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Engineering Standard

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Design Criteria for Blast Resistant Buildings

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1 Scope

This standard establishes mandatory structural design criteria for new blast resistant buildings, including requirements for selection of structural systems, analysis methods, and design of ancillary items such as doors and openings. This standard also contains design criteria for non-structural items (e.g., architectural or electrical items, HVAC ductwork, etc.) that could pose a hazard to the occupants of blast resistant buildings. Other design aspects such as architectural design and structural design for normal (non-blast) loads and foundation design are covered in SAES-M-100 – *Saudi Aramco Building Code*, and SAES-Q-005 – *Concrete Foundations*.

Commentary Note:

> *Building designs and construction types that are based on this standard and may conflict with requirements in the Safety and Security Directives (SSDs), published by the Saudi Arabian Government High Commission for Industrial Security (HCIS), will require approval of a deviation request. The user of this standard is encouraged to submit a deviation request to the Manager, Consulting Services Department, in compliance with the procedures in SAES-O-100, for any design that could result in significant cost savings.*

2 Conflicts and Deviations

2.1 Any conflicts between this standard and other applicable Saudi Aramco Engineering Standards (SAESs), Materials System Specifications (SAMSSs), Standard Drawings (SASDs), or industry standards, codes, and forms shall be resolved in writing by the company or buyer representative through the Manager, Consulting Services Department of Saudi Aramco, Dhahran.

2.2 Direct all requests to deviate from this standard in writing to the company or buyer representative, who shall follow internal company procedure SAEP-302 and forward such requests to the Manager, Consulting Services Department of Saudi Aramco, Dhahran.

3 References

The selection of material and equipment, and the design, construction, maintenance, and repair of equipment and facilities covered by this standard shall comply with the latest edition of the references listed below, unless otherwise noted.

3.1 Saudi Aramco References

Saudi Aramco Engineering Procedure

SAEP-302	*Instructions for Obtaining a Waiver of a Mandatory Saudi Aramco Engineering Requirement*

Saudi Aramco Engineering Standards

SAES-A-112	*Meteorological and Seismic Design Data*
SAES-A-113	*Geotechnical Engineering Requirements*
SAES-A-204	*Preparation of Structural Calculations*
SAES-B-014	*Safety Requirements for Plant and Operations Support Buildings*
SAES-B-055	*Plant Layout*
SAES-K-100	*Saudi Aramco Mechanical (HVAC) Code*
SAES-M-100	*Saudi Aramco Building Code*
SAES-O-100	*General Requirements Safety and Security*
SAES-P-100	*Basic Power System Design Criteria*
SAES-P-119	*Onshore Substations*
SAES-Q-005	*Concrete Foundations*
SAES-S-060	*Saudi Aramco Plumbing Code*

Saudi Aramco Materials System Specification

09-SAMSS-016	*Concrete Masonry Units and Concrete Building Bricks*

3.2 Saudi Arabian Standards Organization

SASO SSA 2	*Steel Bars for the Reinforcement of Concrete*

3.3 Industry Codes and Standards

International Code Council (ICC)

IBC	*International Building Code 2003 Edition*

American Iron and Steel Institute (AISI)

AISI Manual	*Specification for the Design of Cold-Formed Steel Structural Members, Cold-Formed Steel Design Manual, 2002*

American Institute of Steel Construction (AISC)

AISC LRFD	*Load and Resistance Factor Design Specification for Structural Steel Buildings*

American Concrete Institute (ACI)

ACI 318M/318RM	*Building Code Requirements for Structural Concrete (ACI 318M-02) and Commentary (ACI 318RM-02*
ACI 530	*Building Code Requirements for Masonry Structures*
ACI 530.1	*Specification for Masonry Structures*

American Petroleum Institute (API)

API RP 752	*Management of Hazards Associated with Location of Process Plant Buildings*

American Society for Testing and Materials (ASTM)

ASTM A36/A36M	*Standard Specification for Carbon Structural Steel*
ASTM A82	*Standard Specification for Steel Wire, Plain, for Concrete Reinforcement*
ASTM A514/A514M	*Standard Specification for High-Yield-Strength, Quenched and Tempered Alloy Steel Plate, Suitable for Welding*
ASTM A572/A572M	*Standard Specification for High-Strength Low-Alloy Columbium-Vanadium Structural Steel*
ASTM A588/A588M	*Standard Specification for High-Strength Low-Alloy Structural Steel with 50 ksi [345 MPa] Minimum Yield with Atmospheric Corrosion Resistance*
ASTM A653/A653M	*Standard Specification for Steel Sheet, Zinc-Coated (Galvanized) or Zinc-Iron Alloy-Coated (Galvannealed) by Hot-Dip Process*
ASTM A706/A706M	*Standard Specification for Low-Alloy Steel Deformed and Plain Bars for Concrete Reinforcement*
ASTM A992/A992M	*Standard Specification for Structural Steel Shapes*
ASTM C90	*Standard Specification for Loadbearing Concrete Masonry Units*

American Welding Society (AWS)

AWS D1.1	*Structural Welding Code - Steel*

3.4 Published Blast Design Guidelines

The following documents shall be used with this standard as referenced:

ASCE Report	*Design of Blast Resistant Buildings in Petrochemical Plants, American Society of Civil Engineers, 1997*
TM5-1300	*Structures to Resist the Effects of Accidental Explosions, US Dept. of the Army, November 1990*

4 Definitions

Definitions of the key blast resistant design terminology used in this standard are listed below. A more complete list of definitions can be found in the ASCE Report.

Angle of Incidence: The angle between the direction of the blast wave travel and a line perpendicular to the surface of a structure at the point of interest.

Blast Loads: The transient dynamic loads from the blast effects of an explosion, usually stated in terms of peak pressure and impulse or duration.

Conventional Loads: Loads applied in the conventional (non-blast) design of structures including dead, live, wind and seismic loads as required by SAES-M-100. These loads are typically statically applied.

Dynamic Increase Factor (DIF): A multiplier applied to the static strength of a material to reflect the increased effective strength due to fast strain rates caused by rapidly applied blast loads.

Ductility Ratio: A measure of the degree of plasticity in a member at maximum dynamic response, equal to the maximum displacement divided by the displacement at yield. This value is a key measure of dynamic response.

Duration: The length of time from start of the initial positive phase of the blast pressure to the return to ambient pressure.

Dynamic Reaction: The support reaction of a structural component to the dynamic blast loading, taking into account inertia effects.

Engineer: The engineer with overall authority and responsibility for the structural design of the blast resistant building.

Fragment Resistant: The resistance to high-speed fragments that are the result of the break up of equipment or structures that are close to the explosion source.

Free-Field Pressure: The rise in pressure above ambient pressure produced by a blast wave sweeping unimpeded across a surface not facing the blast source. Also referred to as side-on pressure.

Impulse: A measure used, along with the peak blast pressure, to define the ability of a blast wave to do damage. Impulse is calculated as the integrated area under the positive pressure versus duration curve and is shown in units of MPa-ms (psi-ms).

Multi-Degree-of-Freedom (MDOF): Representation of a structure or component as a spring-mass system with more than one degree-of-freedom.

Multi-Unit Building: Building used for support of multiple process units, where loss would adversely impact several, separate process units.

Negative Phase: The portion of the pressure-time history typically following the positive (overpressure) phase in which the pressure is below ambient pressure (suction).

Nonlinear Response: Deformation of a component or system beyond the elastic limit.

OME/Team Building: An occupied in-plant building housing operations, maintenance, and/or engineering personnel.

Owner: Saudi Aramco or a designated representative.

Period: The fundamental natural period of a structural component if modeled as a single-degree-of-freedom (SDOF) system.

PES: Potential Explosion Site is a congested/confined volume where a VCE could occur. A PES is a potential blast source.

PIB: Process Interface Building

Positive Phase: The portion of the pressure-time history in which the pressure is above ambient pressure.

Rebound: The deformation in the direction opposing the initial blast pressure. This occurs after a component has reached a peak deformation and returns in the direction of its initial position.

Reflected Pressure (P_r): The rise in pressure above ambient produced by a shock wave or pressure wave striking a surface facing the direction of blast wave propagation.

Response Range: The degree of structural damage permitted for blast resistant buildings. The following descriptions apply to the response ranges mentioned in this standard:

Low (L): Localized building/component damage. Building can be used; however repairs are required to restore integrity of structural envelope. Total cost of repairs is moderate.

Medium (M): Widespread building/component damage. Building cannot be used until repaired. Total cost of repairs is significant.

High (H): Building/component has lost structural integrity and may collapse from additional environmental loads (i.e., wind, snow, rain). Total cost of repairs approach replacement cost of building.

Single Degree of Freedom (SDOF): Representation of a structure or component as a spring-mass system with one degree of freedom. Displacement of the SDOF system corresponds to the displacement of a single point in the real system, typically corresponding to the point of maximum deflection.

Side-On Pressure (P_{so}): The rise in pressure above ambient produced by a blast wave sweeping unimpeded across any surface (walls or roof) not facing the blast source. This is also referred to as free-field or incident pressure.

Strength Increase Factor (SIF): A multiplier applied to the nominal strength properties of a material to reflect its actual strength above minimum specified values.

SIH: Satellite Instrument House

Single-Unit Building: Building used for support/control of only one process unit.

Support Rotation: The angle formed between the axis of a member loaded between its endpoints and a straight line between one endpoint and the point of maximum deflection. This value is a key measure of dynamic response.

5 General

5.1 Owner-Specific Data and Requirements

A Blast Design Requirement (BDR) Data Sheet (see Appendix A) will be prepared, for each blast resistant building, by or on behalf of the Owner, and provided to the Engineer as a part of the job or project specifications.

5.1.1 The following blast design requirements shall be included in the BDR Data Sheet:

5.1.1.1 Building performance requirements and acceptable response range (Low, Medium, or High) (refer to Section 7.4.3).

5.1.1.2 Performance categories (I - IV) (refer to Table 11) for blast resistant doors.

5.1.1.3 Blast loads specified as peak side-on positive pressure with corresponding impulse or duration at the building (see Section 6.3).

5.1.2 Other SAESs for Buildings:

5.1.2.1 Conventional (non-blast) design requirements per SAES-M-100 and SAES-A-112

5.1.2.2 Non-structural requirements:

plumbing per SAES-S-060

mechanical per SAES-K-100

electrical per SAES-P-100

substations per SAES-P-119

5.1.2.3 Siting and Safety

safety per SAES-B-014

siting per SAES-B-055

5.2 Engineer's Responsibilities

5.2.1 ASCE Report - *Design of Blast Resistant Buildings in Petrochemical Facilities* Section 1.4 and Figure 1.1, delineate information to be provided by the Owner and tasks performed by the Engineer. Items with overlapping responsibility in the flowchart shall be the ultimate responsibility of the Engineer.

5.2.2 The Engineer shall be responsible for producing a design, using sound engineering principles that meet the requirements of this standard.

5.2.3 The Engineer shall be responsible for designing the facility to meet the performance requirements specified in the Blast Design Requirements (BDR) Data Sheet.

5.2.4 The Engineer shall bring any items requiring clarification to the Owner's attention.

5.3 Documentation

5.3.1 The final design shall be prepared by the Engineer per SAES-A-204 and shall include the following documentation:

5.3.1.1 Blast Design Requirements (BDR) Data Sheet

5.3.1.2 Supporting calculations covering the design criteria, methodology, results, and the references and tools used.

5.3.1.3 Detailed structural drawings and specifications for construction, as appropriate.

6 Basic Requirements

6.1 Building Performance

The degree of structural damage permitted for blast resistant buildings, known as "building response range", will be as specified in Table 1. The building shall be designed to resist the applied blast loads in the BDR Data Sheet within the required building response range.

