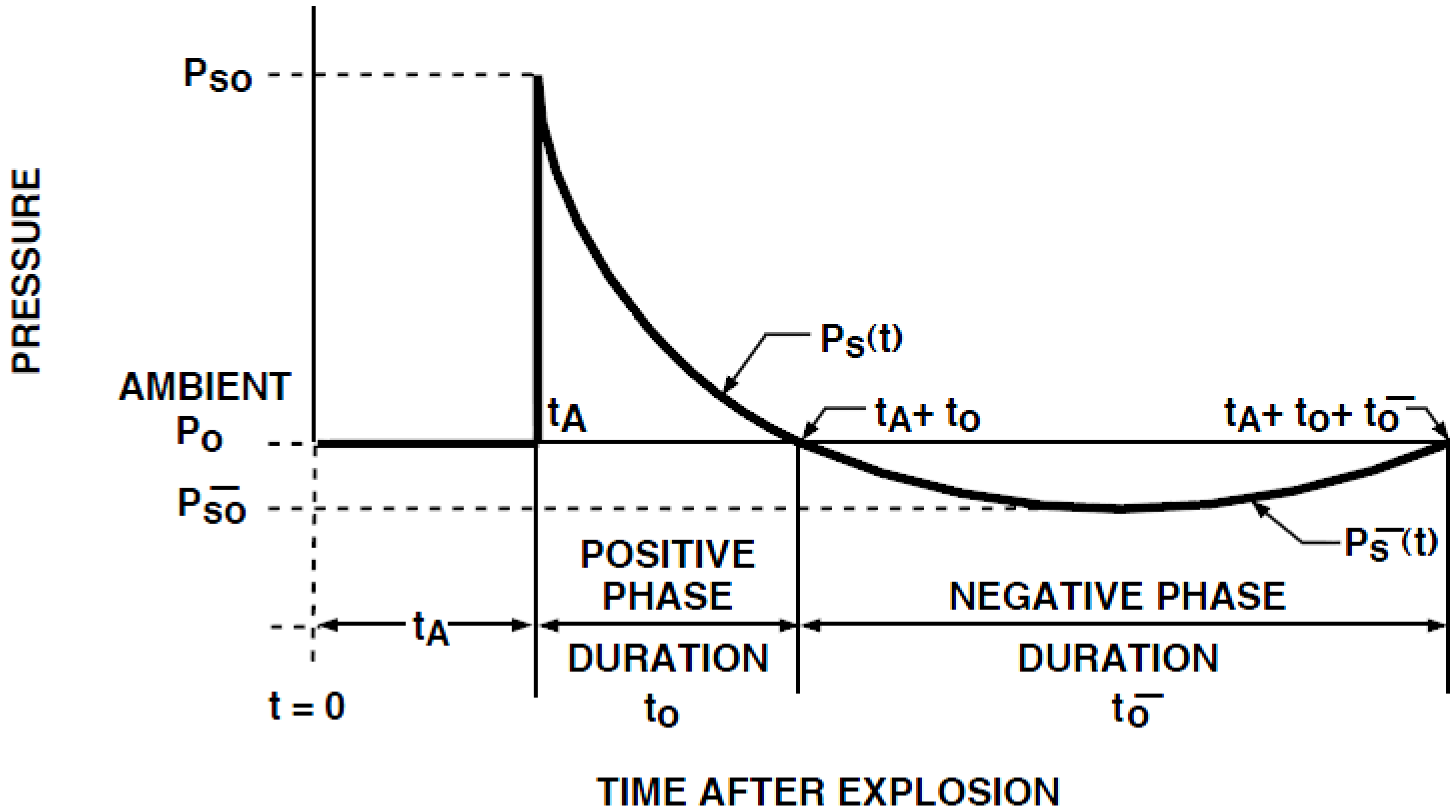
- Helpful to classify explosions into two basic categories
  - *Ideal*
    - Produces a shock wave
  - *Non-ideal*
    - Can produce a shock wave
    - More commonly, produces a pressure wave

BakerRisk

Definition of an Ideal Explosion

- An instantaneous release of energy
  - *Initially stored as internal chemical energy in the explosive*
  - *Instantaneously (or nearly) converted to heat and pressure through rapid chemical reaction*
- Energy dissipates radially outwards
  - *Blast wave*
  - *Thermal radiation*
- Chemical reaction converts explosive material into detonation products at high temperature, pressure

Ideal Blast Wave



Ref: UFC 3-340-02, Fig. 2-2, p.78

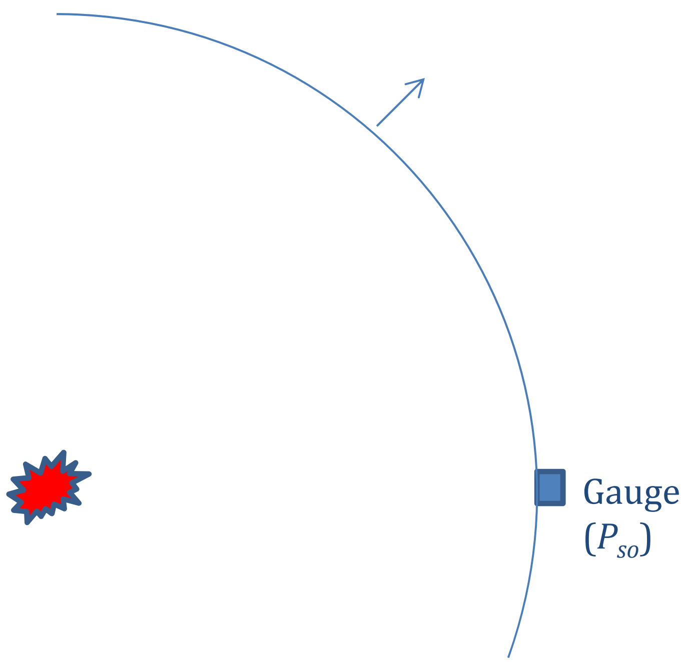
BAKERRISK

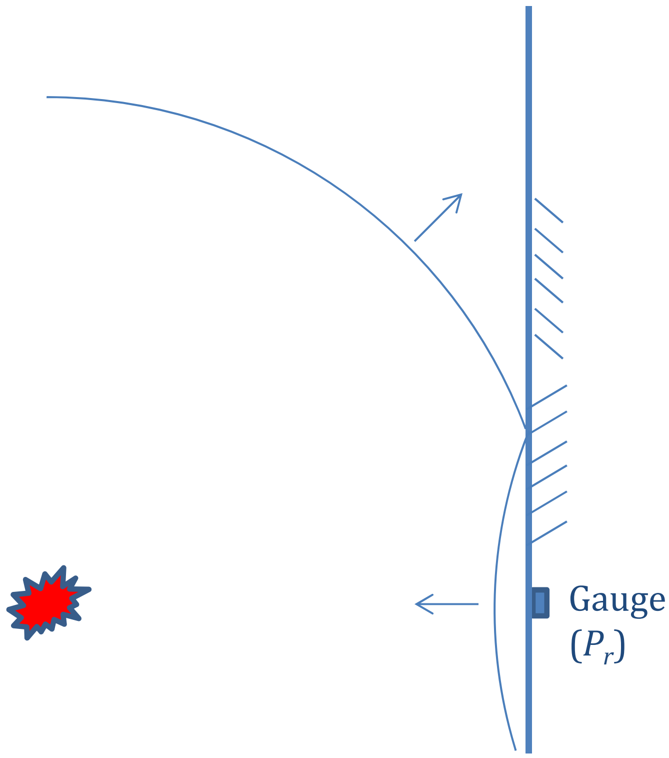
Incident vs. Reflected Pressure

Incident
Side-On
Free-field

Used interchangeably

Reflected





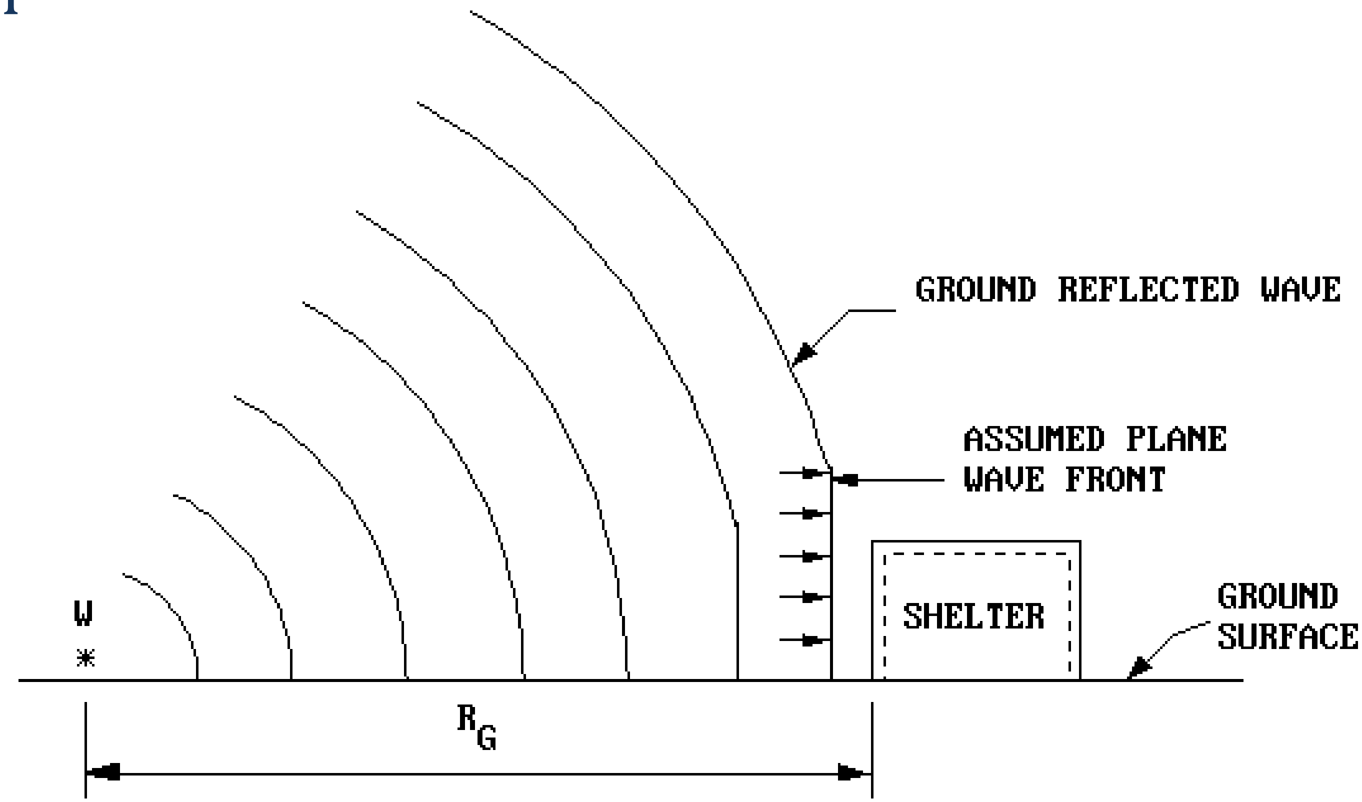
Incident vs. Reflected Pressures

- When blast wave propagation is interrupted by a rigid surface, the pressure increases to values greater than those for the incident blast wave
  - *Rigid boundary generates 2× reflection factor*
- Reflection factor for shock waves
  - *Approaches 2.0 as peak incident pressure decays below 1.0 psi [7 kPa]*
  - *At higher pressures, factor can be as high as 10-15*

