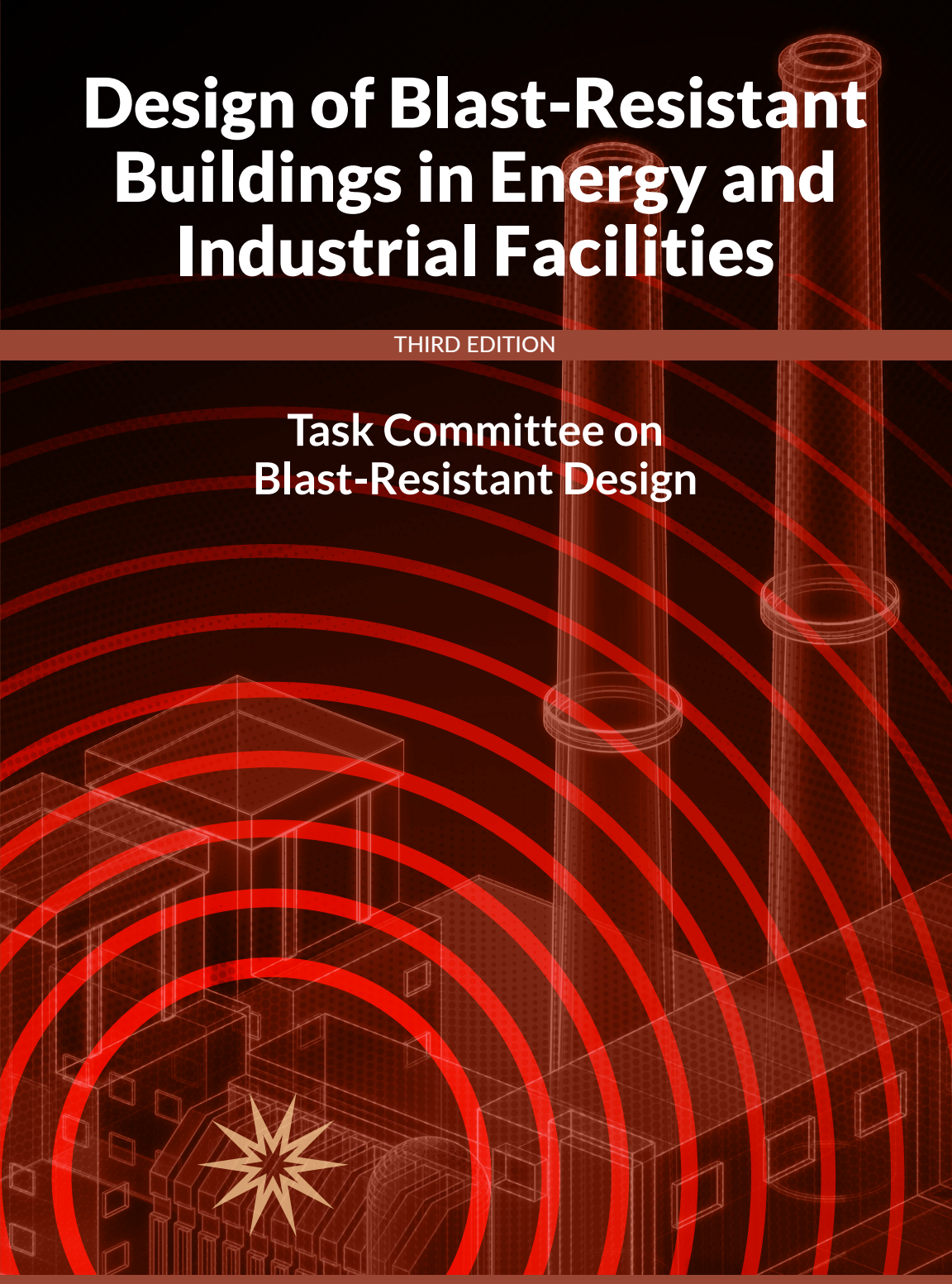
Design of Blast-Resistant Buildings in Energy and Industrial Facilities

THIRD EDITION



Task Committee on Blast-Resistant Design

Edited by Luca Magenes, P.E.