Table 1 – Building Blast Design Requirements

Building Type	Response Range	Door Performance Category(1)	Permitted Structural Systems (see Table 2)
Multi-Unit Control Building	L	I	1,2,3,4
Single-Unit Control Building	M	II	1,2,3,4 & 6
Multi-Unit PIB/SIH	L	I	1,2,3,4
Single-Unit PIB/SIH	M	II	1,2,3,4 & 6
Multi-Unit Substation	L	I	1,2,3,4
Single-Unit Substation	M	II	1,2,3,4 & 6
Warehouse/Storage	H	II	1,2,3,4,5
Maintenance Shop	M	II	1,2,3,4,5,6
OME/Team Building	M	II	1,2,3,4,5,6
Operator Shelter	H	II	1,2,3,4,5,6
Prayer Shelter/Musalla	H	II	1,2,3,4,5,6
Utility Building	M	II	1,2,3,4,5,6
Emergency Generator Building	M	II	1,2,3,4 & 6
Other Buildings	(see note 2)	(see note 2)	(see note 2)

Notes:

(1) This performance category is required for doors that are designated as egress doors. All other doors shall be designed to Door Performance Category III.

(2) For building types not shown, contact the Supervisor, Civil Engineering Unit, Consulting Services Department for the design requirements.

Table 2 – Building Structural Systems

Number	Structural System	Wall Cladding	Roof Deck
1	Cast-In-Place Concrete Frame or Shear Walls	Precast or Cast-In-Place Concrete	Precast or Cast-In-Place Concrete
2	Cast-In-Place Concrete Frame or Shear Walls	Solid-Grouted Reinforced CMU	Precast or Cast-In-Place Concrete
3	Hot-Rolled Steel Frame	Precast or Cast-In-Place Concrete	Precast or Cast-In-Place Concrete
4	Hot-Rolled Steel Frame	Solid-Grouted Reinforced CMU	Precast or Cast-In-Place Concrete
5	Hot-Rolled Steel Frame	Steel Single Sheet or Sandwich Panel	Steel Single Sheet or Sandwich Panel
6	Load-Bearing, Solid-Grouted Reinforced CMU or Precast Concrete panels	Load-Bearing, Solid-Grouted Reinforced CMU or Precast Concrete panels	Precast or Cast-In-Place Concrete

6.2 Building Configuration

6.2.1 Blast resistant control buildings are limited to single-story construction. Multi-story construction shall not be used without prior written approval from the Supervisor, Civil Engineering Unit, Consulting Services Department. When approved, the number of stories shall be minimized and special design considerations shall be given to the inter-story response to the blast loading.

6.2.2 The floor plan and elevation shall have a clean rectangular profile without re-entrant corners and recessed areas. Exceptions to these requirements are only permitted with prior written approval from the Supervisor, Civil Engineering Unit, Consulting Services Department

6.3 Blast Loads

6.3.1 General

6.3.1.1 Each blast resistant building shall be designed for the dynamic blast loads provided in the BDR Data Sheet.

6.3.1.2 Blast loads on individual building surfaces shall be calculated from the specified side-on pressure using the methods described in Chapter 3 of the ASCE Report - *Design of Blast Resistant Buildings in Petrochemical Facilities*.

6.3.1.3 Blast pressure amplifications due to re-entrant corners or recessed areas (when approved) shall be evaluated and considered during design.

6.3.2 Component Loads

6.3.2.1 Structural components, doors, or appurtenance on an exterior surface of a blast resistant building shall be designed for the blast loading applicable to that surface. Specifically, each such component shall be designed for any one of the following:

6.3.2.1.1 The direct tributary blast load applicable to the surface of the building on which it is located

6.3.2.1.2 The dynamic reaction to the blast load on a supported component, as appropriate

6.3.2.1.3 The ultimate load capacity of the supported component.

6.3.2.2 Although the blast effects on an appurtenance to the building are of little consequence, the building component shall still be designed for the ultimate or failure load from the appurtenance.

6.3.3 Foundation Load

The foundation for a blast resistant building shall be designed per Section 7.7 and SAES-Q-005 using any one of the following:

6.3.3.1 The peak dynamic reactions from the supported superstructure treated statically

6.3.3.2 The ultimate static capacity of the supported superstructure or

6.3.3.3 The tributary area method. This method may be used in conjunction with the applied blast loads to determine foundation response using a dynamic analysis method.

6.4 Construction and Materials

6.4.1 General

The structural system and materials shall be selected to provide the most economical design that meets all performance requirements or as dictated by the Owner's specifications or architectural considerations.

6.4.2 Brittle Construction

Brittle construction, including unreinforced concrete, unreinforced masonry (block, brick, clay tile), poured gypsum, etc., shall not be used for load carrying components of blast resistant buildings.

6.4.3 Prestressed Concrete

6.4.3.1 Prestressed concrete shall be used only with prior written approval from the Supervisor, Civil Engineering Unit, CSD.

6.4.3.2 If prestressed concrete is used, non-prestressed reinforcement shall be added to carry tensile forces that may develop because of rebound or negative phase loading. The amount of rebound resistance shall be greater than one-half the resistance available to resist the blast load.

6.4.3.3 See TM 5-1300 for additional design requirements for prestressed concrete elements and their connections.

6.4.4 Advanced Materials

Advanced materials, such as composites, may be used if adequate test data are available to confirm their satisfactory performance for the intended application, and with the prior written approval of the Supervisor, Civil Engineering Unit, Consulting Services Department. Such test data shall include the ultimate capacity and behavior of the material under dynamic conditions representative of blast loading. Satisfactory performance of the material under seismic conditions is not sufficient to indicate blast capacity.

6.4.5 Fragment Resistance

Reinforced concrete or fully-grouted reinforced masonry of appropriate strength and thickness shall be used as cladding where fragment resistance is required per the BDR Data Sheet.

Commentary:

TM5-1300 contains design procedures for structures that are fragment resistant in the BDR Data Sheet.

6.5 Material Properties

6.5.1 Dynamic Material Strength

6.5.1.1 Dynamic yield stress, F_{dy} , shall be calculated as follows:

$$F_{dy} = F_y * SIF * DIF \qquad (1)$$

where, F_y = specified minimum static yield stress
DIF = dynamic increase factor per Section 6.5.3

SIF = strength increase factor per Section 6.5.2

6.5.1.2 Dynamic Design Stress, $F_{ds,}$ used to calculate the dynamic capacity of structural components shall be accordance with the values listed in Tables 6 and 7 for structural steel and reinforcing steel, respectively.

6.5.1.3 Dynamic ultimate strength, F_{du} , shall be computed as follows:

$$F_{du} = F_u * DIF \quad (2)$$

where, F_u = specified ultimate strength;
DIF = dynamic increase factor per Section 6.5.3.

6.5.2 Strength Increase Factor (SIF)

A SIF shall be applied to the specified minimum yield strength of structural materials to estimate the actual static value. The SIF shall be taken from Table 3 below.

Table 3 – Strength Increase Factors (SIF) for Structural Materials

Structural Material	SIF
Structural Steel Yield Strength of 345 MPa (50 ksi) or less	1.1
Concrete Reinforcing Steel of 420 MPa (Grade 60)	1.1
Prestressed Reinforcement	1.0
Cold formed steel cladding panels: - Yield strength of 228 MPa (33 ksi) or less - Yield of strength 345 MPa (50 ksi) or more	 1.2 1.1
Concrete and masonry	1.0
Other materials	1.0

6.5.3 Dynamic Increase Factor (DIF)

To account for strain rate effects caused by rapidly applied blast loads, dynamic increase factors (DIF) shall be applied to the static material yield and ultimate strengths to determine their dynamic values in accordance with Tables 4 and 5.

Table 4 – Dynamic Increase Factors (DIF) for Reinforced Concrete/Masonry

Stress Type	DIF			
	Reinforcing Bars		Concrete	Masonry
	F_{dy}/F_y	F_{du}/F_u	f'_{dc}/f'_c	f'_{dm}/f'_m
Flexure	1.17	1.05	1.19	1.19
Compression	1.10	1.00	1.12	1.12
Diagonal Tension	1.00	1.00	1.00	1.00
Direct Shear	1.10	1.00	1.10	1.00
Bond	1.17	1.05	1.00	1.00

Table 5 – Dynamic Increase Factors (DIF) for Steel and Aluminum

Material	DIF		
	Yield Stress		Ultimate Stress
	Bending/Shear	Tension/Compression	
	F_{dy}/F_y	F_{dy}/F_y	F_{du}/F_u
A36/A36M	1.29	1.19	1.10
A572/A572M, A588/A588M, A992/A992M	1.19	1.12	1.05
A514/A514M	1.09	1.05	1.00
A653/A653M	1.10	1.10	1.00
Prestress Reinforcement	1.00	1.00	1.00
Stainless Steel Type 304	1.18	1.15	1.00
Aluminum, 6061-T6	1.02	1.00	1.00

Table 6 – Dynamic Design Stress, Fds, for Structural Steel

Type of Stress	Maximum Ductility Ratio	Dynamic Design Stress (Fds)
All	$\mu < 10$	Fdy
All	$\mu > 10$	Fdy + (Fdu - Fdy) /4

Where μ = ductility ratio
F_{du} = dynamic ultimate strength
F_{dy} = dynamic yield stress

Table 7 – Dynamic Design Stress, Fds, for Concrete Reinforcing Steel

Type of Stress	Type of Reinforcement	Maximum Support Rotation	Dynamic Design Stress (F_{ds})
Bending	Tension and Compression	$0<\theta\leq2$ $2<\theta\leq5$ $5<\theta\leq12$	F_{dy} $F_{dy} + (F_{du} - F_{dy})/4$ $(F_{dy} + F_{du})/2$
Direct Shear	Diagonal Bars	$0<\theta\leq2$ $2<\theta\leq5$ $5<\theta\leq12$	F_{dy} $F_{dy} + (F_{du} - F_{dy})/4$ $(F_{dy} + F_{du})/2$
Diagonal Tension	Stirrups	all	F_{dy}
Compression	Column	all	F_{dy}

Where θ = support rotation (deg.)

7 Structural Design

7.1 Design Methods and Procedures

All blast resistant buildings and their structural components shall be designed in accordance with the methods outlined in ASCE *Design of Blast Resistant Buildings in Petrochemical Facilities*. Alternate design methods may be used only with prior written approval of the Supervisor, Civil Engineering Unit, Consulting Services Department.

7.2 Load Combinations

7.2.1 In addition to the load combinations prescribed by SAES-M-100, blast resistant buildings shall be designed for the blast load condition as follows:

$$U(t) = D + aL + B(t) \qquad (3)$$

where:

- U(t) = total applied time dependent load or its effect
- D = static dead load
- B(t) = time dependent blast load or its effect (horizontal and vertical)
- L = conventional static live load
- a = reduction factor applied to conventional live loads to reflect the portion of live load expected to occur simultaneously with the blast load. Zero shall be used for the reduction factor if doing so will result in a more severe condition.

7.2.2 The blast load combination shall consider either the direct loads or their effects. In combining blast load effects with those from static dead and live loads, the time dependence of the blast loading shall be considered.