BakerRisk

Loads on Structures

- Front wall
- Side wall
- Roof
- Back wall



Ref: UFC 3-340-02, Fig. 2-14, p. 89

Idealized Internal Explosions

- Explosions inside a structure produce loads in two phases
  - *Shock*
  - *Gas, or quasi-static*
- Shock similar to exterior blast discussed previously
  - *Complicated by presence of numerous internal reflections*
- Gas pressure
  - *Due to confinement of detonation products within a finite volume*
  - *Function of type of explosive, explosive weight, and room volume*
  - *Subject to venting*

BakerRisk

Comparison of Shock and Gas Pressure

Shock	Gas
Instant rise to peak	Slow rise to peak
High magnitude	Low magnitude
Short duration	Long duration
Dependent on charge location	Independent of charge location
Spatially varying (highly dependent on location)	Spatially independent (assumed constant throughout room)
Not dependent on openings	Venting highly dependent on area of openings

BAKERRISK

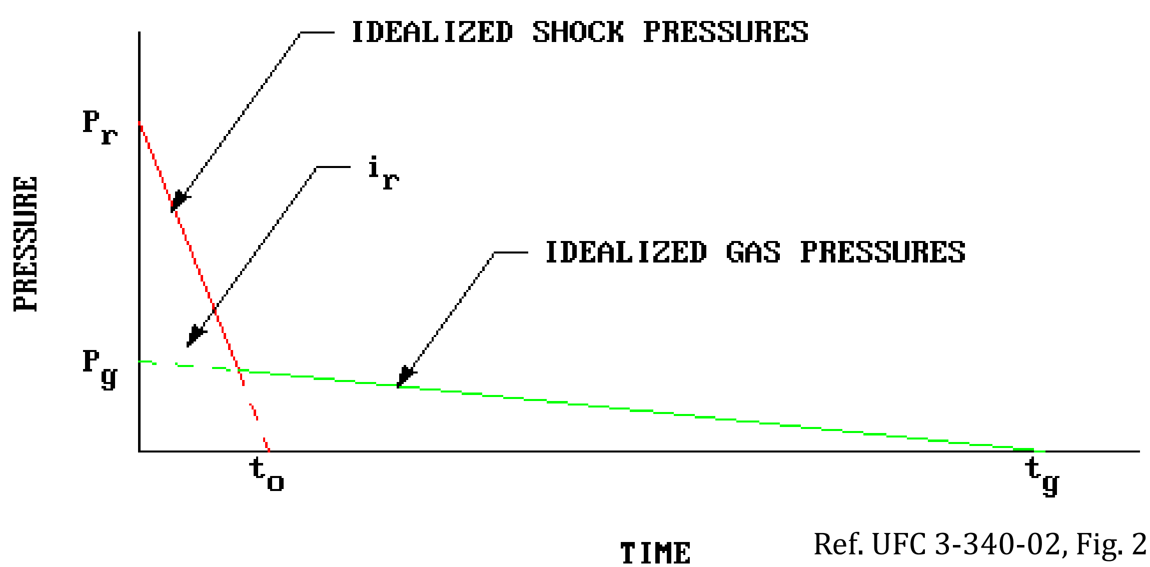
Internal Blast Loads

- Must account for *both* shock and gas phases
- Shock loads must include effects from internal reflections
- Gas loads must include effects of venting

BakerRisk

Combination of Shock and Gas Pressures

- Internal blast loads typically simplified as bilinear pulse
  - *Shock pressure idealized as triangle*
  - *Gas pressure idealized as triangle*
  - *Design pressure uses envelope of the two triangles*

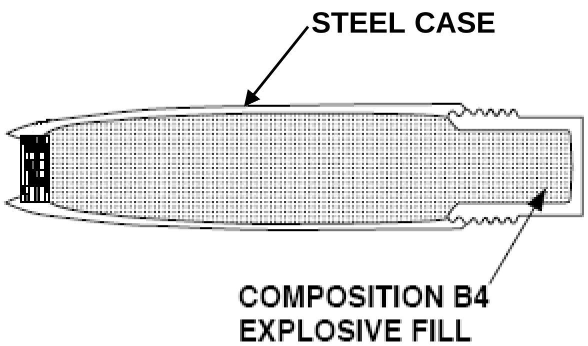


Ref. UFC 3-340-02, Fig. 2-165, p. 240

BAKERRISK

Effect of Casing on Blast Parameters

- Typical conventional weapons use steel casing around explosive
- Casing acts to absorb energy from the detonation and reduce the energy in the blast wave
- The heavier the casing, the greater the reduction
- Note: casing fragments (shrapnel) provide additional source of loading and damage to structural components (and lethality to humans) and must be accounted for separately



Non-Ideal Explosion Characteristics

- Characterized by a relatively low detonation or deflagration velocity
- Low energy density (energy / volume) also creates a non-ideal explosion
  - *Not a point source explosion as HE detonations are generally idealized*

Examples of Non-Ideal Explosions

- Vapor cloud explosions (VCE)
- Fuel/air explosives (weaponized version of VCE)
- Bursting pressure vessels
- Dust explosions
- Boiling liquid expanding vapor explosion (BLEVE)
- Rapid phase transition (sudden conversion from liquid to gas)

BAKERRISK

Self-Acceleration in VCEs

- Flame is accelerated by turbulence
- Turbulence is created by obstacles in the flame path and confinement
- Flame speed and blast generated is a function of:
  - *Congestion*
  - *Confinement*
  - *Fuel reactivity*
  - *Volume of cloud*
    - If deflagration, then volume of congested/confined region (i.e., not the total volume of the cloud)
    - If detonation, total volume of cloud

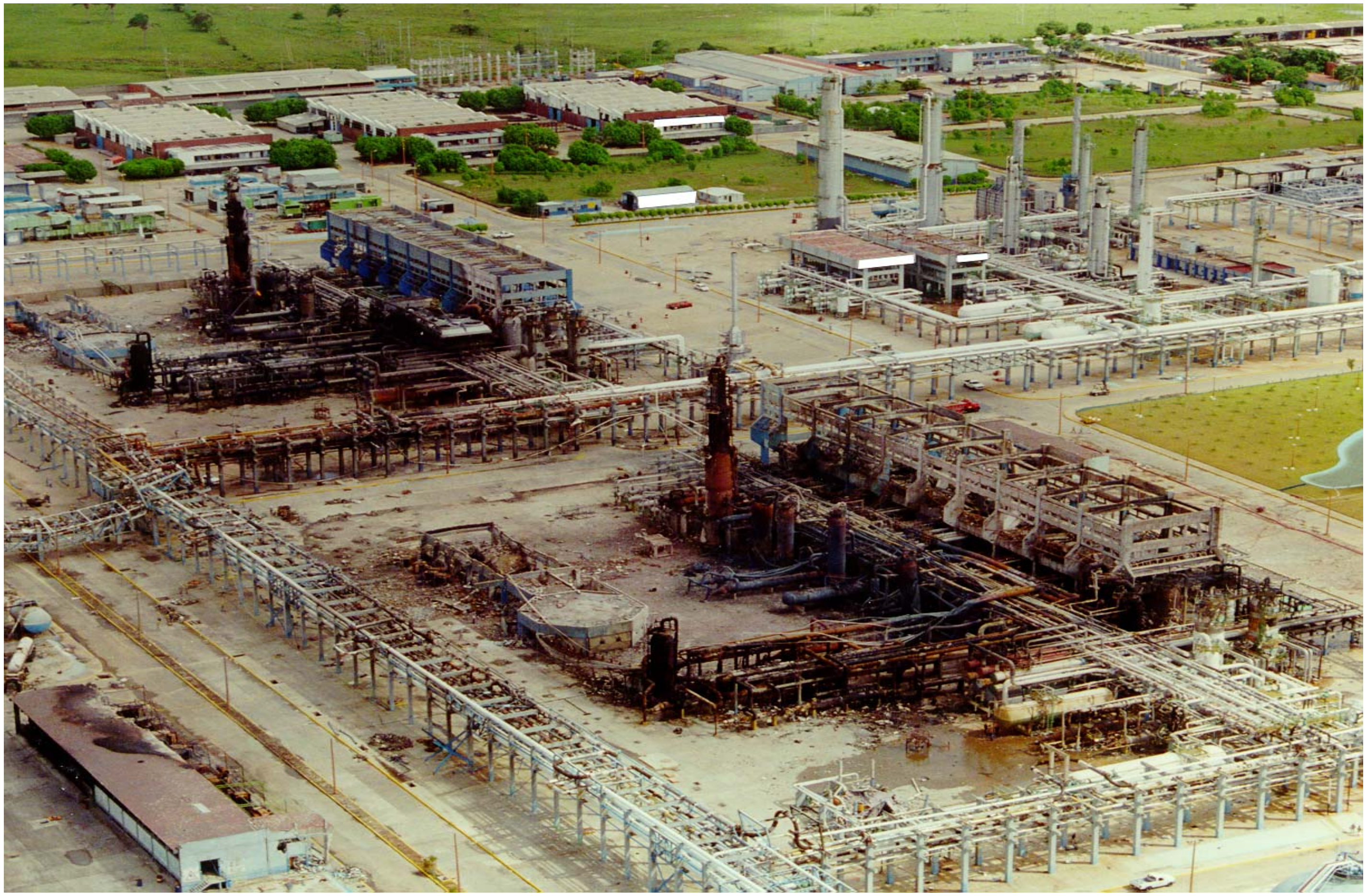
BAKERRISK

VCE Explosions

- Generally considered the most credible catastrophic explosion hazard on a plant site
  - *Especially where hydrocarbons are being processed*
- Typically external, but may also be internal
- Most commonly result in deflagrations
  - *But may undergo deflagration-detonation transition (DDT) under some circumstances and produce a detonation*