ASCE | ENERGY

Design of Blast-Resistant Buildings in Energy and Industrial Facilities

Other Titles of Interest

Seismic Evaluation and Design of Petrochemical and Other Industrial Facilities, Third Edition, by Task Committee on Seismic Evaluation and Design of Petrochemical Facilities (ASCE/Energy Division 2020). This report provides practical recommendations affecting the safety of new and existing petrochemical and other industrial facilities during and following an earthquake. (ISBN 978-0-7844-1548-1)

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Third Edition

Sponsored by
Task Committee on Blast-Resistant Design of the Energy Division of the
American Society of Civil Engineers

Edited by
Luca Magenes, P.E.

Published by the American Society of Civil Engineers

Published by American Society of Civil Engineers
1801 Alexander Bell Drive
Reston, Virginia 20191-4382
www.asce.org/bookstore | ascelibrary.org

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Errata: **Errata, if any, can be found at https://dx.doi.org/10.1061/9780784485897.**

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ISBN 978-0-7844-8589-7 (PDF)
ISBN 978-0-7844-1629-7 (Print)
ISBN 978-0-7844-8590-3 (ePub)

Manufactured in the United States of America.

29 28 27 26 25 1 2 3 4 5

Photo Credit: The photo appearing on the back cover of the book shows a deflagration test of a pre-engineered metal building. It is provided courtesy of Baker Engineering and Risk Consultants and the Explosion Research Cooperative.

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Acknowledgments

The Task Committee for this publication update would like to thank the following individuals who independently reviewed the manuscript and provided valuable comments: Raymond Bennett, Ph.D, P.E., John Geigel, and Lauren Stewart, Ph.D. In particular, we would like to acknowledge John Geigel for his substantial contribution to this publication and its previous editions and for his lifelong contributions to the civil engineering field at large.

A special acknowledgment goes to Jason Florek, Ph.D., P.E., who lead the significant updates to the practical example chapters (Ch.10, 11, and 12). The committee would like to recognize the efforts of the previous two Task Committees, and the past committee Chair, William Bounds, who built the foundation for this publication update.

The authors are grateful for the support received from the ASCE Energy Division and Committee on Technical Advancement, which continue to sponsor the updates of this important industry publication.

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Preface

This report is the third edition of this publication. The previous version was titled *Design of Blast-Resistant Buildings in Petrochemical Facilities* and was published in 2010. The title of this report was changed for this edition to better represent the broad range of applications for which the report has been used and for its intended audience. In addition to the previously mentioned petrochemical industry, some additional industries to which this report holds applicability include, but are not limited to, power generation, hydrogen and ammonia production, battery manufacturing and utilization, pharmaceuticals, and other chemical processing industries.

This new edition includes updates that are in line with new developments in the practice of structural blast engineering in energy and industrial facilities including

- Expanded discussions on risk-based facility siting,
- New building types (e.g., timber and unreinforced masonry buildings),
- Loading on elevated buildings,
- New screening-level guidance,
- Mitigation using energy-absorbing systems,
- Updated response criteria for prestressed concrete and reinforced concrete, and
- Updated and expanded example chapters.

We hope that this updated report provides useful guidance to a wide community of structural engineers working on the design of structures and buildings to resist the effects of blasts, explosions, and impulsive/impactive loads.

Nomenclature

a = Acceleration
a_H = Horizontal acceleration
a_V = Vertical acceleration
a_θ = Rotational acceleration
A_1 = Bearing area
A_2 = Pedestal area
A_b = Nominal bolt area
A_g = Gross area
A_n = Nominal area
A_{nv} = Net section area
A_{ps} = Area of prestressed reinforcing in the tension zone
A_s = Area of steel
A_v = Shear area of steel
A_w = Weld area

b = Member width
b_f = Flange width
B_H = Building height
B_L = Building length
B_p = Plate width
B_W = Building width
BL = Blast load

c = Impulse factor for a decaying shock wave
c_1 = Distance from the center to the edge of the element
c_h = Horizontal weld eccentricity
c_v = Vertical weld eccentricity
C = Viscous damping constant
C_d = Drag coefficient
C_e = Side wall reduction factor
C_F = Loading reaction coefficient
C_r = Reflection coefficient
C_R = Resistance reaction coefficient
C_V = Shear coefficient

d = Depth
d_b = Bolt diameter

d_h = Hole diameter
d_{na} = Depth to neutral axis
d_p = Depth to the center of prestressing steel
d_{sb} = Depth of a concrete stress block
DL = Dead load