7.2.3 Wind and seismic loads shall not be combined with blast loading.

7.2.4 Rebound effects shall be calculated and combined with the effects of negative phase blast loads, if any, based on time dependent response.

7.3 Analysis Methods

The Engineer shall use analysis methods appropriate for the specific blast design. The selected methods shall adequately model the dynamic response of the structure to the applied blast loads and the structural component interaction. Except as specified in Sections 7.3.1, 7.3.2 and 7.3.3, the analysis methods shall be in accordance with ASCE *Design of Blast Resistant Buildings in Petrochemical Facilities,* Chapter 6.

7.3.1 Equivalent Static Load

The equivalent static load or required resistance for each structural component shall be based on the peak blast pressure (or load) and duration, the natural period of the component, and the maximum allowable response (deformation). The formulas and charts provided in Chapter 6 of the ASCE *Design of Blast Resistant Buildings in Petrochemical Facilities*, TM5-1300, or other similar references for the approximate solution of the elastic-plastic SDOF system with a triangular or rectangular load, may be used in determining the required resistance (equivalent static load) for a directly loaded structural component, subject to the limitations specified below for the SDOF method.

7.3.2 Single-Degree-of-Freedom (SDOF)

The required resistance for each structural component shall be based on the peak blast pressure (or load) and duration, the natural period of the component, and the maximum allowable response (deformation). An SDOF analysis can be used where the connected components differ in natural period by a factor of two or more. The formulas and charts provided in ASCE *Design of Blast Resistant Buildings in Petrochemical Facilities,* Chapter 6, TM5-1300, or other similar references for the approximate solution of the elastic-plastic SDOF system may be used in determining the required resistance.

7.3.3 Multi-Degree-of-Freedom (MDOF)

MDOF analysis shall be used if structural component interaction cannot be adequately modeled using the simpler equivalent static load or SDOF methods. The MDOF method can involve finite element analysis (FEA) requiring the use of a special or general purpose structural analysis computer program with non-linear transient dynamic analysis capability. The use of such software requires prior, written approval by the Supervisor, Civil Engineering Unit, Consulting Services Department.

7.4 Deformation Limits

7.4.1 Response Parameters

Structural members shall be designed based on maximum response (deformation) in accordance with the performance requirements or permissible damage level specified in Table 1. Deformation limits shall be expressed as ductility ratio (μ), support rotation (θ), or frame sidesway, as appropriate.

7.4.2 Building Response Range

The design response range (Low, Medium, or High), shall be based on the building design requirements provided in Table 1.

7.4.3 Response Limits

Maximum response shall not exceed the limits specified in Tables 8, 9, and 10 for structural steel, reinforced concrete, and reinforced masonry, respectively.

Table 8 – Deformation Limits for Structural Steel

Element Type	Response Range(2)					
	Low		Medium		High	
	μ	θ	μ	θ	μ	θ
Beams, Girts, Purlins	3	2	10	6	20	12
Frame Members (1)	1.5	1	2	1.5	3	2
Single Sheet Metal Panels	1.75	1.25	3	2	6	4
Open-Web Joists	1	1	2	1.5	4	2
Plates	5	3	10	6	20	12

(1) Sidesway limits for steel frames:

low = H/50
medium = H/35
high = H/25

(2) Response parameter: μ = ductility ratio, θ = support rotation (degrees)

Table 9 – Deformation Limits for Concrete

Element Type	Controlling Stress	Ductility Ratio, μ	Support Rotation, θ (2)		
			Low	Medium	High
Beams	Flexure Shear: (1) - Concrete Only - Concrete + Stirrups - Stirrups Only Compression	N/A 1.3 1.6 3.0 1.3	1	2	4
Slabs	Flexure Shear: (1)	N/A 1.3	2	4	8
Beam-Columns	Flexure Compression Tension Shear (1)	N/A 1.3 (3) 1.3	1	2	4
Shear Walls, Diaphragms	Flexure Shear (1)	3 1.5	1	1.5	2

(1) Shear controls when shear resistance is less than 120% of flexural resistance.

(2) Stirrups are required for support rotations greater than 2 degrees.

(3) Ductility ratio = 0.05 (ρ - ρ') < 10, where ρ and ρ' are the tension and compression reinforcement ratios, respectively.

Table 10 – Deformation Limits for Reinforced Masonry

Element Type	Ductility Ratio, μ	Support Rotation, θ (deg)		
		Low	Medium	High
One-Way	1	0.5	0.75	1
Two-Way	1	0.5	1	2

7.5 Component Design

7.5.1 General

Ultimate strength (limit state) methods shall be used for designing structural components for blast resistance. The ultimate strength capacity shall be determined in accordance with the applicable codes, practices and guides specified in Section 3, subject to the following additional requirements:

7.5.1.1 In-plane and secondary bending stresses shall be accounted for in the design.

7.5.1.2 Interaction of forces in two directions, including biaxial bending, shall be considered as provided in the ASCE *Design of Blast Resistant Buildings in Petrochemical Facilities*.

7.5.1.3 Dynamic strength properties shall be used to reflect increased material strength under rapidly applied loads.

7.5.1.4 Load and resistance factors shall be taken equal to 1.0 in all blast load combinations.

7.5.1.5 Composite sections can be used for design; however, adequate rebound resistance shall be provided to ensure satisfactory response under rebound or negative phase loads.

7.5.1.6 Components shall be adequately laterally braced to prevent premature buckling failure during the positive and rebound response.

7.5.1.7 Connections shall be designed for 120% of the member's controlling resistance (flexure or shear, whichever is less). Except as noted for reinforced concrete members, the deformation limits indicated in Tables 8, 9, and 10 are based on flexure-controlled resistance. To use these limits, the member's shear capacity shall be at least 120% of the flexural capacity.

7.5.1.8 Design for compression elements, such as load-bearing walls and exterior columns, should consider secondary bending effects including P-delta and slenderness.

7.5.2 Reinforced Concrete

Reinforced concrete components shall be designed, using ultimate strength methods, in accordance with the provisions of ACI 318M and ASCE *Design of Blast Resistant Buildings in Petrochemical Facilities.* The following specific requirements shall also apply:

7.5.2.1 The strength reduction factor (ϕ) shall be 1.0 for load combinations that include blast loads.

7.5.2.2 Deformation limits for shear shall be used if the member's shear capacity is less than 120% of the flexural capacity.

7.5.2.3 The design compressive strength of 28 MPa (4,000 psi) shall be used for the design of concrete construction. With prior written approval compressive strength up to 35 MPa (5,000 psi) may be allowed for prestressed concrete.

7.5.2.4 Reinforcing bars shall conform to SASO SSA 2/1979 High Yield 420 MPa (grade 60), except that ASTM A706/A706M shall be used where welding of bars is required. The maximum bar size shall be 32 mm (No. 10).

7.5.2.5 Minimum reinforcing requirements of ACI 318M apply, however, the option to use one third more reinforcing than computed shall not be taken.

7.5.2.6 Wall and roof components shall be designed for in-plane and out-of-plane loads that act simultaneously by using the following interaction equation:

$$[\Delta_C/\Delta_A]_{i^2} + [\Delta_C/\Delta_A]_{0^2} < 1.0 \qquad (4)$$

where:

Δ_C = calculated deformation (ductility ratio or support rotation)
Δ_A = allowable deformation
$_i$ = in-plane
$_o$ = out-of-plane

7.5.2.7 Slenderness effects shall be included for load bearing walls and members with significant axial loads.

7.5.2.8 Support shall be provided for roof slab to prevent failure during rebound. Headed studs can be used for this purpose; however, unless composite action is required and included in the design the studs shall be located and spaced to minimize composite action.

7.5.3 Structural Steel

Structural steel components shall be designed in accordance with the provisions of AISC LRFD, supplemented by the following requirements:

7.5.3.1 Materials with a specified yield strength of 345 MPa (50 ksi) or less shall be used for flexural design. Higher strength materials may be used where ductile behavior is not required.

7.5.3.2 Oversized holes shall not be used in connections that are part of the lateral force-resisting system.

7.5.3.3 Structural welding shall comply with AWS D1.1.

7.5.3.4 Field welded connections should be avoided.

7.5.3.5 Column base plates shall be designed to develop the peak member reactions applied as a static load. Dynamic material properties can be used for design of base plates.

7.5.3.6 Flexural members shall be laterally braced on both faces to provide consistent moment capacity in both positive and rebound responses.

7.5.4 Cold-Formed Steel

Cold-formed steel components shall be designed in accordance with the AISI Manual, supplemented by the following specific requirements:

7.5.4.1 Ultimate resistance shall be determined using a factor of 0.9 applied to the plastic moment capacity.

7.5.4.2 Tensile membrane capacity of wall panels can be used if adequate anchorage of panel ends is provided.

7.5.4.3 Tensile membrane capacity of cold-formed girts and purlins can be used in the design if the girts and purlins are supported on the exterior face of a frame member and are continuous over three or more spans.

7.5.4.4 Oversize washers shall be provided for wall panel anchorage screws to prevent failure caused by rebound or negative phase loads.

7.5.5 Open Web Steel Joist (OWSJ)

Design of OWSJ for blast loads shall be performed using published load tables for static, working loads with appropriate factors applied to obtain the ultimate capacities with the following limitations:

7.5.5.1 Unless special provisions are made to enhance ductility of the joist, a 10% reduction in ultimate moment capacity shall be used.

7.5.5.2 Lateral bracing shall be provided for the top and bottom chords as required to provide the necessary rebound resistance and positive moment capacity.

7.5.6 Reinforced Masonry

Design of reinforced masonry shall be in accordance with the ultimate strength method in ACI 530, ACI 530.1 and the IBC supplemented by the following specific requirements:

7.5.6.1 Hollow concrete masonry units (CMU) shall be in accordance with 09-SAMSS-016 and ASTM C90 with a minimum compressive strength (f_m) of 10.3 MPa (1,500 psi).

7.5.6.2 All cells of hollow CMU shall be fully-grouted.

7.5.6.3 Joint reinforcing shall be in accordance with ASTM A82 with a minimum yield stress of 485 MPa (70 ksi) and a minimum ultimate strength of 550 MPa (80 ksi).

7.5.6.4 Primary reinforcing bars shall be in accordance with SASO SSA 2/1979 High Yield 420 MPa (grade 60).

7.5.6.5 Wall components subjected to in-plane and out-of-plane loads shall be designed using the interaction equation (4) given in 7.5.2.6.

7.6 Structural Framing Design

Design of the overall structural framing system shall include analysis of global response including sidesway, overturning, and sliding. Sidesway analysis shall be performed with and without leeward side (rear wall) blast loads.

7.6.1 Static Analysis

Support members may conservatively be designed statically for the reactions due to the ultimate resistance of the wall and roof components being supported or for the peak dynamic reactions from the supported components treated as static loads. For blast load combinations, factors of safety for overturning shall be 1.2, and 1.0 for sliding.

7.6.2 Dynamic Analysis

As an alternative to the simplified, but conservative, static analyses specified above, a dynamic analysis may be performed to determine interaction of components, sidesway, sliding and overturning response of the overall structural system to the blast loading.

7.7 Foundation Design

Foundation design shall be based on a geotechnical report per SAES-A-113 and the geotechnical data summarized in the Section A-4 of the Basic Design

Requirements (BDR) Data Sheet. Foundation components shall be designed per ASCE *Design of Blast Resistant Buildings in Petrochemical Facilities* and SAES-Q-005 to resist the peak reactions produced by supported components resulting from the dead, live, and blast loads, treated either statically or dynamically, as noted below.