BakerRisk

Consequences of VCE

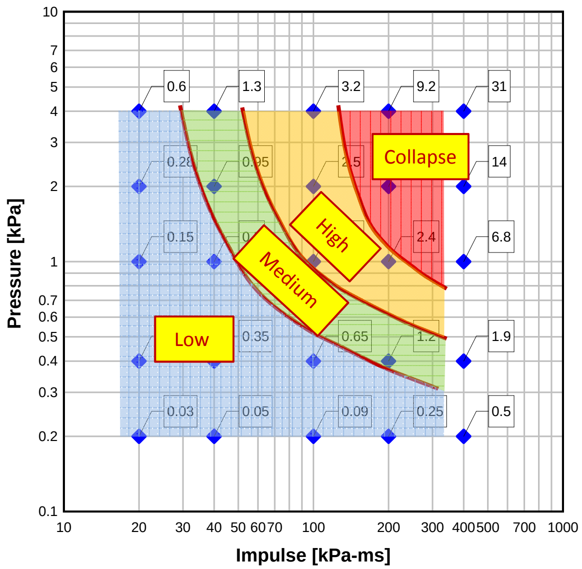


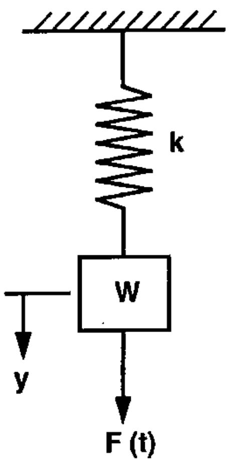
Scene after Fertilizer Plant Explosion

Energetic Materials Plant Accident

BAKERRISK

1.4 Blast Analysis and Mitigation Techniques

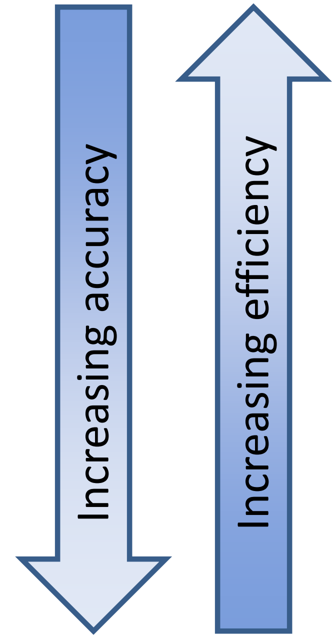




BAKERRISK

Overview of Methods

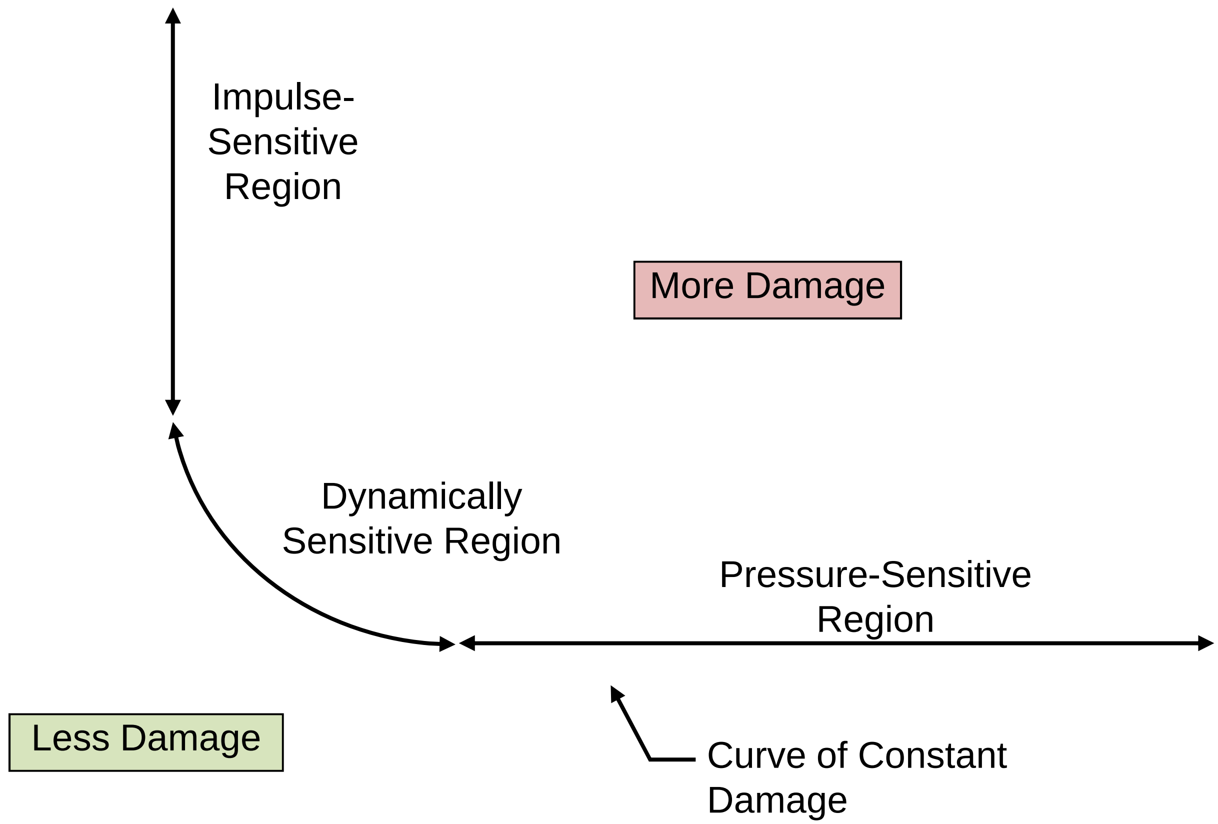
- Look-up tables
- P-i curves
- Single degree of freedom (SDOF) models
- Multiple degree of freedom (MDOF) models
- Finite element analysis (FEA)



BAKERRISK

Pressure-Impulse Curves

- Simple but powerful tool
- Allows rapid assessment of a structure or component



BakerRisk

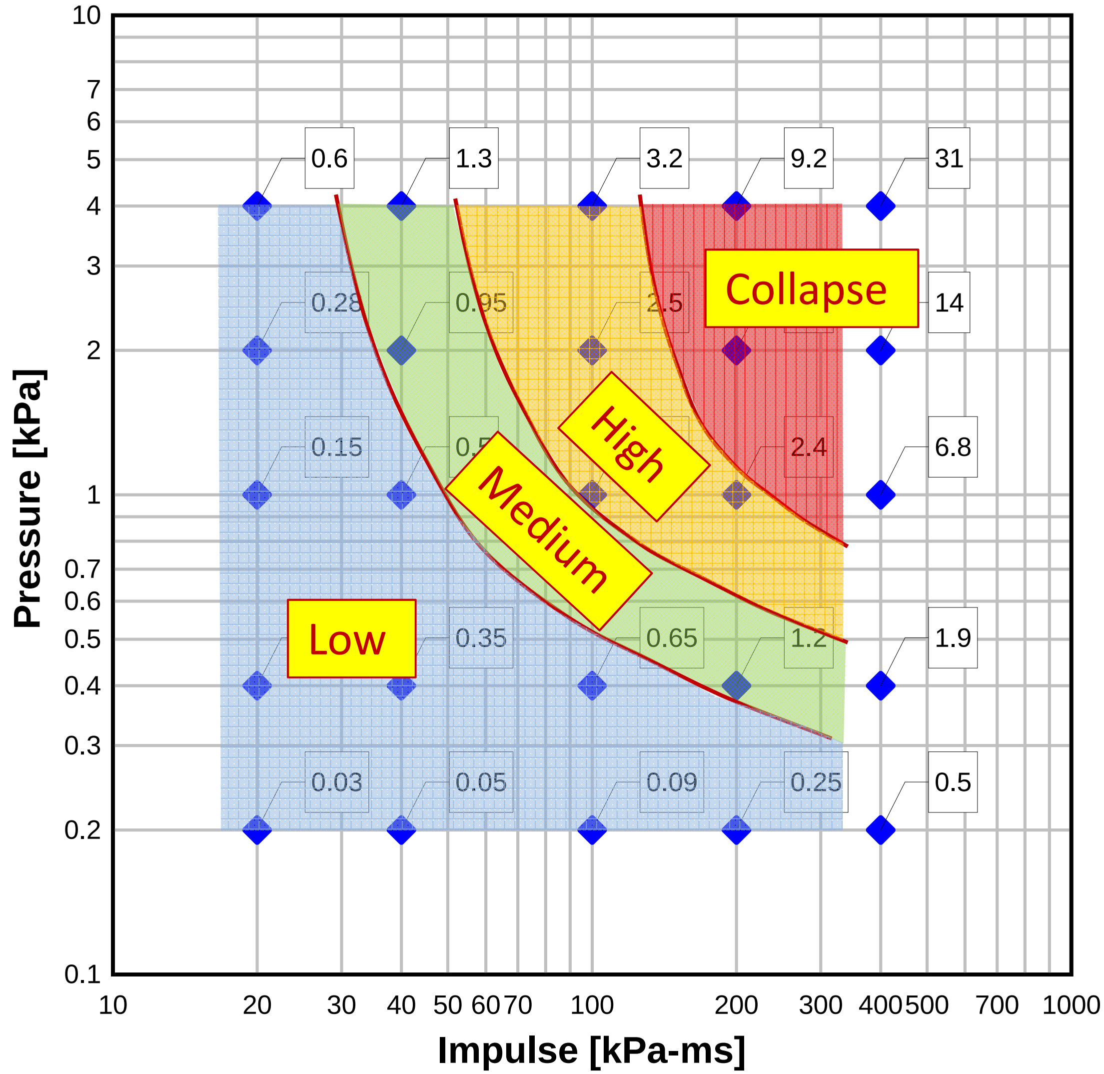
Prerequisites for Developing Pressure-Impulse Curves

- Define loading waveform shape
  - *Right triangle, isosceles triangle, etc.*
  - *Include or exclude negative phase*
  - *Many other options possible*
- Select a predictor of structural response
  - *SDOF model*
  - *FE model*
  - *Test data*
  - *Accident data*
- Select a level of response
  - *P-i curves are iso-response curves ("iso" = equal)*