E = Modulus of elasticity
E_c = Modulus of elasticity of concrete
E_m = Modulus of elasticity of masonry
E_s = Modulus of elasticity of steel

f = Frequency of vibration
f_c = Concrete stress
f'_c = Concrete strength
f_{cr} = Compression stress
f'_{dc} = Dynamic concrete strength
f'_{dm} = Dynamic masonry strength
f'_m = Masonry strength
f_{ps} = Calculated stress in prestressing steel at the design load
f_r = Modulus of rupture
f_{vh}, f_{v1}, f_{v2} = Shear stress
F = Blast force
$F_1 \ldots F_7$ = Blast force
F_{cr} = Flexural buckling stress
F_C = Compression force
F_{du} = Steel dynamic ultimate strength
F_{ds} = Dynamic design stress
F_{dy} = Steel dynamic yield strength
F_e = Equivalent force
F'_e = Elastic critical buckling stress
F_{EXX} = Weld electrode strength
F_H = Horizontal dynamic force
F_{nt} = Nominal bolt tension strength
F_{nv} = Nominal bolt shear strength
F_o = Peak blast force
F_{RL} = Reflection load
F_s = Static load
F_{SL} = Stagnation load
F_T = Tension force
F_u = Steel ultimate strength
F_V = Vertical dynamic force
F_w = Weld strength
F_y = Steel yield strength
F_θ = Rotational dynamic force

FS = Factor of safety

g = Acceleration of gravity
g_b = Bolt gauge
G = Shear modulus

h = Height
J_w = Polar moment of inertia

i = Time step number
I = Moment of inertia
I_a = Averaged moment of inertia
I_{bar} = Nondimensionalized impulse
I_{cr} = Cracked moment of inertia
I_g = Gross moment of inertia
I_o = Positive phase impulse
I_o^- = Negative phase impulse
I_w = Equivalent triangular impulse
I_x = Moment of inertia about the x-axis
I_y = Moment of inertia about the y-axis
ip = (subscript) In-plane deformations

k_v = Shear width-thickness coefficient
K = Stiffness
K_a = Coefficient of active soil pressure
K_e = Equivalent or effective stiffness
K_{ep} = Elastic-plastic stiffness
K_H = Horizontal soil stiffness
K_L = Load or stiffness transformation factor
K_{LM} = Load-mass transformation factor
K_M = Mass transformation factor
K_p = Coefficient of passive soil pressure
K_V = Vertical soil stiffness
K_x = Effective length factor for the x-axis
K_y = Effective length factor for the y-axis
K_θ = Rotational soil stiffness
KE = Kinetic energy
KEY = Response indicator

L = Length
L_1 = Length of the surface parallel to a traveling blast wave
L_c = Clear distance
L_h = Horizontal weld length
L_p = Limiting unbraced length for plastic design

L_s = Spacing
L_v = Vertical weld length
L_w = Blast wave length
L_x = Unbraced length in the x-axis
L_y = Unbraced length in the y-axis
LL = Live load

m_1 = Baseplate design dimension
M = Mass
M_1 = Foundation moment
M_c = Midspan moment
M_{cr} = Cracking moment
M_e = Equivalent mass
M_p = Plastic moment
M_{ps} = Moment capacity at the support
M_{pc} = Moment capacity at midspan
M_y = Yield moment
M_θ = Mass moment of inertia

n = Modular ratio
n' = Baseplate design dimension
n_1 = Baseplate design dimension
n_w = Horizontal weld center
N = Number of structural elements
N_p = Plate length
N_u = In-plane capacity of the element
N'_u = Ultimate applied in-plane load

OM = Overturning moment
op = (subscript) Out-of-plane deformations

P = Pressure
$P_1 \ldots P_5$ = Vertical static load on the foundation
P_2 = Vertical static load on the foundation
P_3 = Vertical static load on the foundation
P_a = Effective side-on overpressure
P_b = Rear face overpressure
P_c = Permissible compression
P_{bar} = Nondimensionalized pressure
P_{nc} = Nominal compression capacity
P_{nt} = Nominal tension capacity
P_o = Ambient atmospheric pressure
P_p = Available strength
P_r = Peak-reflected overpressure