7.7.1 Static Analysis

Static application of the peak dynamic reactions from the wall and roof components can be used to design supporting members and to calculate overturning and sliding effects. For blast load combinations, factors of safety for overturning shall be 1.2, and for sliding shall be 1.0.

7.7.2 Static Capacity

Foundations shall be designed using vertical and lateral soil capacities as follows:

7.7.2.1 Vertical - 80% of the ultimate net soil bearing capacity for shallow foundations, including footings and mats. For piles and other deep foundations 80% of the ultimate static capacities in compression and in tension may be used.

7.7.2.2 Lateral - Passive resistance of grade beams may be used to resist lateral loads if compacted fill is placed around the building perimeter. Frictional resistance of spread footings and floor grade slabs shall be based on the coefficient of friction determined by the geotechnical study. The normal force shall be the sum of the dead loads and the vertical load associated with the ultimate resistance of the roof. Frictional resistance of floating slabs shall not be used.

7.7.2.3 If only passive resistance, frictional resistance, vertical piles, or battered piles are used to support the lateral blast loading, the design resistance shall be 80% of the ultimate static value. However, if two or more of these resistances are used to support the lateral blast loads, the lateral capacity shall be limited to 67% of the combined ultimate static resistance.

7.7.2.4 Foundation sliding can be permitted if demonstrated that all underground and aboveground utility, electrical, and instrumentation lines entering and exiting the building have adequate flexibility to accommodate the slide.

7.7.3 Dynamic Analysis

To optimize the design, the foundation components can be analyzed dynamically for the calculated reaction-time history of the supported components. The required dynamic material properties of the foundation soils, including resistance and stiffness, shall be determined based on an appropriate geotechnical investigation. No deformation limits are specified for dynamic response of foundations. Based on the results of the dynamic analysis, it shall be determined whether the predicted maximum response is acceptable for the permissible damage level of the building.

8 Ancillary Items

8.1 Blast Doors

Blast resistant doors shall be provided according to the following:

8.1.1 The performance category for the blast resistant doors shall be in accordance with Table 1. The response limits and other requirements shall be as given in Table 11.

Table 11 – Blast Door Performance Requirements

Category	Hardware	Panels	Ductility Limit, μ	Edge Rotation, θ (deg)	Door Function
I	Operable	Elastic	1.0	1.2	Primary exit or repeated blasts
II	Operable	Significant damage	3	2	Prevent entrapment
III	Inoperable	Substantial damage	10	8	Prevent blast from entering building
IV	Inoperable	Failure in rebound	20	12	Prevent door from becoming debris hazard

8.1.2 In buildings large enough to require more than one egress door in accordance with SAES-M-100 and the IBC, at least two doors shall be designated as egress doors for the purpose of limiting the damage to these doors if subjected to blast loads. Designated egress doors shall not be located on the same side of the building.

8.1.3 Doors, door frames, and door hardware shall be designed for the performance criteria and applied blast loads in accordance with the BDR Data Sheet.

8.1.4 Doors shall be outward opening and shall seat against the frame in response to positive phase blast wave.

8.1.5 Door hardware shall be capable of restraining the door under rebound forces and negative phase blast loads.

8.1.6 Blast door manufacturer's calculations or test data shall be provided to verify adequate blast resistance and door performance for the design load conditions.

8.1.7 Manually operated egress doors shall meet the requirements of IBC, Section 1008 for the maximum opening force. Power-operated door shall be used for exit doors that exceed the maximum opening force.

8.2 Windows

Exterior windows shall not be used in blast resistant buildings, except as permitted in SAES-B-014.

8.3 Openings

Large openings in the building envelope, such as intake ducts, shall be designed to prevent entry of blast pressures.

8.3.1 Blast valves, blast attenuators, or other devices shall be used to limit blast pressure entry into the structure. Performance of the blast valve or attenuator shall be substantiated by test data and calculations.

8.3.2 Blast valves shall be provided for openings greater than 1000 cm^2 (150 in^2) in any surface in which the peak applied blast pressure is greater than 0.07 MPa (10 psi). Blast attenuators can be used for openings greater than 1000 cm^2 (150 in^2) if the peak applied pressure is not greater than 0.035 MPa (5 psi).

8.4 Penetrations

8.4.1 Wall and roof penetrations in reinforced concrete and masonry shall be sleeved. Sleeves shall be anchored with a minimum of 2 each 12 mm inch diameter x 100 mm (½" x 4") long headed studs.

8.4.2 Penetrations in metal clad structures shall be anchored with substantial framing attached to structural steel members.

8.5 Suspended Items

Equipment and furnishings such as ceilings, HVAC ductwork and light fixtures suspended from the roof inside the building shall be secured to structural framing members. Anchorage shall be designed to resist a statically applied force equal to the mass of the item times the maximum acceleration of the roof or five times the weight of the item, whichever is less.

8.6 Externally Mounted Items

8.6.1 To avoid the potential for hazardous debris, large non-structural features such as canopies and post-mounted signs on the building exterior shall not be permitted. However, small items such as instruments, fire alarms, lights, strobes and beacons can be mounted on the exterior walls.

8.6.2 Roof and wall mounted equipment (e.g., HVAC equipment) shall not be used without prior written approval from the Supervisor, Civil Engineering Unit, Consulting Services Department. If approved, such equipment shall be securely anchored, and the supporting structural components shall be specifically designed for actual equipment dynamic loads if subjected to the blast.

8.6.3 Equipment and other items mounted on the exterior surfaces (walls or roof) of the building shall be designed similar to the structural components if they are to withstand the applied blast loads. The reactions from such items shall be considered in the design of the supporting structural components. If the externally mounted items are not required to resist the blast loading, the supporting components shall be designed for the "failure," or ultimate resistance, loads from these items.

8.7 Equipment and Internally Mounted Items

8.7.1 Instrumentation or electrical equipment shall not be mounted on the interior face of walls subjected to blast loads without prior written approval from the Supervisor, Civil Engineering Unit, Consulting Services Department.

8.7.2 All fixed floor supported items (e.g., lockers, electrical cabinets, racks, etc.), shall have a minimum clearance from exterior walls equal to the maximum calculated lateral blast load deflection. The maximum deflection shall consider both the overall building sidesway and the deflection of any wall component(s) and shall be calculated based on the maximum blast loads defined in the BDR Data Sheet. Supports and anchorage for such equipment shall be designed to resist a lateral force equal to 20% of the equipment weight.

Revision Summary

19 October 2005 General revision and revised the "Next Planned Update".

Appendix A – Blast Design Requirements (BDR) Data Sheet

Page 1 of 3

Facility Name/Location: ______________________

Unit: ______________ Job Number: ______________

Building Name: ______________ Building Number: ______________

AA-1. Blast Resistant Building Construction

A-1.1 Building Response Range: ☐ Low ☐ Medium ☐ High

A-1.2 Building Structural System:
(Check construction type from each column below – refer to Tables 1 & 2. Provide details on under Special Requirements if necessary.)

Frame	Wall	Roof
☐ Cast-In-Place Concrete	☐ Cast-In-Place Concrete	☐ Cast-In-Place Concrete
☐ Hot-Rolled Steel	☐ Precast Concrete	☐ Precast Concrete
☐ Pre-Engineered Metal	☐ Reinforced Masonry / CMU	☐ Single Sheet Metal Panel
☐ Load Bearing Wall	☐ Single Sheet Metal Panel	☐ Insulated Metal Sandwich Panel
	☐ Insulated Metal Sandwich Panel	☐ Composite Concrete Deck
☐ Other: ________	☐ Other: ________	☐ Other: ________

A-1.3. Fragment Resistant Required: ☐ Yes ☐ No

A-2. Blast Load Design Requirements

Peak side-on pressures and durations for the following table shall be taken from the Building Risk Assessment. (See Figure A1 on following page.)

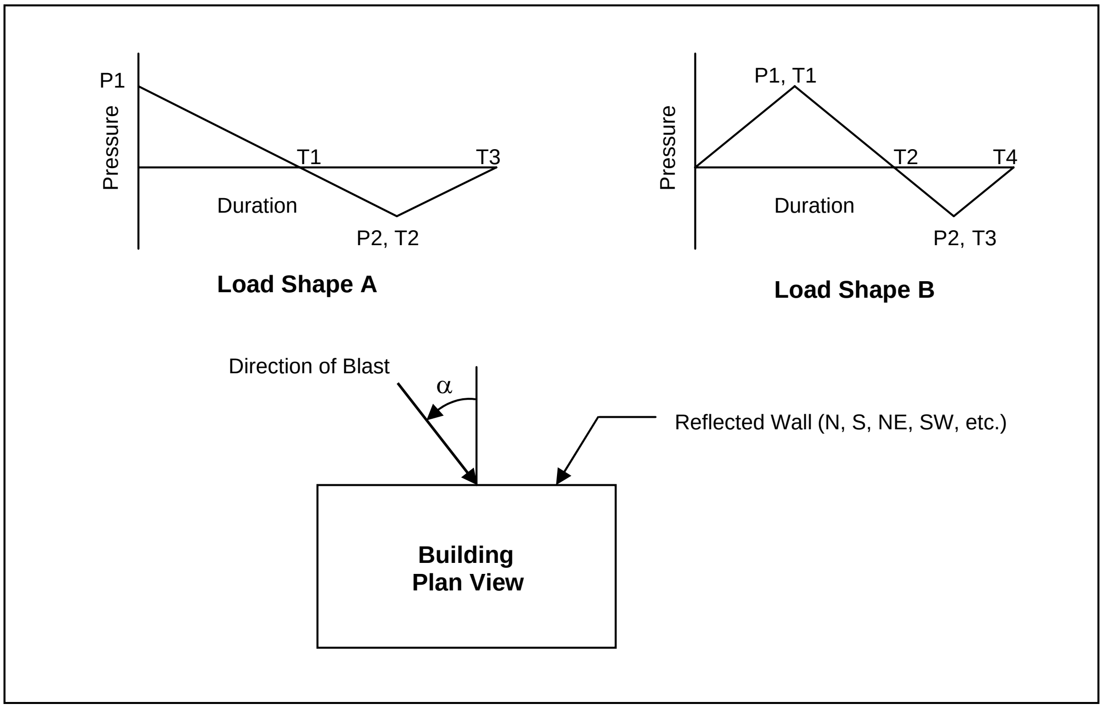
Blast Load Parameters

(1) PES #	PES Description	Reflected Wall (3) (N, S, NE, SW, etc.)	Load Shape (6) and Angle (4)		Peak Side-On Pressure (2) unit: (5):		Duration (6) msec			
			A , B	α (4)	P1	P2	T1	T2	T3	T4

Notes:
(1) A PES (Potential Explosion Site) is a congested/confined volume where a VCE could occur. A PES is a potential blast source.
(2) Side-on pressure shall be computed at the wall nearest to the blast center.
(3) The reflected wall(s) may be different for each PES. Indicate the reflected wall(s) (N, S, NE, SW, etc.) facing the blast center.
(4) Indicate angle of blast center (in degrees) measured from a line normal to reflected wall. See Figure A1 on next page.
(5) Specify pressure unit (psig, MPa, millibar, bar, etc.).
(6) If rise time is a small percentage of the positive phase duration then use load shape A as shown in Figure A1. Negative phase pressure is typically not considered, however if the explosion modeling software predicts a significant negative phase pressure it should be tabulated.

No.	Date	Description	By	Check.	App.