BakerRisk

Development of P-i Curves

- If the response levels correspond to damage criteria, then the zones between curves represent damage levels
  - *< 1 in = Low*
  - *1 – 2 in = Medium*
  - *2 – 5 in = High*
  - *> 5 in = Collapse*

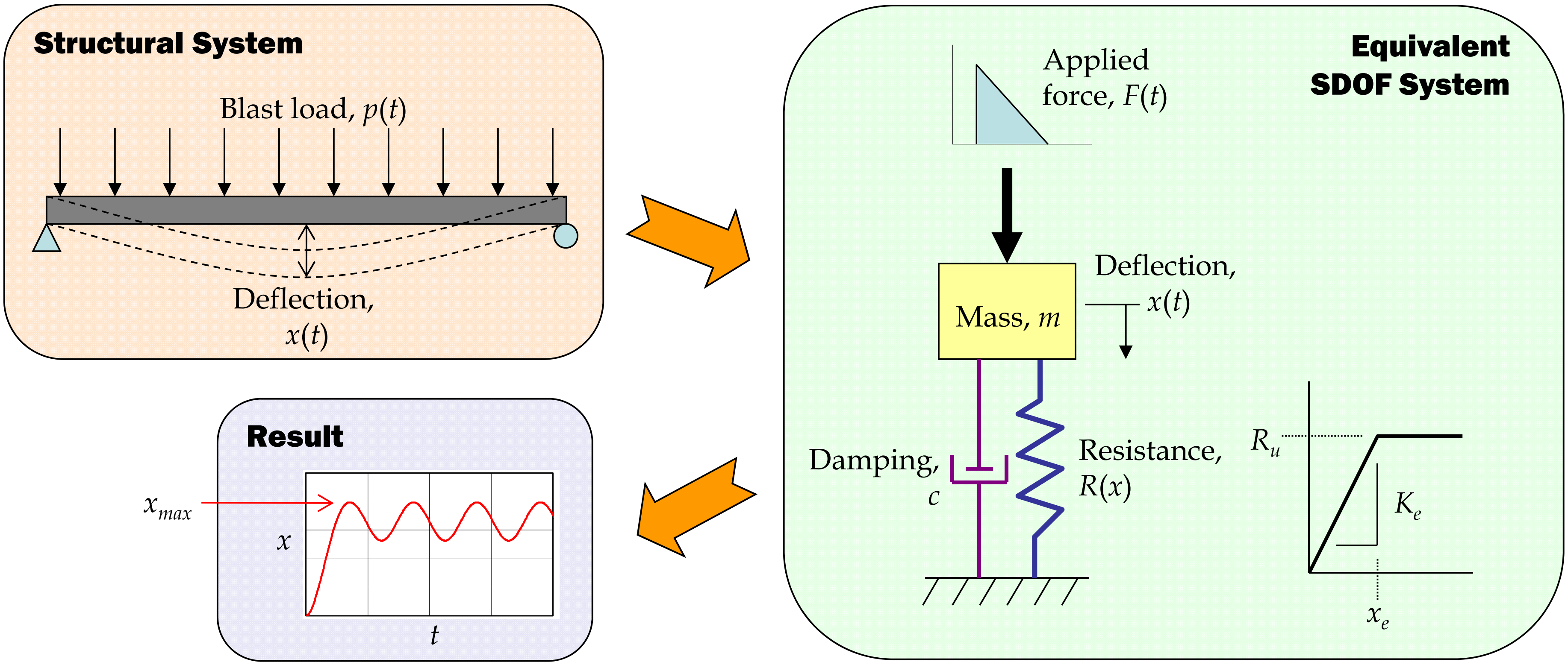


SDOF Analysis

- Simplest possible dynamic model
  - *"Dynamic" because it calculates a time-dependent response to a time-dependent loading*
  - *Simplest because it only allows one degree of freedom*
- Requires numerous simplifying assumptions
  - *Must assume response mode*
    - 99% of the time, assume it is first-mode flexure
  - *Must assume load distribution*
    - 95% of the time, assume it is uniform
  - *Must simplify load-displacement characteristics of structure*

BakerRisk

Equivalent SDOF System



Equivalent SDOF Systems

- Response of actual structural component to blast load can be determined by calculating response of an "equivalent" SDOF system
- The equivalent SDOF system is a spring-mass system with properties (M, K, R_u) equal to the corresponding properties of the component (modified by transformation factors)
- The deflection of the spring-mass system will be equal to the deflection of a characteristic point on the actual system (i.e., the maximum deflection)
- Based on kinematic equivalency (equal displacement, velocity, and acceleration for the equivalent and actual system)
- Properties of the equivalent system are derived from energy relationships

BakerRisk

SBEDS Input for "Reinforced Concrete Slab" Model Option

Configuration			
Span Length, L:		14	ft
Leave Input Blank for One-Way Response			
Boundary Conditions:	One-Way: Simple-Simple, Uniformly Loaded		
Response Type:	Flexural Only		
Structural & Material Properties			
Slab Thickness, t:		6	in
Bar Spacing			
Bars Spanning Parallel to L, b_L:		12	in
Not Used for One-Way Response			
Reinforcing Steel Areas	Inbound	Rebound	
Positive Moment Steel Parallel to L, AspL:	0.44	0.44	in^2
Negative Moment Steel Parallel to L, AsnL:			in^2
Not Used for One-Way Response			
Not Used for One-Way Response			
Distance of Cover to Center of Bars: d_c	(see diagram below)		
Non-Loaded Side Spanning Parallel to L:		1.5	in
Loaded Side Spanning Parallel to L:		1.5	in
Not Used for One-Way Response			
Not Used for One-Way Response			
Supported Weight, w:			psf
Concrete Density, γ:		150	lb/ft^3
Poisson's Ratio, ν:		0.167	
Concrete Compressive Strength, f'_c:		5,000	psi
Concrete Static Strength Increase Factor (>=1):		1.0	
Concrete Dynamic Compr. Increase Factor (>=1):		1.25	
Concrete Dynamic Compr. Strength, f'_{dc}:		6,250	psi
Concrete Elastic Modulus, E_c:		4,030,509	psi
Select Reinforcement:	A615, A616, A706 (All Gr. 60)		
Reinf. Steel Yield Strength, f_s:		60,000	psi
Reinf. Steel Ultimate Strength, f_u:	Click for User Defined Steel	90,000	psi
Static Strength Increase Factor:		1.1	
Dynamic Increase Factor:		1.23	
Dynamic Reinf. Steel Yield Stress, f_{ds}:		81,180	psi
Reinf. Steel Elastic Modulus, E_s:		29000000	psi

Blast Load Input Type

Manual input

Gravity Displacement

None (vertical component)

Pressure-Time Input

Time (ms)	Pressure psi
0	33.6
4.5	0
20	0
30	0
40	0
50	0
60	0
70	0

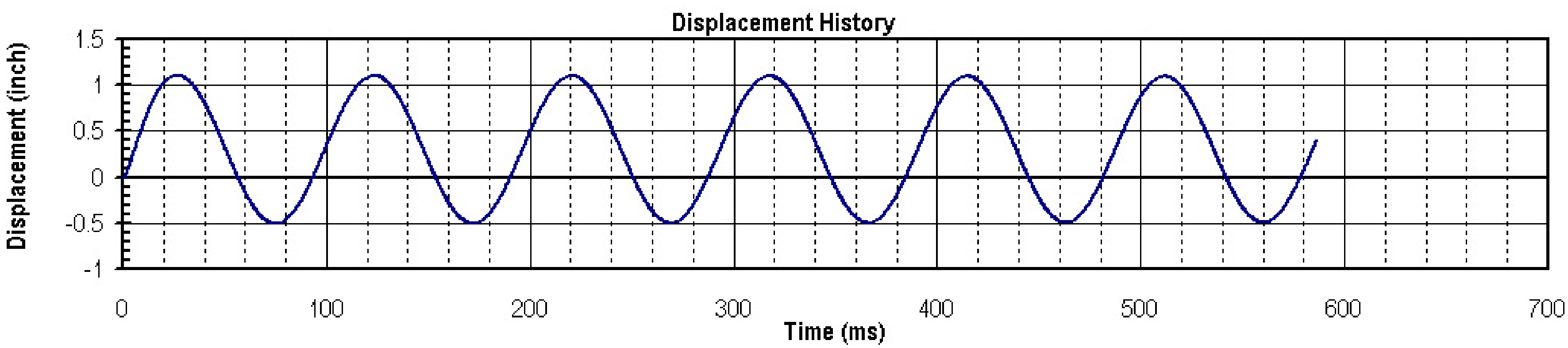
BakerRisk

SBEDS RC Slab Model Results

Results Summary				
θ_{max} =	0.8	deg.		
μ =	1.37			
X_{max} =	1.11	in	at time =	26.40 msec
X_{min} =	-0.50	in	at time =	75.00 msec
R_{max} =	3.56	psi	at time =	14.20 msec
R_{min} =	-3.55	psi	at time =	75.00 msec

Reactions		
Peak Dynamic Reactions		
$V_{max,Long}$ =	0.00	psi
$V_{max,Short}$ =	0.00	psi
Strain Rate to First Yield*		
For Steel	0.106	1 / sec
For Concrete	0.076	1 / sec

* First yield, or maximum response if no yield



BAKERRISK

Finite Element Analysis

- High fidelity numerical models are widely used in engineering analysis, focusing on:
    - *Solids and structures*
    - *Fluids*
    - *Heat transfer*
- Use of the modern finite element method has become widespread as computers have become more powerful
- Finite element analysis (FEA) has proven effective and widely applicable in engineering practice