P_s = Stagnation pressure
P_{so} = Peak side-on overpressure
P_{so}^- = Negative peak side-on overpressure
P_t = Permissible tension
P_u = Factored axial load

q = Bearing pressure
q_o = Peak dynamic pressure
Q_u = Shear capacity of the element
Q_u' = Ultimate applied shear load

r_x = Radius of gyration about the x-axis
r_y = Radius of gyration about the y-axis
R = Resistance
R_1 = Axial component of a battered pile
R_b = Bending resistance
R_{b-} = Negative bending resistance
R_e = Equivalent resistance
R_{HORIZ} = Lateral load component of a battered pile
R_m = Maximum resistance
R_{MAX} = Maximum axial pile load
R_{MIN} = Minimum axial pile load
R_n = Nominal resistance
R_s = Shear resistance
R_u = Ultimate resistance
R_{u-} = Rebound resistance
R_y = Yield resistance
RM = Resisting moment

S = Clearing distance
S_x = Section modulus about the x-axis
SE = Strain energy

t = Time
t_a = Time of arrival
t_c = Clearing time
t_d = Positive phase duration
t_d^- = Negative phase duration
t_e = Equivalent duration
t_f = Flange thickness
t_m = Time of maximum response
t_n = Natural period
t_o = Total positive phase duration
t_p = Plate thickness

t_r = Rise time
t_w = Web thickness

U = Shock front velocity

v = Velocity
V = Dynamic reaction
$V_1..V_9$ = Lateral load on the foundation
V_f = Fixed end reaction
V_n = Nominal shear
V_p = Pinned end reaction
V_u = Ultimate shear

w_p = Reinforcement index
W = Width
X = Baseplate design factor
X_a = Allowable sidesway
X_e = Elastic sidesway
X_m = Maximum sidesway

y = Deflection
y_d = Dead load deflection
y_e = Yield deflection
y_{e-} = Rebound yield deflection
y_{ep} = Elastic-plastic deflection
y_H = Horizontal deflection
y_m = Maximum deflection
y_{m-} = Maximum rebound deflection
y_p = Plastic deflection
y_{st} = Static deflection
y_V = Vertical deflection
y_θ = Rotational deflection

Z = Calculation case indicator
Z_x = Plastic modulus about the x-axis

α = Angle of incidence
α_1 = Angle
α_2 = Angle

Δ_a = Allowable deformation (ductility ratio or support rotation)
Δ_d = Computed deformation (ductility ratio or support rotation)
Δ_f = Flexural deflection
Δ_s = Shear deflection

ε_u = Maximum strain
ε_c = Concrete strain
ε_s = Steel strain
ε_u = Ultimate concrete strain
ε_y = Steel yield strain

ϕ = Strength reduction factor
Φ = Curvature or deflected shape

γ = Soil density

λ = Roughness coefficient
λ_{bp} = Baseplate design factor
λ_c = Compression slenderness factor
λ_f = Flange slenderness factor
λ_p = Limiting plastic slenderness factor
λ_{ps} = Limiting seismic plastic slenderness factor
λ_v = Shear slenderness factor
λ_w = Web slenderness factor

μ = Ductility ratio
μ_a = Allowable ductility ratio
μ_d = Demand ductility ratio
$\mu_{d\text{-}}$ = Demand rebound ductility ratio
μ_f = Friction coefficient

ν = Poisson's ratio

θ = Rotation or hinge rotation
θ_a = Allowable support rotation
θ_d = Demand support rotation
θ_1 = Support rotation
θ_2 = Midspan rotation

ρ = Tension-reinforcing ratio

τ = Ratio of load duration to the natural period (t_d/t_n)

CHAPTER 1
Introduction

The focus of this report is on blast-resistant structural aspects of designing new buildings, as well as evaluating and modifying/strengthening existing buildings. The term "petrochemical facility", which was included in the original title of this publication, typically refers to a facility that refines or manufactures petroleum-based products. However, the guidelines related to such facilities can also be used for buildings located on any type of industrial facility that have hazards with the potential to generate blast overpressure from accidental events arising from handling hydrocarbons and other flammable or reactive materials, or from generating dust. These industrial facilities can include, for example, upstream oil and gas processing and storage facilities, refineries, liquefied natural gas (LNG) liquefaction and regasification facilities, chemical manufacturing plants, sugar factories, biofuel plants, and others. For these reasons, the title of this publication was changed to *Design of Blast-Resistant Buildings in Energy and Industrial Facilities*. The term petrochemical facility is still used in the body of this book and should be interpreted as inclusive of those energy and industrial facilities that have the potential for accidental explosions.