Figure A1 - Load Shapes and Building Orientation



A-3. Blast Door Requirements

The table below summarizes the design requirements for each blast door located in the exterior walls of blast resistant buildings.

Blast Door ID or No.	Building Face Door Location (N, S, NE, SW, etc.)	Performance Category (see Table 11) (I, II)

A-4. Geotechnical Requirements (Refer to SAES-A-113)

A-4.1. Foundation Type (Select one and provide data in the appropriate section.):

☐ Mat Foundation ☐ Spread Footing ☐ Pile Supported

A-4.2. Mat Foundation

Item	Value	Unit (*) / Special Unit	
Ultimate Net Bearing Capacity			kN/m² (psf)
At Depth			M (ft)
Dynamic Modulus of Subgrade Reaction			kN/m³ (pcf)
Sliding Friction Coefficient			
Passive Pressure Coefficient			

A-4.3. Spread Footing Foundation

Ultimate Net Bearing Capacity			kN/m² (psf)
At Depth			m (ft)
Sliding Friction Coefficient			
Passive Pressure Coefficient			

A-4.4. Pile-Supported Foundation

Pile Description			
Maximum Vertical Pile Capacity			kN (kips)
Maximum Horizontal Pile Capacity			kN (kips)
Vertical Pile Spring Constant			kN/m (kips/in)
Horizontal Pile Spring Constant			kN/m (kips/in)

(*) Note: Choose unit from list or enter user-defined name under Special Unit.

A-5. Other Special Requirements:

☐ Blast Valves ☐ Blast Attenuators

Special Requirements:

Appendix B – Commentary

B-1 Introduction

B-1.1 Purpose

This Engineering Standard focuses on the structural design of blast resistant buildings to be performed by a structural engineering professional (Engineer). The requirements for the conventional and the non-structural (architectural, electrical, HVAC, etc.) designs of such buildings are covered in other Saudi Aramco standards as indicated in Section 5.1.2.

This commentary to the Standard provides additional information regarding the selection and application of the blast design requirements. The commentary is not a part of the design requirements but is intended to assist the Owner and Engineer in applying the criteria during the course of the design.

B-1.2 Scope

This Standard is meant to cover new facilities when the Owner invokes it. It does not specifically address existing facilities; however, the methods discussed are applicable to analysis of existing buildings and the design of retrofits for such buildings. The Engineer should refer to the ASCE *Design of Blast Resistant Buildings in Petrochemical Facilities* (1) for specific guidance on analysis of existing facilities.

Some buildings may not require design for blast for a variety of reasons, including negligible blast loads levels or non-essential functions, or they may not be occupied according to the Owner's occupancy criteria. The Owner should determine whether blast design is required for each facility and specify this in the project or job specifications.

A common issue related to design of structures at petrochemical facilities is the lower limit of overpressure below which blast resistant design is not required. Many companies have cutoffs ranging from 0.5 psi (3.4 kPa) to 1.0 psi (6.9 kPa) side-on overpressure. This load level will produce damage to conventional buildings, with damage ranging from cosmetic to moderate requiring repair for continued use.

The most rational approach is to design each building at a site for the predicted blast load predicted from Building Risk Assessment studies. However, this may not always be practical, in which case an acceptable lower bound overpressure level must be established for conventional construction below which blast design need not be considered.

Building occupancy may be used in determining the need for blast resistance in new or existing buildings. However, this Standard does not cover occupancy criteria, which are addressed in standard SAES-B-014 and other industry guidelines such as *API RP 752*[2].

Application of this Standard for blast design may be influenced by future plant or process unit development. A building may be at risk at some point in the future if a process unit is modified or if a new unit is added that can produce higher overpressures at a given structure. A master plan for facility siting is highly desirable to address this issue.

B-3 References

The Standard is based primarily on the design methods and procedures provided in *ASCE Design of Blast Resistant Buildings in Petrochemical Facilities* [1]. However, other similar references and guidelines may be used. There are a number of other applicable references for design of blast resistant structures, including those developed for U.S. Department of Defense purposes. One of the most widely used of these references, *TM5-1300*[3], is also applicable to petrochemical facilities. However, the *ASCE Design of Blast Resistant Buildings in Petrochemical Facilities* [1] is a "how to" document, which covers all aspects of blast design for buildings at petrochemical plants.

This commentary lists references relevant to blast resistant design some of which are also included in the References Section of SAES-M-009.

1. ASCE *Design of Blast Resistant Buildings in Petrochemical Facilities, American Society of Civil Engineers (ASCE), 1997*
2. *Management of Hazards Associated with Location of Process Plant Buildings*, API Recommended Practice 752, American Petroleum Institute, Washington, D.C., Nov. 2003.
3. TM 5-1300 - *Structures to Resist the Effects of Accidental Explosions, U.S. Dept. of the Army, November 1990*
4. *Siting and Construction of New Control Houses for Chemical Manufacturing Plants*, Safety Guide SG-22, Manufacturing Chemists Association, Washington, DC, 1978.
5. *An Approach to the Categorization of Process Plant Hazard and Control Building Design*, Issued by the Safety Committee of the Chemical Industry Safety and Health Council, Chemical Industries Association, 1992.
6. *Design of Structures to Resist Nuclear Weapons Effects*, Manual No. 42, Committee on Dynamic Effects, American Society of Civil Engineers, New York, NY, 1985.
7. *Explosion Hazards and Evaluation*, W. E. Baker, Elsevier Scientific Publishing Company, New York, NY, 1983.
8. *Guidelines for Evaluating Process Plant Buildings for External Explosions and Fires*, Center for Chemical Process Safety of the American Institute of Chemical Engineers, New York, NY, 1996.

9. *Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires and BLEVE's*, Center for Chemical Process Safety of the American Institute of Chemical Engineers, New York, NY, 1994.

10. *Method for the Determination of Possible Damage to People and Objects Resulting from Releases of Hazardous Materials (CPR 16E)*, (Green Book), Committee for the Prevention of Disasters Due to Dangerous Substances, The Director-General of Labour, The Hague, 1992.

11. *Structural Dynamics: Theory and Computation*, third edition, M. Paz, Van Nostrand Reinhold Inc., New York, NY, 1991.

12. *Introduction to Structural Dynamics*, J. M. Biggs, McGraw-Hill Book Company, New York, NY, 1964.

13. *Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary (ACI 318R-05)*, ACI Committee 318, American Concrete Institute, Detroit, MI, 2005.

14. *Load and Resistance Factor Design Specification for Structural Steel Buildings*, American Institute of Steel Construction, Chicago, IL, December 27, 1999.

15. *Specification for the Design of Cold-Formed Steel Structural Members, Load and Resistance Factor Design*, Cold-Formed Steel Design Manual, American Iron and Steel Institute, 1997.

16. *Standard Specifications and Load Tables for Steel Joists and Joist Girders*, Steel Joist Institute, August 2002.

17. *Structural Welding Code - Steel*, ANSI/AWS D1.1/D1.1M:2004, American Welding Society, 2004.

18. *Building Code Requirements for Masonry Structures*, ACI 530-05/ASCE 5-05/TMS 402-05, American Concrete Institute, 2005.

19. *International Building Code*, International Code Council, Whittier, CA, 2003.

20. *Design of Structures to Resist the Effects of Atomic Weapons*, Technical Manual 5-856-1, Department of the Army, Washington, DC, January 1960.

21. *Overturning and Sliding Analysis of Reinforced Concrete Protective Structures*, Technical Publication 4921, U.S. Army Picatinny Arsenal, Dover, NJ, 1976.

SG-22 and *An Approach to the Categorization of Process Plant Hazard and Control Building Design* (commentary references 4 and 5, respectively) have been widely used for a number of years. These documents provide requirements for design of new facilities but are based on TNT-equivalent blast loads and the equivalent static load design method. They do not cover the more accurate design methods, the more complex forms of blast loads, or the structural design tools, which are now available and commonly used.

B-4 Definitions

The terminology used in this Standard is consistent with *ASCE Design of Blast Resistant Buildings in Petrochemical Facilities* [1] and other blast design manuals such as *TM5-1300*[3] and *ASCE Manual 42*[6]. Some differences in definitions, especially for symbols, may exist in blast load prediction manuals. The Engineer should verify any conflicting definitions.

B-5 General

B-5.1 Owner-Specific Data and Requirements

In addition to the need for blast resistance, this Standard requires that the Owner provide certain data and requirements to the Engineer performing the design in accordance with the Blast Design Requirements (BDR) Data Sheet. The Data Sheet is provided as Appendix A to this Standard.

B-5.2 Engineer's Responsibilities

The Engineer is responsible for designing a structure that provides protection in accordance with the response criteria based on the building performance requirements provided by the Owner or defined in this Standard. In situations for which a particular blast protection requirement is not covered in this Standard, conservative design assumptions should be made to ensure safety. The Owner should cover topics or issues not addressed. The Engineer should bring items requiring clarification to the Owner's attention as soon as possible to avoid project delays.

B-5.3 Documentation

The BDR Data Sheet should completely describe the design criteria, blast loads, structural system, and ancillary equipment. Material and section properties should be tabulated to aid in future evaluation of alternate blast loads.

B-6 Basic Requirements

B-6.1 Building Performance

The required building performance is an important consideration by the Owner in establishing the building response range (permissible damage level) for a building under the design blast conditions. The building response range may be a function of many factors related to the acceptable risk for a given facility. A building response range must be selected, on the basis of the building performance required, and included in the BDR Data Sheet. Such building performance requirements may be developed on the basis of the occupancy and function classification of the building as illustrated in Table B1.

Table B1. Building Performance Requirements

Building Classification	Example and Typical Performance Requirements	Building Response Range
Critical/Essential	Central control center, main electrical station. Continued use; reusable with cosmetic repairs	Low
Normally Occupied	Administration and engineering offices, laboratory. Damage-limited for occupant protection; not reusable without major repairs/replacement	Medium
Other	Operator shelters, warehouse. Collapse-limited; not repairable; abandon/replace	High

The Owner should decide what philosophy is to be adopted in setting the response range for evaluating and retrofitting existing buildings for blast resistance. In some cases because it is normally much less costly to incorporate blast resistance into a new facility than to retrofit a structure to increase its blast capacity, greater damage to an existing facility may be more tolerable than would be permitted for a new design.

B-6.2 Building Configuration

Blast resistant buildings should preferably be one-story construction with eave heights ranging up to 6 m (20 ft). Two-story construction may be required but should be used only when absolutely required. Two-story construction may be required if limited plot area prevents the layout of a single-story building. The floor plan for a building requiring blast resistance should be as simple as possible. A box type structure is preferable, in which the shorter side is exposed to the larger reflected blast load, and the longer side is exposed to the lower side-on blast load value. Roof overhangs, canopies, and re-entrant corners should be avoided if possible to avoid additional blast wave reflections. Architectural items such as canopies and signs should be designed with light construction materials, such as canvas, to avoid creating a debris hazard for the structure.

B-6.3 Blast Loads

This Standard does not cover development of explosion scenarios or prediction of blast loads, which therefore remain for the Owner to determine in accordance with SAES-B-014. Methods for blast load prediction and considerations for determining the design basis accident scenarios are provided in commentary references 6 through 10.