Classes of FEA

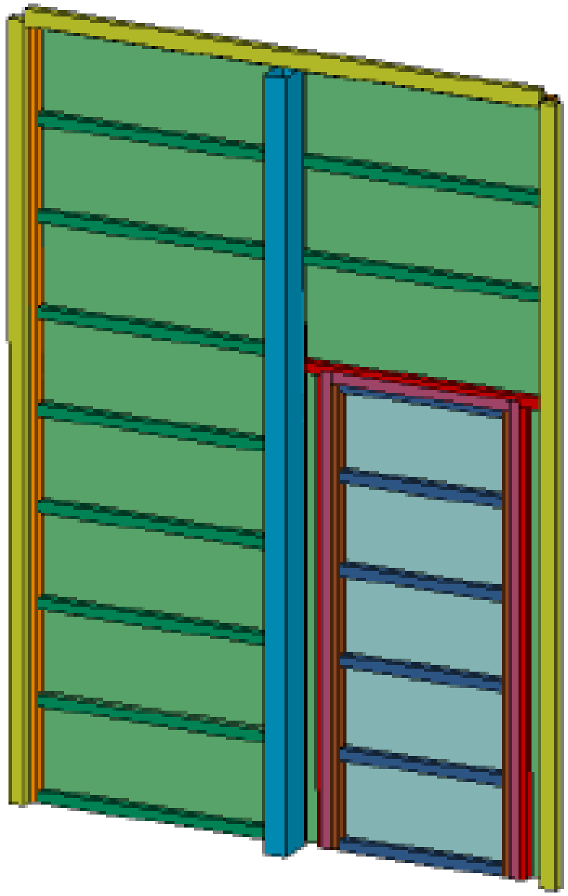
- Structural (Lagrange)
  - *Explicit solver*
    - Best for impulsive loadings, transient events
    - Requires very small time step
    - But result is inherently stable
  - *Implicit solver*
    - Best for steady-state loads (e.g., gravity, equivalent static seismic and wind, etc.)
    - No minimum time step required
    - But convergence is not guaranteed (particularly problematic for heavily nonlinear problems)
- Fluids (Euler)
- Fluid-structure interaction

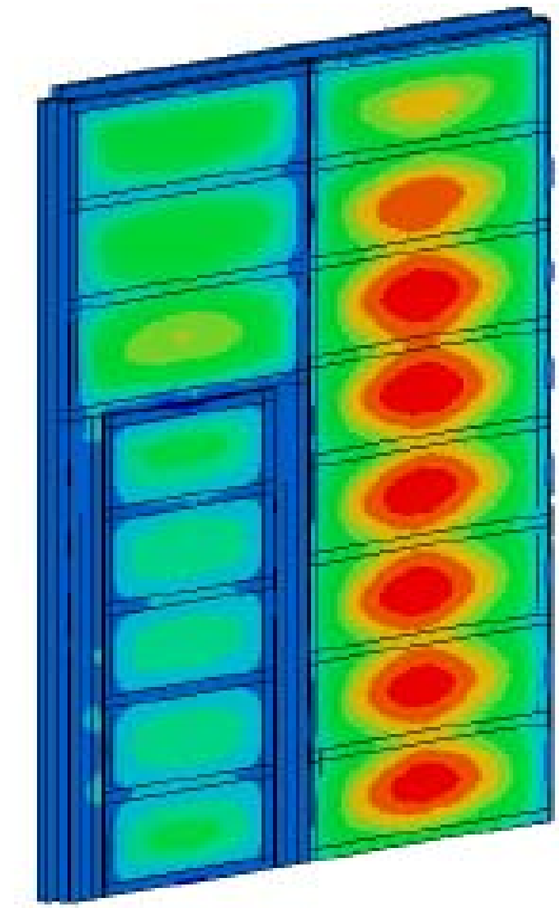
BAKERRISK

When to Use FEA?

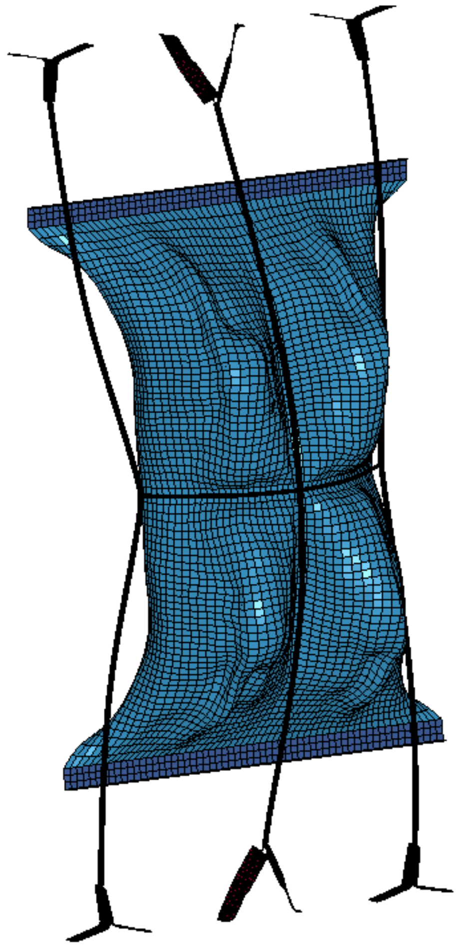
- Whenever the problem does not meet the limitations of the SDOF idealizations
  - *Inclusion of multiple response modes in single problem*
  - *Irregular structural geometry*
  - *Inclusion of higher-order effects (e.g., buckling, contact)*
  - *Non-uniform loading distribution*
  - *Nonlinear, rate-dependent material properties*
  - *Large displacement effects*
  - *Structural system with multiple interacting components*
  - *Failure predictions*
  - *Realistic boundary conditions*
  - *Need to generate "pretty pictures"*

Design of Door within a Door



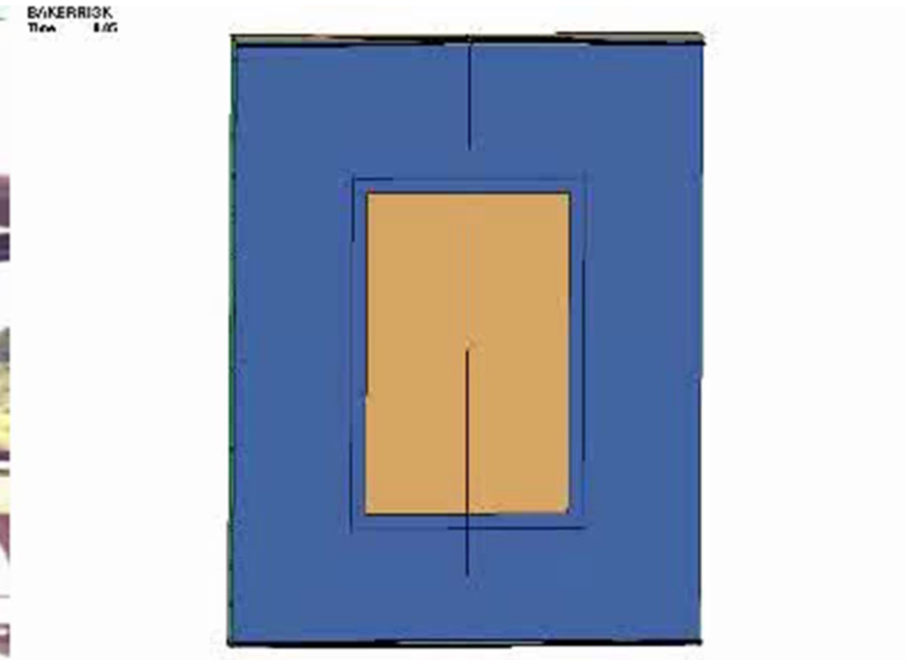


Post-Test Photos Compared to Window Catch System in LS-DYNA



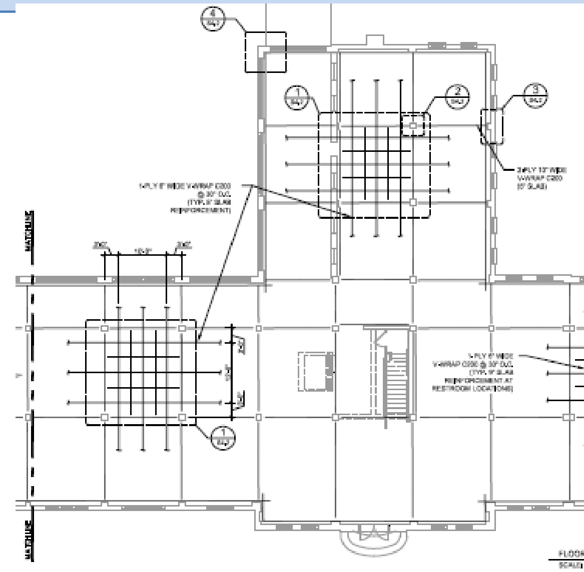
BakerRisk

LS-DYNA Analysis of Polyurea Window Catch System



Case 1- Fort Sam Houston, TX

- Blast Upgrades for Historic façade and glazing components
- Progressive Collapse and Structural Upgrades
- New Building Designs to meet DoD criteria



IMCOM Headquarters, Buildings 2266 & 2264

BAKERRISK

ATFP and Progressive Collapse Requirements

- Design Requirements:
  - Blast design for major modernization of several existing buildings and design of new buildings
  - Assessment and upgrades to existing structural system during demolition, construction, and new operation loads (change of use)
  - Exterior façade (walls, glazing, etc) evaluation and upgrades for Anti-Terrorism and Force Protection (AT/FP)
  - Progressive collapse prevention evaluations, designs and upgrades