The Owner should specify the design blast load data in the Data Sheet (see Appendix A). As a minimum, the side-on overpressure and duration at the building location should be provided. The Engineer may use the procedures provided in *ASCE*[1] to calculate the component blast loads on the basis of given side-on blast effects. The Owner may also provide more detailed information from a site-specific study, including the side-on or reflected pressure-time profile and orientation (angle of incidence) of the blast loading on each surface of the building. In this case, the Engineer should verify the location of the point of reference for the design blast loads. If sufficient information is available, including the location of the explosion reference point (epicenter) and the attenuation of the blast effects with distance from this point, variation of the blast load over the surfaces of the structure may be considered in the design.

Generally there are three approaches to specifying blast load for designing new facilities:

1. **Using existing code/industry practice (default) values such as provided in SG-22(4) and the UK CIA(5) Guide**
2. **Establishing company generic values**
3. **Basing the blast loads on site or facility-specific explosion hazard studies. SAES-B-014 and API RP752 contains information about conduction Building Risk Assessment studies including acceptable explosion modeling software.**

In some cases, it is appropriate to develop site and building-specific blast loads on the basis of potential explosion hazards from any existing, planned, or future facilities. Default or generic blast loads are not based on the specific site hazard but on certain standard conditions such as spacing, process unit size, and hazard level. In addition, if the building location is not determined or if sufficient process information and physical configuration of the process unit is not available, the blast loads can only be approximated. In these situations, generic blast loads may be appropriate. Such loads may be based on a building category or classification defined by its occupancy or function following a blast and the separation distance from a potential explosion hazard, as illustrated in Table B2.

Table B2. Building Classification Matrix

Building Classification Based on Blast Severity or Spacing	Separation Distance ft (m)	Pressure psi (kPa)	Impulse psi-ms (kPa-ms)	Building Performance Requirement & Damage Level (H, M, & L)		
	Minimum	Maximum		Damage Limiting	Collapse Limiting	Hazard Limiting
				I (L, M)	II (H)	III (N/A)
A						
B						
C						
D						

For reference, both SG-22[4] and the CIA Guide[5] specify two sets of blast loads for control buildings spaced 100 ft (30 m) to 200 ft (60 m) from a blast hazard (Building Class A-I, per Table B2). The first set is based on a side-on overpressure of 10 psi (69 kPa) for 20 msec, and the second on 3 psi (20.7 kPa) for 100 msec. The CIA Guide[5] also specifies that such building should not collapse (that is, Class C-II) if subject to a worst-case blast load corresponding to 14.5 psi (100 kPa) side-on overpressure for 30 msec.

B-6.3.2 Component Loads

The blast load on each component of a building depends on the orientation of the building surface on which it is located. The following is a discussion of the blast loads for the main building components:

1. Wall Load

Normal reflection may be assumed without consideration of the angle of incidence of the blast wave. Clearing effects of the reflected blast wave may be considered by using the approach described in *ASCE*[1] or *TM5-1300*[3].

2. Roof Load

Roof load should be calculated using the methods provided in ASCE[1], on the basis of the blast wave direction, component span, and spacing. For a flat roof (slope less than 20 degrees), roof load may be conservatively taken as the side-on value unless otherwise specified. For roofs sloped more than 20 degrees, the effects of blast wave reflection should be considered.

3. Side/Rear Wall Loads

The blast loads on the side walls and rear wall relative to the explosion source should be considered in the analysis of the overall building. These loads may be calculated using the methods given in Chapter 3 of *ASCE*[1] or may be conservatively assumed to be the side-on values.

4. Overall Building (Frame) Loads

The overall structural framing should be designed for net vertical and lateral blast loads acting on the building, considering the time phasing of these loads, as provided in *ASCE*[1].

The blast load on the rear face may be used to reduce the net lateral load for design of the overall structural framing system including diaphragm, shear walls, and foundation. The rear wall blast load may be ignored if considering the load produces a more conservative design. However, if the rear wall loading is considered in the overall lateral blast loading, the lag time (delay in time of arrival) should be taken into consideration.

5. Negative Phase (Suction) Load

A negative phase load following the positive (overpressure) phase should be considered in the design if specified by the Owner. The effects of such a load should be considered in combination with the rebound effect from the direct blast pressure load.

B-6.4 Construction and Materials

A wide choice of construction types are available for blast resistant buildings, ranging from conventional construction to bunker-like concrete structures. The construction type is typically dictated by such factors as cost, blast load level, local practice, architectural considerations, and Owner preference. *ASCE*(1) (Chapter 4) describes some of the common types of construction used for blast resistant buildings in petrochemical plants.

Conventionally designed buildings can provide some level of protection against blast loads. The degree of protection provided depends on the ductility and redundancy of the structure. Ductile structures, such as metal frame/metal clad, can typically respond well into the plastic range and absorb blast energy. If connections are robust, components can develop tensile membrane action, which significantly increases their capability to resist load.

Table B3 lists some common types of building construction in the petrochemical industry, typical building function/use, the blast load ranges for each type of construction, and the tolerable damage level appropriate for the building function/use.

Table B3. Construction Type Matrix

Construction Type	Typical Building Function	Blast Load Range, Side-on Overpressure psi (kPa)	Tolerable Damage Level
Reinforced concrete	Central control room	High 7 (48) 10 (69)	Low
Precast concrete	Lab, office	Moderate - High 5 (35) 7 (48)	Low - Medium
Reinforced masonry	Office	Moderate 3 (21) 5 (35)	Medium
Metal frame, metal clad	Maintenance shop	Moderate - Low 2 (14) 3 (21)	Medium - High
Pre-engineered metal building	Warehouse	Low 1 (7) 2 (14)	High

B-6.4.1 General

Brittle structures, such as unreinforced masonry, have little ductility and can fail under very low blast loads. Failures of brittle structures are sudden and should be avoided in all cases. For this reason, unreinforced masonry construction is not permitted for design of blast resistant structures.

Redundant construction is also desirable for blast design. Redundancy is accomplished by providing alternate load paths and designing the structure to redistribute loads if a single component failure occurs. In metal frame buildings, where resistance to lateral loads is provided by girts and main frames, redundancy may be provided by strengthening the roof deck to act as a diaphragm and to distribute the load to other frames. Specific provision for redundancy is not required for design; however, redundancy should be provided where feasible and cost effective.

Metal frame, metal clad construction is commonly used in petrochemical plants for warehouses, maintenance shops, and process support office buildings. This type of construction is appropriate for relatively low blast overpressures and should typically be located several hundred feet from major process units.

Moment-resisting frames are typically used in a metal building to resist the lateral load applied on its long side. Vertical bracing is typically used between frames to resist loads applied to the end or short walls of the building. However, the Engineer should be aware of special considerations for blast resistant design including the following:

1. Frame spacing must typically be closer, on the order of 20 ft (6 m), than for conventional construction, where frame spacing

may exceed 30 ft (10 m).

2. Heavier gage wall panels and closer girt spacing are typically required to develop any significant blast resistant capability.
3. It may also be necessary to provide bracing for flexural members to develop a full plastic moment capacity for loads in both directions. This is a departure from typical construction, where bracing is normally required for a load in one direction only.
4. Cladding fasteners should also be detailed to ensure proper resistance to rebound and negative phase blast loading.

Masonry buildings used for conventional construction can be classified as load bearing or non-load bearing. The response for the load-bearing construction is limited to ensure adequate safety against collapse under blast load. If a steel or concrete frame is provided, infill masonry walls can be permitted to suffer significantly more damage without risk of collapse. This non-load-bearing construction is preferred because it provides better redundancy and overall safety. Unreinforced masonry load-bearing construction may be adequate for relatively low blast overpressures (i.e. less than 1 psi (7 kPa)).

A metal deck can be used as a roof diaphragm for relatively low blast overpressures. A poured-in-place concrete deck is typically used for masonry construction that is subjected to blast loads. A concrete deck provides significantly more lateral capacity than does a metal roof deck. A substantial bond beam at the top of the wall or secure ties into a concrete roof deck should be provided for wall rebound.

Precast concrete construction is widely used in petrochemical facilities for control rooms, plant offices, and process support buildings. Precast (non-prestressed) construction can be completed quickly and can provide significant blast resistance. The most significant consideration for blast resistant design is detailing of connections. Precast panels for conventional loads can have minimal blast capability if a small number of connectors are provided. For blast design, the number of connectors should be significantly increased and should be able to develop the full flexural capacity of the panel. If panel thickness is governed by architectural or mechanical considerations, the Engineer should ensure that connections are designed on the basis of the panel capacity rather than the required resistance for the blast.

Precast construction, like masonry, can be classified as a load-bearing or non-load-bearing structural system. For load-bearing construction, detailing of connections to develop moment capacities is especially critical. Secondary bending effects, P-Δ, caused by in-plane vertical loads should also be considered. For non-load-bearing construction, steel frames are used to support the vertical loads. The frames should be recessed from the interior face of the wall panels to avoid applying lateral loads to the columns.

Cast-in-place reinforced concrete construction is typically used to provide resistance to severe blast loads. Wall thicknesses for structures in or immediately adjacent to large process areas are typically 8 inches (200 mm) to 12 inches (300 mm) but can be thicker for some special cases. Reinforced concrete is especially appropriate for short duration loading that produces an impulsive response. Its large mass, relative to the surface area, is especially effective in resisting these types of loads. Reinforced concrete construction is typically used if a protective structure is needed around an existing structure to resist large blast loads because of close proximity to a blast source.

B-6.4.5 Fragment Resistance

Buildings that are required by the BDR Data Sheet to have fragment resistance shall be designed in accordance with *TM5-1300*(3) design procedures. Building with minimum wall thickness required by SSD/9 will provide a significant level of protection against fragments.

B-6.5 Material Properties

B-6.5.1 Dynamic Material Strength

The dynamic design stress (F_{ds}) is used to compute blast capacity of a structural component. Because design strength is constant throughout the response history, an average value should be used. Figure B1 illustrates the relationship of F_{ds} to F_{dy} and F_{du}. If the response is low, the portion of strength above yield is small because the actual stress is nearly equal to F_{dy} for most of the response. If a large deformation is produced, the actual stress is closer to the dynamic ultimate strength (F_{du}). The tables provided in this recommended Standard show the design stresses to use for given levels of response. If the anticipated response is incorrect, a new design stress should be calculated and new member properties determined.

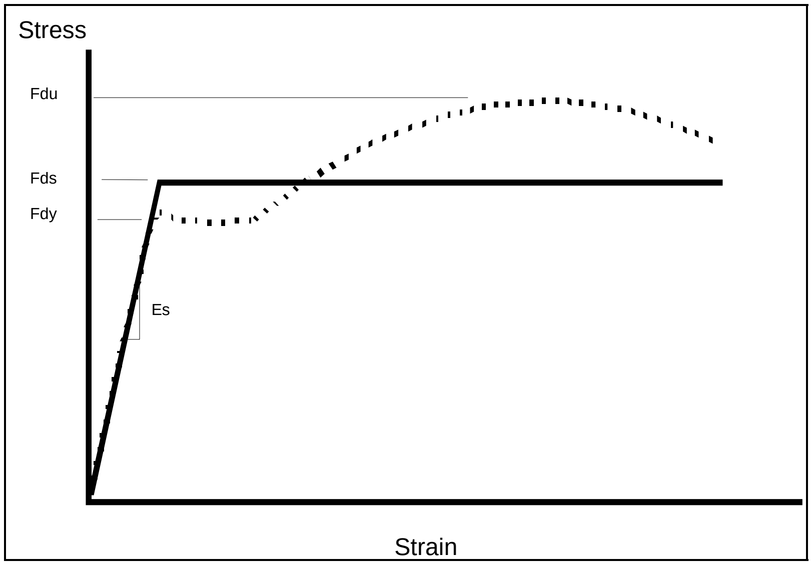


Figure B1. Yield, Ultimate, and Design Stresses

B-6.5.2 Strength Increase Factor (SIF)

The strength increase factor (SIF) is applied because the actual yield and ultimate strength of a material is typically greater than the minimum specified value. Use of the SIF provides more realistic member properties and results in higher structural resistance. Failure to include the SIF can result in underestimating the member resistance and the resulting shear loads and dynamic reactions. This may not be conservative.