BakerRisk

Design Support from Concept to Completion

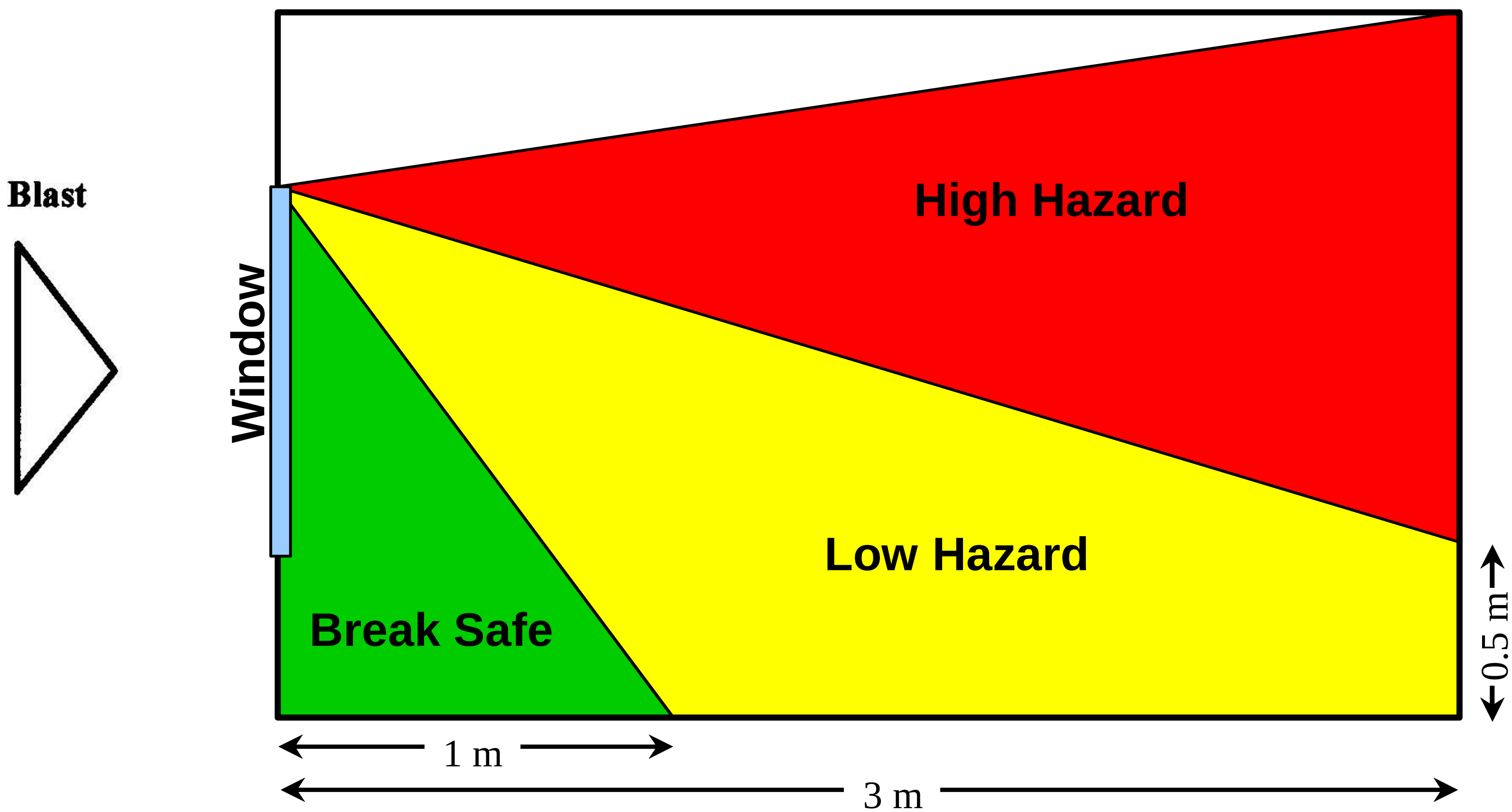
- Project Challenges:
  - Determining as-built information and assumptions for 100 year old structures
  - Historical/heritage preservation requirements
  - Need for solution with minimal impact on existing construction (i.e., minimal additional loads on building from new construction)

BAKERRISK

Existing Building Retrofits

- Solutions
  - Use of non-destructive evaluation methods (such as ground penetrating radar scans) to determine exiting reinforcement layouts
  - Upgrade glazing, window frames, doors, and anchorage to meet blast requirements and match appearance of historic components or mitigate by catching debris
  - Combining façade upgrades for blast with interior architectural wall renovations to eliminate changes to visual appearance of building
  - FRP application to address progressive collapse and increase in design floor loads without increasing dead loads on structure
  - Innovative Products for Close Range Bomb Threats

Hazard Levels – ASTM F1642



Façade Upgrades on Interior Surface

- Masonry Wall Upgrades
- Window System Upgrades

Glazing Catch System and Shields

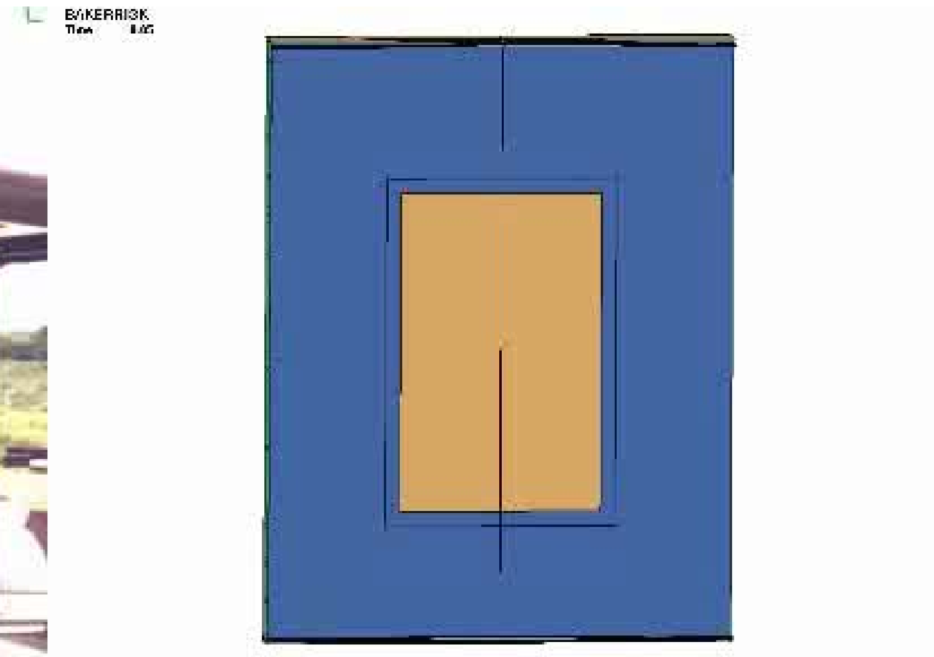
Innovative Catch System

Polycarbonate Shield

Developement of Polyurea Catcher System

Test in Shock Tube

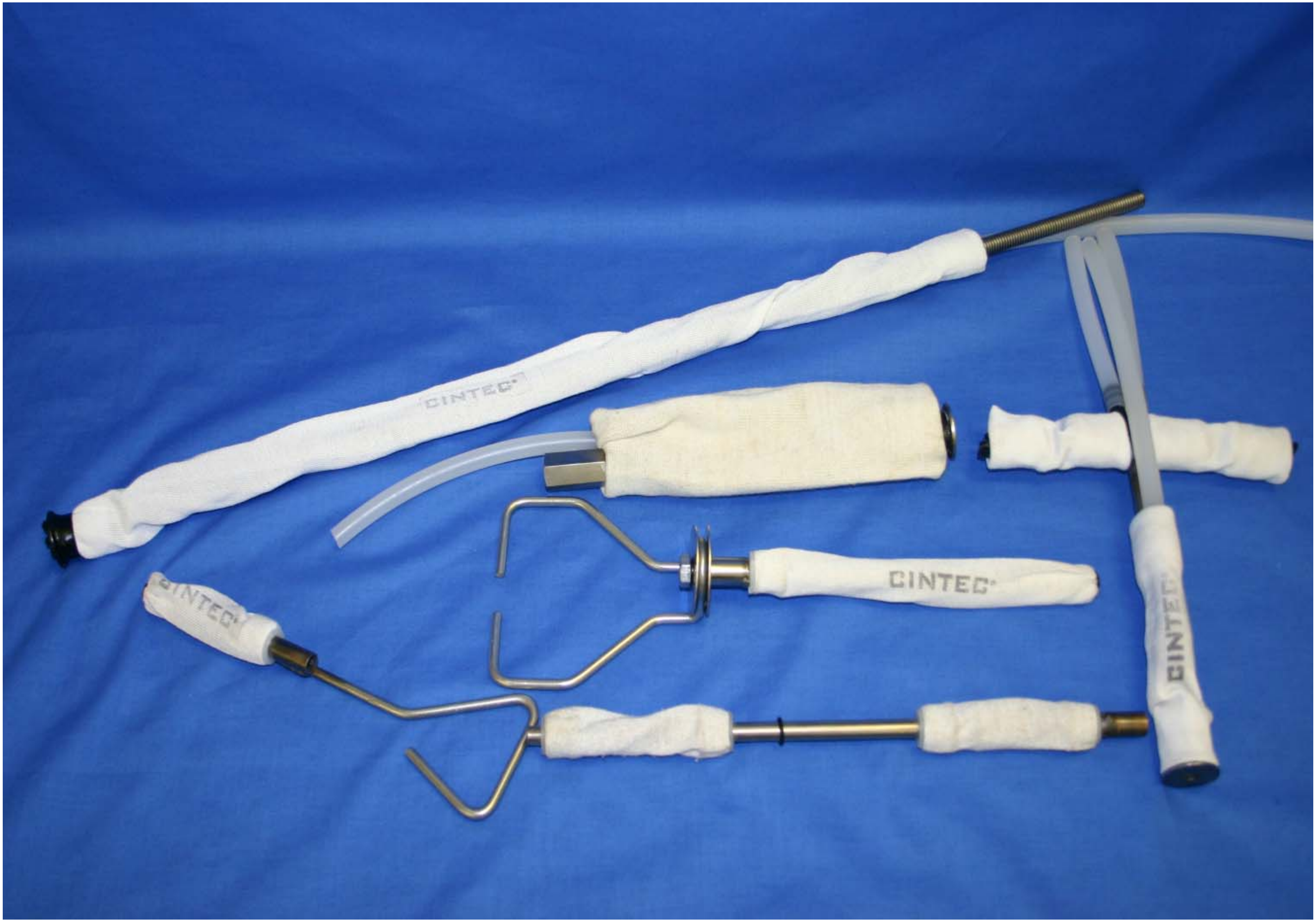
LS-DYNA Analysis



E-Glass Retrofit to CMU Wall

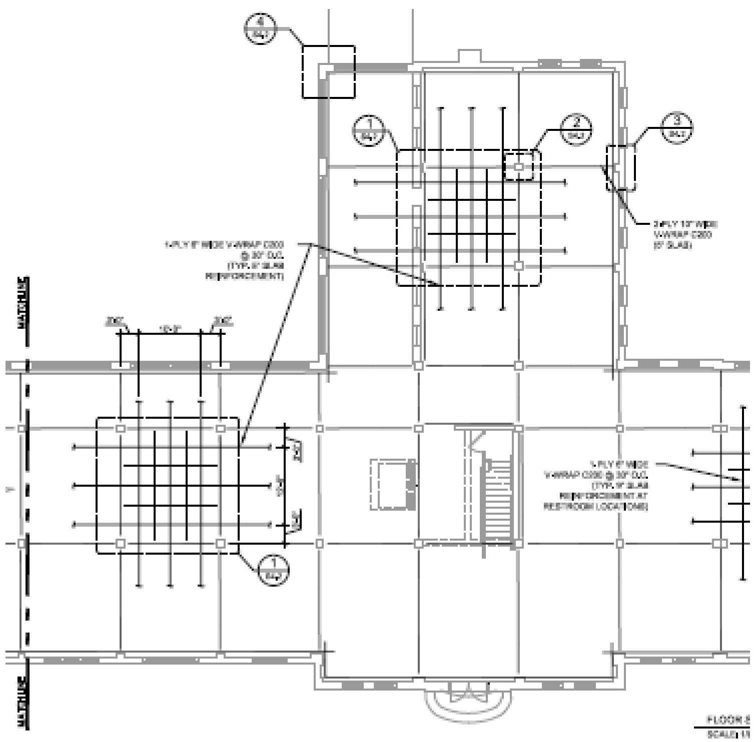
Reuse Damage Level (DL 1)