B-6.5.3 Dynamic Increase Factor (DIF)

The dynamic increase factor (DIF) is used to account for the strain rate effects. Under blast-loading conditions, the material cannot respond as quickly as the load is applied and an apparent strength increase is produced. Failure to include the DIF can also result in the under-prediction of member end shears and reactions. The strain rate can vary depending on whether the blast load is a pressure wave or a shock wave. A pressure wave may not produce strain rates sufficient to require DIFs as high as shown in Tables 4 and 5. *TM5-1300*[3] can be used for guidance on DIF values at relatively slow strain rates.

B-7 Structural Design

B-7.1 Design Methods and Procedures

An overall process for designing blast resistant structures for petrochemical facilities is shown in Figure B2 from ASCE[1]. Most of the overlapping steps in the design process shown in Figure B2 will normally be the responsibility of the Engineer. If the Owner has specific requirements in these areas, the requirements should be provided in the BDR Data Sheet or the project/job design specifications. The Engineer should bring any unclear items to the attention of the Owner at the earliest possible time to avoid project delay.

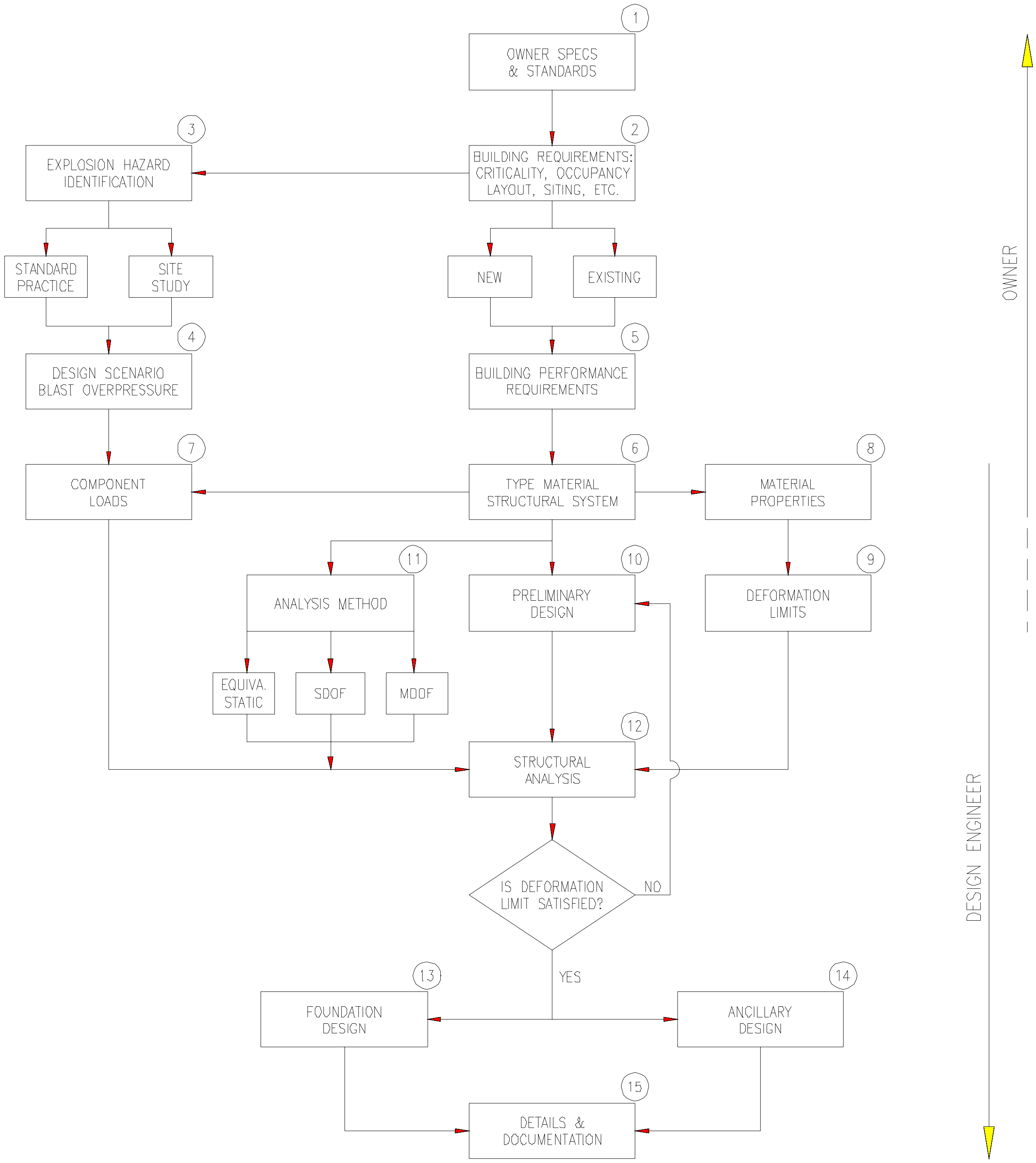


Figure B2. Overall Blast Resistant Design Process (from *ASCE*[1])

B-7.2 Load Combinations

Most design codes for conventional buildings have provisions for combination of design loads such as live, wind, seismic, snow, etc. For blast design, a decision should be made about which of these loads to include simultaneously with blast loads. Dead loads are always included, but most other transient live loads are not, although roof live loads (full or partial) are typically included.

The portion of live load to be applied in combination with blast load should be determined by the Engineer on the basis of the amount of load that could reasonably be expected to occur at the same time as the blast load. This should include roof live loads, and floor loads. The full floor live load should not normally be used because of the low probability of blast occurring during application of the full floor live load. It is not normal practice to combine blast loads with extreme environmental loads such as wind or earthquake. In rare situations, it may be appropriate to analyze structural response for the blast load following application of seismic loads (for example, where an earthquake causes damage to a process unit, which leads to an explosion).

Most conventional design codes specify load factors to be applied to provide a factor of safety in the design. These load factors are typically set at 1.0 for blast design because a blast load is an extreme event.

B-7.3 Analysis Methods

B-7.3.1 - Approximate Solution (Equivalent Static Load)

The equivalent static load analysis method, which treats the required resistance as a static load, is based on the single degree of freedom (SDOF) response to a simplified blast load and may be used for components loaded directly by the blast.

The equivalent static load method has been quite popular in the past because it is simple to apply. It is used to approximate dynamic response without requiring numerical integration of the equations of motion. *ASCE*[1] and *ASCE Manual 42*[6] provide an empirical equation for computing the required resistance or equivalent static load for a component. These documents and *TM5-1300*[3] provide plots of the response of an elastic-plastic SDOF system to a triangular shock load pulse. The plots represent approximate solutions for an elastic-perfectly-plastic SDOF system subjected to a linearly decaying blast load without a rise time.

Use of the equivalent static load method requires iteration. Initial properties for the member are selected to define the period of vibration.

When the static equivalent load is calculated and applied, a new section is selected on the basis of calculated resistance. This new section can have different properties than originally assumed, which can change the equivalent static load. If a new equivalent static load is not calculated, subsequent calculations for member end shear and connection design may not be correct. The equivalent static load method does not directly calculate the dynamic shears and reactions of the member. The equivalent static load is used to determine these parameters, and in some cases may underestimate these items and thus the connection requirements. Another drawback of this method is that it cannot model the interaction of connected components.

The equivalent static load method should be used only for analysis of a linearly decaying blast load without a negative phase. This method should not be used for non-ideal resistance functions nor for modeling differences in resistance for the positive response phase and the rebound phase.

B-7.3.2 Single-Degree-of-Freedom (SDOF)

The Single-Degree-of-Freedom method is the most commonly used method for blast resistant design. This method allows most structural components to be modeled as a single, spring-mass system, which greatly simplifies the analysis of the time-history response. This method can be used to model non-linear resistance functions and the differences in resistance in the positive and rebound phases. The Single-Degree-of-Freedom method can also be used to model complex pressure-time histories including negative pressure effects.

The time-varying end reactions can be calculated using the SDOF method. These reactions can then be applied to supporting members to model component interaction. Special consideration needs to be given to selection of the appropriate mass to be applied to supporting members, based on the relative time to maximum response of the member being supported.

Additional guidance is given in *ASCE*[1] and in references 11 and 12 of this commentary for modeling and analyzing the response of structural components as SDOF systems.

Pressure-impulse (P-I) curves, denoting lines of constant damage corresponding to a particular response limit, may be used to evaluate the response of a structural component to a number of blast loads. This approach is described in *ASCE*[1] and in other References [7, 8, and 10].

B-7.3.3 Multi-Degree-of-Freedom (MDOF)

The multi-degree-of-freedom (MDOF) analysis method can be used to determine the dynamic response of interconnected members. Each component should be modeled as a one-degree-of-freedom spring mass system. Several SDOF systems can be combined numerically to produce a MDOF model. The MDOF method can models mass and dynamic reaction effects on supported members. A typical system for a wall design can be modeled as a three-degrees-of-freedom system consisting of a wall panel, girt, and frame column. MDOF analysis can result in a much lower maximum deflection than a SDOF analysis if the periods of vibration of the connected members are fairly close.

The MDOF method can be used to model non-rigid (spring) supports, which can reduce the required resistance of certain components. A spreadsheet can be used to perform numerical integration of simple models consisting of two or three degrees of freedom. Beyond this, a computer program is more appropriate. A limited number of special purpose computer programs are available that are suitable for this type of analysis although most of these programs have been developed for defense-related applications. Also a commercially available general purpose finite element program, that employs general spring elements to model and analyze non-linear MDOF systems subjected to transient blast loads, may be used.

Finite element analysis (FEA) can be used for analyzing a large system of components that cannot be accurately modeled using SDOF or MDOF methods. MDOF and FEA are essentially the same methods; however, FEA is usually distinguished as capable of modeling complex elements, whereas an MDOF method is based on equivalent spring elements. FEA is typically used to model response of a three-dimensional frame structure if biaxial bending and other three-dimensional effects are important.

A number of commercially available computer programs, referenced in *ASCE*(1), provide general FEA capability and can predict dynamic response to transient loads. These programs are therefore suitable for blast resistant design. It is important to use an FEA program that can accurately model non-linear effects, both material and geometric, and that can incorporate the effects of increased material strength under rapidly applied loads.

B-7.4 Deformation Limits

B-7.4.1 Response Parameters

For blast resistant design, the adequacy of the structural response is determined in terms of maximum deflection rather than stress level because the response typically will be in the plastic region of the stress-strain curve. It is normal practice to design blast resistant structures for plastic deformation if subjected to the extreme blast loads from accidental explosions. It is not cost effective to design such structures to remain elastic.

The two key parameters for evaluating structural response are support rotation (θ) and ductility ratio (μ). Support rotation is a function of the maximum deflection to span ratio. Figure B3 illustrates support rotation for a simple beam.

Ductility ratio is a measure of the degree of plastic response. A ductility ratio of 2 means than the maximum deflection is twice the deflection at the elastic limit. Steel members can achieve relatively high ductility ratios if buckling and shear modes of failure are prevented. The limits on deformation provide some conservatism for these effects.