11 psi,
350 psi-ms
[76 kPa,
2400 kPa-ms]


CINTEC
CINTEC
CINTEC

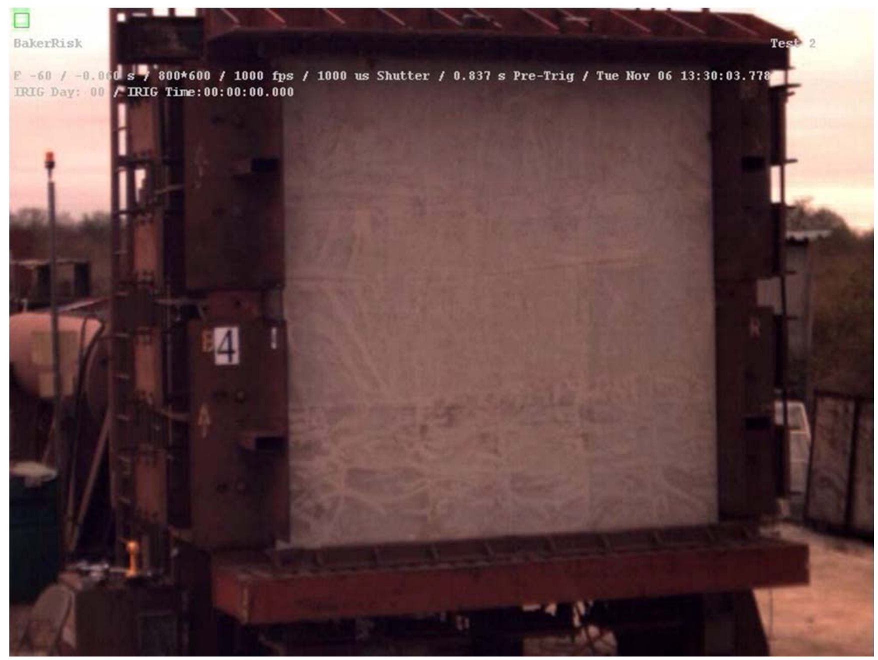
Slab Uplift and Progressive Collapse Upgrades

- Progressive Collapse Retrofit
- Blast Uplift on Slabs



R/C Slab in Uplift: Test Results

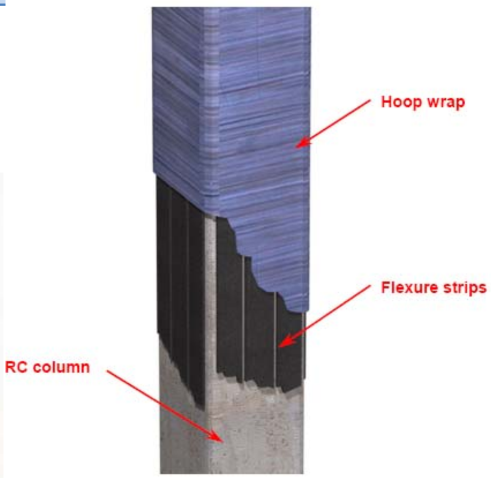
- Test SP4 (for Control Slab)
  - 10.3 psi, 75 psi-ms [71 kPa, 520 kPa-ms]
  - Severe damage
  - Peak deflection of 9.5 inches [240 mm]



R/C Slab in Uplift: Test Results (cont'd)

- Test SP5 (for SF-1 scheme)
  - 17.6 psi, 127 psi-ms [121 kPa, 876 kPa-ms]
  - Moderate damage
  - Peak deflection of 3.25 inches [83 mm]

Concrete Column Carbon Wrap System



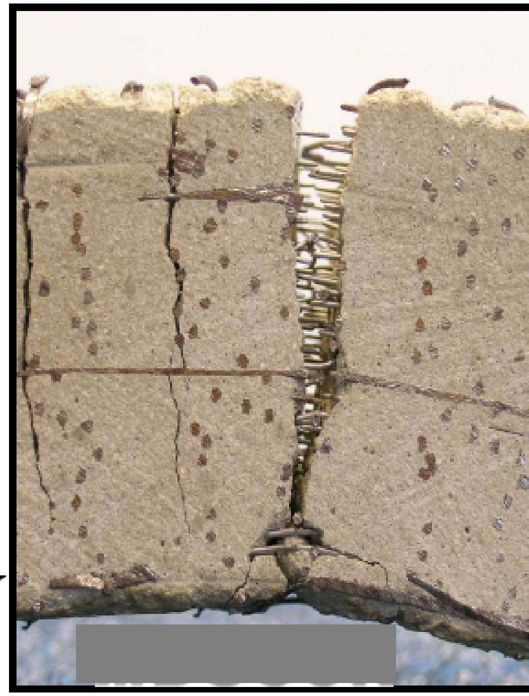
High-Performance Micro-reinforced Concrete

Micro-reinforced Concrete

Resistant to high grade explosives

Adjustable properties, behaves similar to steel

No Spalling, No Fragment projectiles

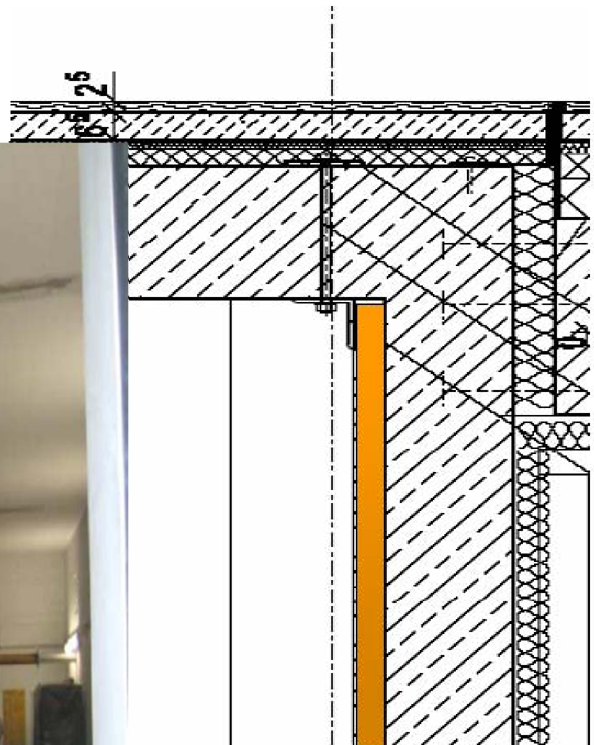


Ideal for close range or contact blast

Extremely ductile with high degree of deformation

Highly durable, waterproof & fire resistant

Wall Retrofits & Shields for Close Range Threats



Retrofits & Shields for Close Range Threats

100lbs Close range detonation testing

Rear Side

Case 2- Industrial Faciltiy- Existing Control Room

- Objective is to protect building occupants
- Blast Upgrades with Minimal Interruption to Building Function

Design Support from Concept to Completion

- Design Requirements:
  - *Determine design blast loads on buildings based on possible industrial release scenarios*
  - *Generate blast mitigation concepts for a moderate level of damage*
  - *Conduct site inspection to document deviations from existing drawings*
  - *Develop detailed drawing package and specifications necessary for construction*
  - *Review vendor submittals for doors, windows, etc.*
  - *Provide construction administration services to address issues that arise during construction*

Upgrades with Minimal Interruption

- Challenges:
  - *Structures Must Remain Fully Functional*
    - Interruption of services would result in substantial financial ramifications
    - Retrofits to structure that function as an integral part of facility operations and not compromise safety requirements (fire, toxicity, etc..)
    - Upgrades around sensitive equipment
    - Design modification for equipment that cannot be relocated
  - *Existing Construction*
    - Conventional construction, brittle materials, poorly maintained, more than 50 years old where blast and seismic design was not a consideration

Unreinforced CMU Wall Response

Collapse Damage Level

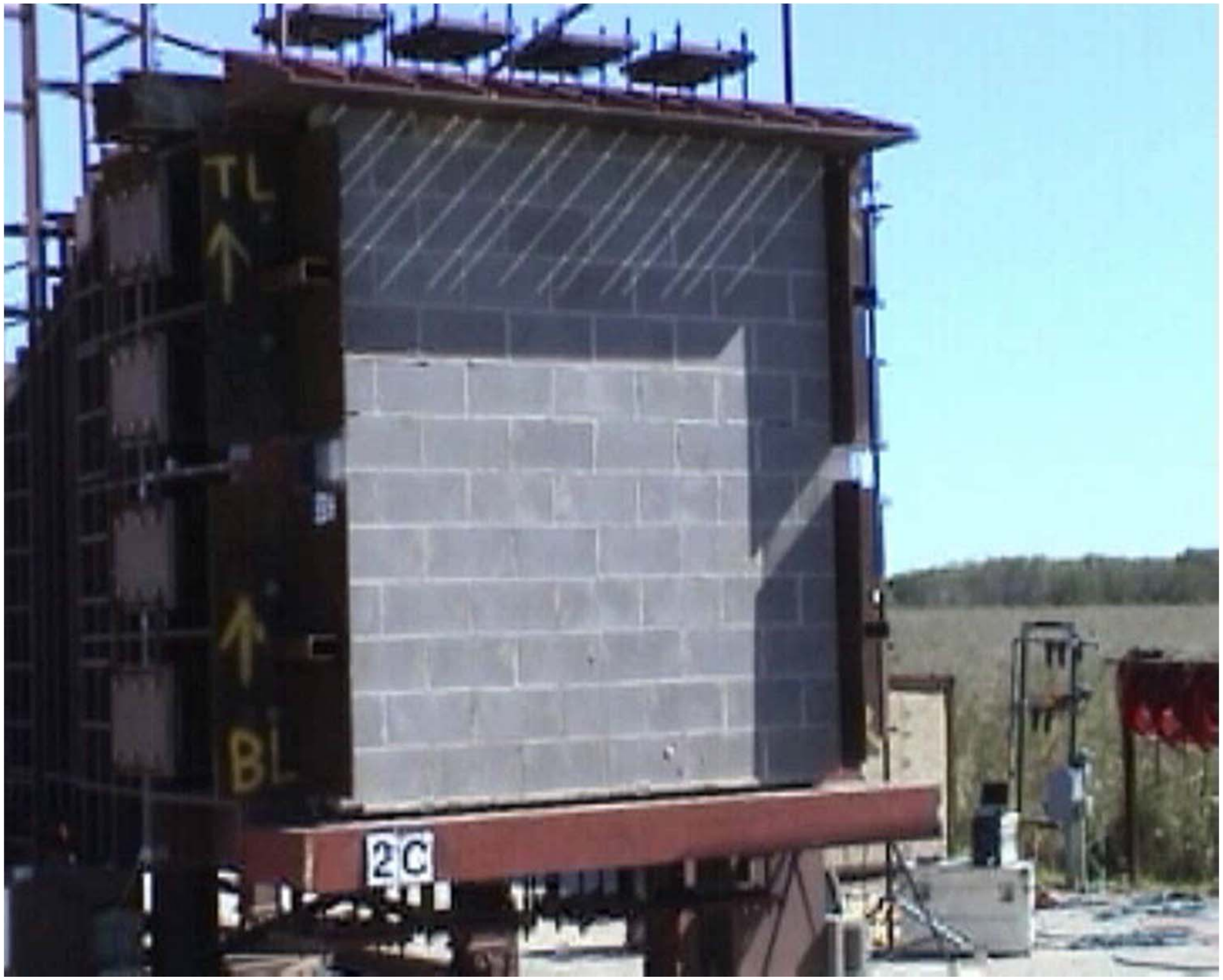
4 psi, 40 psi-ms
[28 kPa,
280 kPa-ms]

Steel Post Upgrade to CMU Wall

Steel Tube Reinforcement on Loaded Side of CMU Wall

BAKERRISK

Test of CMU Wall After Upgrade



Example- Masonry Wall Upgrade

BAKERRISK

Examples of Post Upgrades in the Field

New Exterior Posts and Angles

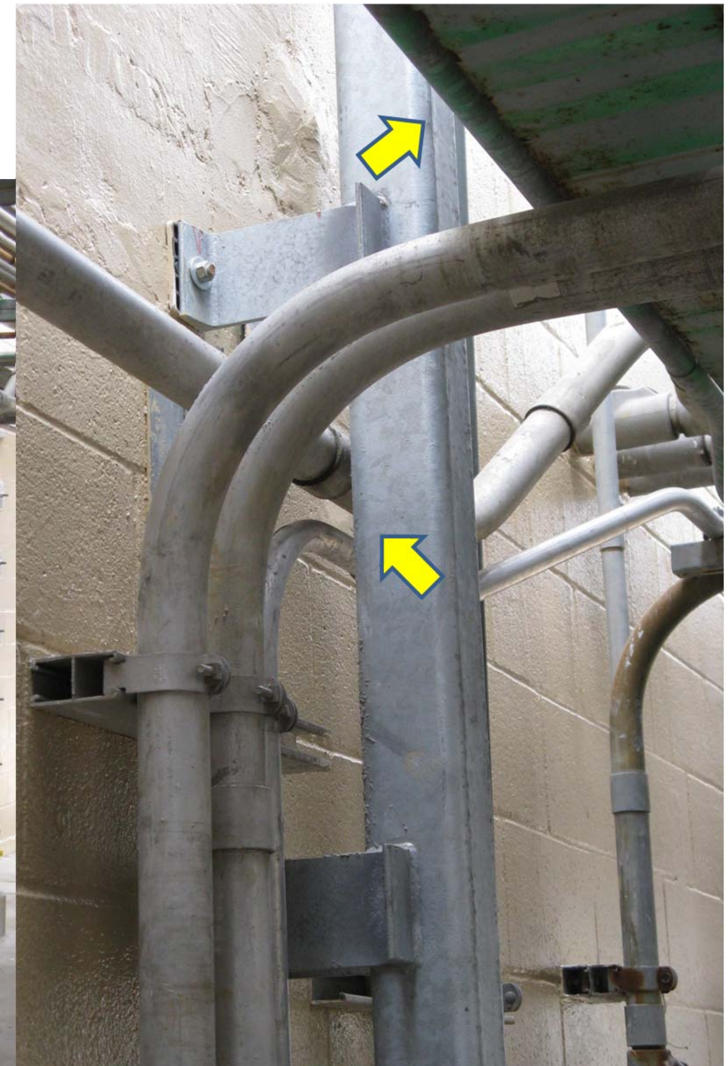
New Door Frame for
Blast Resistant Door

BAKERRISK

Upgrades with Minimal Interruption

- Solutions:
  - *Use of dynamic analysis for optimum solution*
  - *Relocate retrofits to exterior building surface to minimize impact on occupants or existing equipment*
  - *Use exterior retrofits techniques that been validated through testing*

Control Rooms with Exterior Obstruction



Metal Building Upgrades

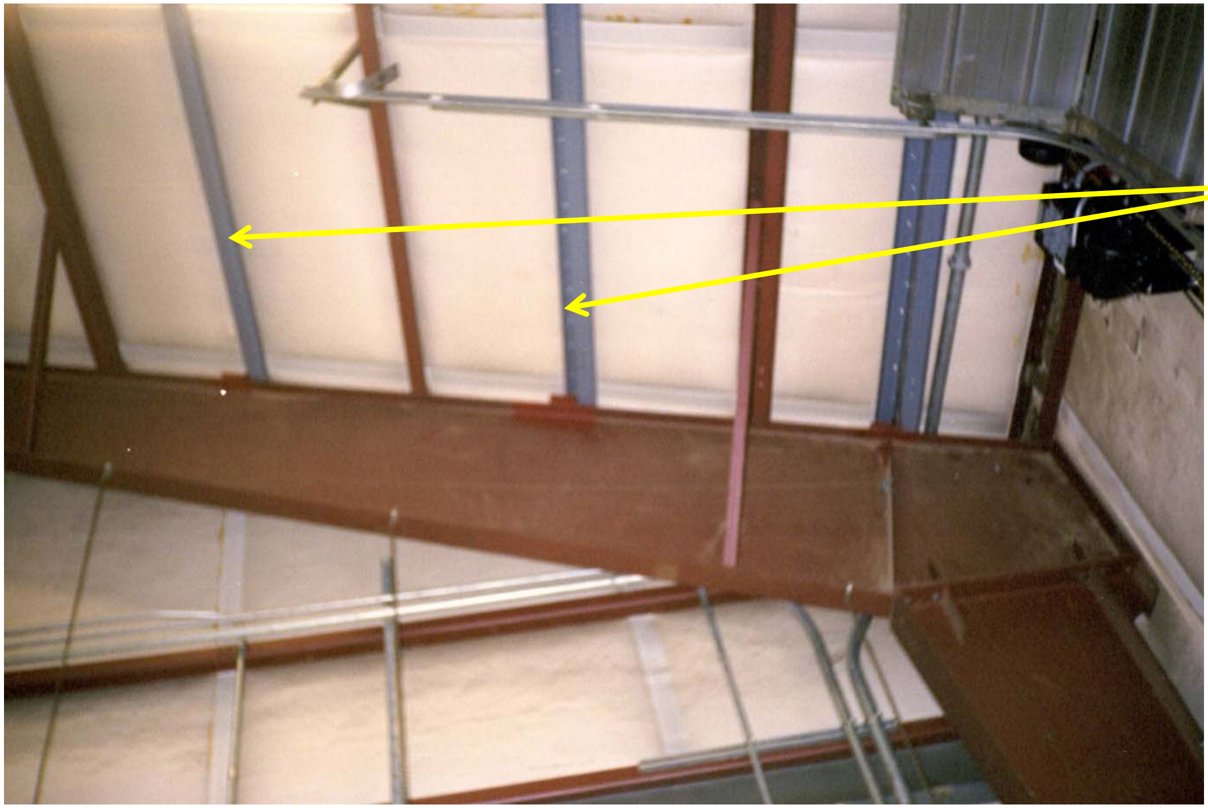
New wall girts

New Stiffeners added to frames

New Tees added to frames

BAKERRISK

Example of Roof Strengthening



New purlins (grey)

Door Strengthening

Typical Existing Door

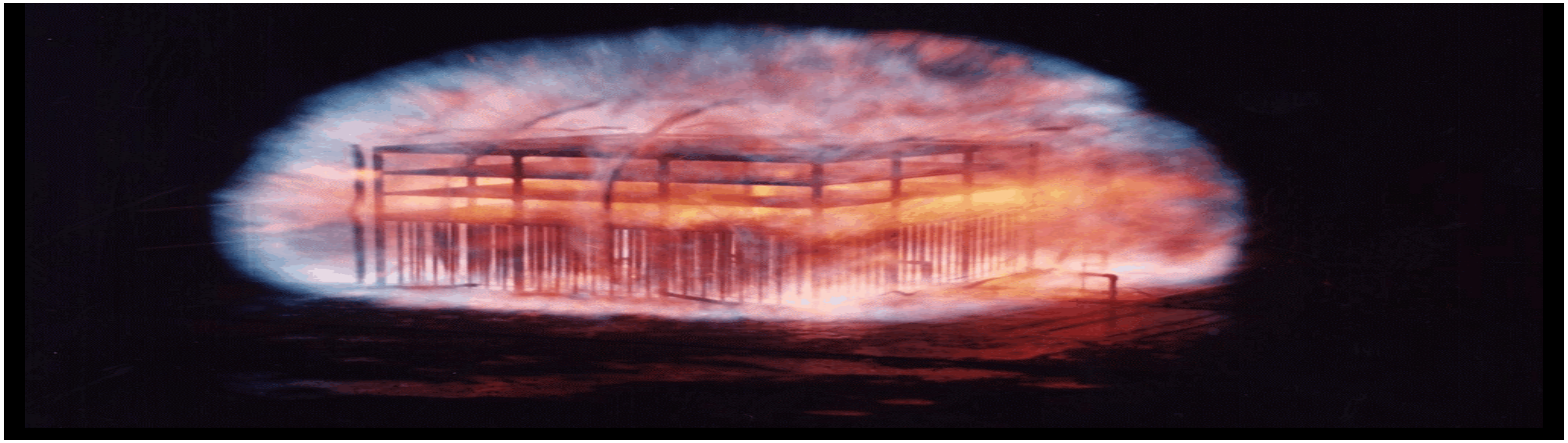
Retrofitted Door

BakerRisk

Thank You!

Questions?

www.BakerRisk.com



Khaled El-Domiaty
Structures Principal Supervisor
keldomiaty@bakerrisk.com

BakerRisk