Ductility ratio is an appropriate criterion for steel members, but it is a less reliable performance indicator for reinforced concrete components. Concrete members tend to be very stiff, which produces a very low elastic deflection. Therefore, small dynamic deflections can produce large ductility ratios. Support rotation is a more reliable measure of performance for concrete or masonry.

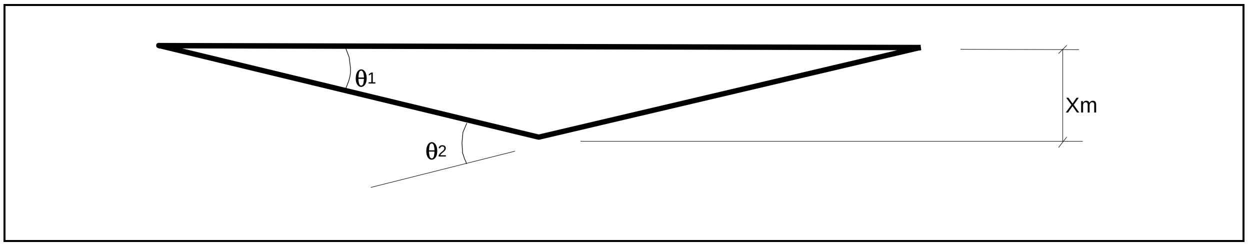


Figure B3. Definition of Support Rotation

θ_1 = Support rotation
θ_2 = Center hinge rotation = $2*\theta_1$

B-7.4.2 Building Response Range

The structural response or allowable damage level should be in accordance with the Owner-specified performance requirements for the building. The recommended response limits in this Standard corresponding to three damage levels (low, medium, high) are described in Table B4.

Table B4. Response Range Descriptions

Response Range	Damage Description
Low	Localized building/component damage. Building can be used; however, repairs are required to restore integrity of structural envelope. Total cost of repairs is moderate.
Medium	Widespread building/component damage. Building cannot be used until repaired. Total cost of repairs is significant.
High	Building/component has lost structural integrity and may collapse because of environmental conditions (i.e. wind, snow, rain). Total cost of repairs approaches replacement cost of building.

B-7.5 Component Design

B-7.5.1 General

Structural components designed using SDOF analysis should include in-plane loads and secondary bending effects. These effects are typically incorporated as statically applied loads together with the flexural response to the transient loads.

Components should be designed to develop the full flexural capacity to avoid brittle failure modes. This type of response provides the maximum blast-absorbing capability and results in a controlled failure mode. This type of response requires that components have sufficient shear and connection capacities. The shear and connection capacities of a component are typically based on the component's full flexural resistance. Adequate bracing should also be provided to prevent lateral buckling, which can result in sudden failures.

The primary response for short span components is in shear, and thus it is not feasible in many cases to develop the full flexural capacity. In these cases, the maximum resistance produced by the transient load should be determined for the entire response history. End shears and reactions should be based on 120% of the maximum attained resistance applied as a uniform load on the member.

B-7.5.2 Reinforced Concrete

Design of reinforced concrete should be in accordance with the ultimate strength method according to *ACI 318-05*[13] or comparable concrete design methods. The customary strength reduction factor (ϕ) should be 1.0, and a dynamic stress factor (SIF * DIF) should be applied in accordance with Sections 6.5.2 and 6.5.3 respectively. In addition, because of the importance of adequate shear capacity to develop ductile flexural behavior in reinforced concrete components, the minimum static compressive strength for blast resistant design is set at 4,000 psi (28 Mpa). The higher strengths assure a more reliable performance in shear. Compressive strength less than 3,000 psi (21 Mpa) should not be permitted. A compressive strength of 5,000 psi (35 Mpa) is considered acceptable for concrete design. However, compressive strengths above this value have not yet had adequate testing to assure proper dynamic performance under blast load conditions.

Reinforcing steel higher than Grade 60 (420 Mpa) should not be permitted. In addition, bar sizes above a #10 (32 mm) should not be used because of decreased ductility for large bars. Use of a greater number of smaller bars is preferred to decrease development length requirements.

Time phasing of the interaction equation may be used; however, because of inaccuracies in load-time phasing and response, it is important to apply some conservatism to the design.

Prestressed concrete members are typically limited to roof members only. Prestressed components are typically designed for load application in one direction and do not provide adequate rebound resistance. If permitted these elements require special attention to insure that they have sufficient non-prestressed reinforcement added to the compression zone to prevent catastrophic failure during rebound or negative phase loading. Additionally, careful attention to the design and selection of precast concrete connections is required to ensure constructability and sufficient strength to transfer forces through the connections. Because of the relative lack of ductility of prestressed concrete members, conservative response limits should be established. *TM 5-1300*[3] provides guidance for the design of prestressed concrete.

B-7.5.3 Structural Steel

Methods in accordance with *AISC Load and Resistance Factor Design Specification for Structural Steel Building* [14] or comparable limit state methods may be used for the blast resistant design of structural steel. As in reinforced concrete design, ϕ should be 1.0 and the dynamic strength increase factors should be used. Steel materials with 50 ksi (345 Mpa) yield material should be used because of the wide variation in material strength for A36 steel. Use of A36 material, which has an actual yield strength significantly greater than 36 ksi, can result in an unconservative prediction of reaction forces and required shear resistance.

B-7.5.4 Cold-Formed Steel

The load and resistance factor design (LRFD) method of *AISI*(15) or a comparable strength limit state method may be used for the blast resistant design of cold-formed steel members. A $\phi = 0.9$ factor should be applied to plastic moment capacity when computing an ultimate resistance to reflect the potential buckling of a section before developing the full plastic moment. The dynamic strength increase factors in Section 6.5.3 of this Standard should be applied.

B-7.5.5 Open Web Steel Joists (OWSJ)

OWSJ are not well suited for blast design because of difficulties in developing ultimate moment capacity. Web buckling can occur, especially at member ends, resulting in premature failure. Instability of the bottom chord during rebound can significantly reduce the rebound capacity, but this potential problem can be remedied by supplying additional bracing to the bottom chord. If used, OWSJ should be designed on the basis of applicable standard specifications by the Steel Joist Institute(16). Joist manufacturers' allowable load capacity tables may be used in determining the ultimate capacity of OWBJ under blast loading by multiplying the listed stress-based values by the applicable safety factor and by the appropriate dynamic strength increase factors.

Quality control in the manufacture of OWSJ can be an issue. Welding of bar joists is typically not in accordance with *AWS D1.1*(17) and may not be capable of developing the plastic moment capacity of the joist. Because of these potential deficiencies in blast resistant designs, OWSJ should be used with caution.

B-7.5.6 Reinforced Masonry

Only fully inspected reinforced masonry (concrete or brick) is appropriate for blast resistant design. The *ACI 530*(18) and the *IBC*(19) requirements for ultimate strength for reinforced masonry should be used for blast resistant design, particularly the requirements pertaining to seismic design. *ASCE*(1)and *TM5-1300*(3) also provide guidance specific to the design of reinforced masonry for blast resistance.

Masonry construction responds similarly to singly reinforced concrete. Fully grouted cells normally provide adequate compression and shear capacity to develop flexural strength. Horizontal truss or ladder type reinforcing provides minimal flexural capacity and is not generally classified as reinforced masonry.

Connections at floor and roof are typically weak links in conventional reinforced masonry construction. The connections should be capable of resisting inward and rebound loads. Connections for load-bearing construction are especially critical. Walls should be doweled into floor and roof slabs.

B-7.6 Structural Framing Design

Analysis of frame sidesway should include analysis with and without blast overpressure on the leeward side of the building. Normally, excluding this load will produce the maximum response; however, in some cases the load applied to the leeward side may produce the maximum response if it occurs in phase with the rebound response. Accurate calculation of time of arrival for the blast wave is important for this part of the analysis.

Dynamic analysis of sliding and overturning effects requires judgment on allowable deformations. Some guidance is provided in References 20 and 21. Vertical movement on the order of 1 inch (25 mm) is considered acceptable, while lateral movement as much as 2 inches (50 mm) may be acceptable. Using static methods, it is normally possible to show an adequate resistance to overturning and sliding. However, multi-story structures and buildings with a large aspect ratio floor plan may require dynamic analysis to show acceptable response.

ASCE(1), as well as other references (3, 11, 12), provides guidance in modeling and calculating the dynamic response of structural systems to blast loading.

B-7.7 Foundation Design

Analysis of explosion accident data has shown that foundation failure is rare because of the inability of the supported structure to transfer the entire blast load to the foundation. Also, foundation members are typically massive compared with superstructures and provide greater resistance to blast loads than does the supported building. Usually foundation components are simply designed statically for the capacities of the structural components they support. However, if this proves to be too conservative or costly, a more accurate dynamic analysis of the structure/foundation system can be performed.

B-8 Ancillary Items

B-8.1 Blast Doors

The Owner should specify whether blast doors are required for the building. Blast doors are expensive, even for low blast loads, and may not be cost effective at low risk levels. Conventional hollow metal doors may not be operational above approximately 1.0 psi (7 kPa) applied peak pressure. If the blast pressure entering a structure is not sufficient to cause damage, a conventional door may be acceptable.

Door hardware may not be required to remain operational if additional protected exits are provided. This may be the case for doors on a wall receiving reflected loads. It may be appropriate to permit these doors to be substantially damaged if a sufficient number of doors are located in building faces receiving side-on blast loads. The Owner should select an allowable response category for design of each door and specify the categories on the BDR Data Sheet. Additional information regarding door performance and design is provided in ASCE[(1)].

Support for blast door frames is very important. Typically, subframes are provided by the building contractor during wall construction. This allows construction to continue while blast doors are being fabricated, which may take several weeks or months. Door framing should be provided by the manufacturer.

B-8.2 Windows

Windows should be avoided in buildings subjected to significant blast loads. However, laminated glass and polycarbonate glazing can provide substantial blast resistance if they are either:

a. Wet-glazed into the window frames using a structural sealant, or

b. are equipped with a large rebate (bite) to prevent the glazing from pushing through the frame.

If blast resistant windows are designed by a specialty window supplier, supporting calculations and test data should be provided to substantiate performance.

B-8.3 Openings

Small openings or low applied blast loads may not produce an appreciable increase in pressure in the building. In these cases, blast valves or other pressure relieving devices should not be required. For structures near a process unit, leakage pressures through air intake openings can be significant and valves or attenuators are required. Methods for predicting leakage pressure through openings should be in accordance with *TM5-1300*[(3)].

Blast valves typically incorporate a moving disk that seals the opening and prevents entry of blast pressures. Blast attenuators significantly reduce leakage pressures but do not completely eliminate the blast.

Passive blast valves have no moving parts and reduce blast pressures by creating a tortuous exit path rather than a seal.

B-8.4 Penetrations

Pre-manufactured multi-cable transits (MCT) for use in blast resistant buildings have a frame that is anchored into the concrete or masonry. Flexible collars are placed around pipes running through the MCT and are clamped down to prevent leakage of the blast pressure into the structure. MCTs are available in a variety of sizes.

B-8.5 Suspended Items

Light fixtures in suspended ceilings can produce a serious hazard to occupants during a blast. Ceiling grids, unless seismically rated, will not support fluorescent light ballasts and ventilation dampers. These items should be anchored to the roof framing with heavy gauge wire or threaded rod. Any item weighing more than 10 pounds (5 kg) should be independently anchored.