The methodology to design blast-resistant buildings uses the following steps:

1. Identify a range of potential accident scenarios that could result in blast overpressure.
2. Quantify the free field blast loads that could result at the building location.
3. Establish the design blast loads for the various surfaces of the building [walls, roofs, and sometimes floor (for elevated buildings)].
4. Set the structural performance requirements, including building functional performance, after a blast event as it relates to structural, architectural, and mechanical elements.
5. For existing buildings—assess the performance of the structure and other ancillary and architectural features, such as doors, windows, and heating, ventilation, and air-conditioning (HVAC) penetrations, and compare them to structural performance requirements.
6. For new buildings and upgrades to existing buildings—design the structure and other ancillary and architectural features to resist the design blast loads within the structural performance requirements.

Note that Steps 1 and 2 are outside of the purview of these guidelines. See Chapter 3, "Determination of Loads," for additional commentary.

Buildings in energy and industrial facilities can be intended to be occupied by personnel and/or intended to host equipment that controls the facility and its emergency systems. Blast-resistant design, or the structural strengthening of these buildings subjected to explosion hazards, is one of the measures an owner may employ to minimize the risk to people and facilities from the hazards of accidental explosions in a plant. Other mitigative or preventive measures, including siting (adequate spacing from potential explosion hazards) and hazard reduction (inventory and process controls, occupancy limitations, etc.), are not covered in this report.

1.1 BACKGROUND

Petrochemical facilities handle flammable and reactive materials, which can produce (and have) produced accidental explosions in the past. It is recognized that plant design and procedures (operations and maintenance) can reduce the likelihood of accidental explosions; however, if an accidental explosion does occur, severe consequences including safety (casualties and injuries to on-site and off-site populations) and financial loss (property damage, business interruption) could result.

A number of accidental explosions at petrochemical facilities in the past have resulted in fatalities to occupants of plant buildings. For example, the 1989 explosion in Pasadena, Texas, occurred during maintenance of a polyethylene unit and included the collapse of a control building. Losses included 23 fatalities and 120 injured. The 2005 explosion in Texas City, Texas, occurred during the restart of a refinery isomerization unit and resulted in the destruction of trailers used as temporary offices. Losses caused by this accident included 15 fatalities and 170 injured.

Other explosions that have occurred at industrial facilities have resulted in a significant number of fatalities and injuries from the severe damage or collapse of buildings. A sugar dust explosion that occurred in Port Wentworth, Georgia (2009), resulted in 14 fatalities and 39 injuries. More recent explosion accidents that have resulted in damage to buildings, injuries and fatalities include Amauy, Venezuela (2012); West, Texas (2013); Veracruz, Mexico (2016); and Cambria, Wisconsin (2017). Figures 1-1 to 1-4 show some of the extent of damage caused by some of these incidents.

During the Mexichem vapor cloud explosion (VCE) of April 20, 2016, in Coatzacoalcos, Veracruz, Mexico, there were 32 fatalities and more than 100 injured. Figure 1-3 shows a heavily damaged building in the process unit.

A review of these accidents points to the need to design occupied plant buildings to withstand explosion effects so that the building does not pose an added hazard to its occupants. This is an expression of "neutral risk" that has largely been replaced with more stringent protection performance criteria.



Figure 1-1. Port Wentworth, Georgia.
Source: Chemical Safety Board (2009).



Figure 1-2. West, Texas.
Source: US Chemical Safety Board (2013).

In addition to personnel safety, it has been common practice in the industry to consider blast resistance for buildings such as control centers, substations, and emergency response centers that may have limited or no personnel occupancy, but that house critical operations and emergency equipment required to aid in the safe shutdown and emergency response of the facility to an accidental explosion.



Figure 1-3. Veracruz, Mexico (2016).
Source: Thornton Tomasetti Database.



Figure 1-4. Cambria, Wisconsin (2017) (a) before and (b) after the accident.
Source: Chemical Safety Board (CSB.gov).

For buildings, blast loading can be the most damaging effect from an accidental explosion in a process plant. However, in addition to blast loading, such incidents can result in fires, toxic gas ingress, and projectiles that can cause damage to buildings and potentially cause harm to occupants and/or damage equipment within the building.

Historically, blast-resistant design technology in the petrochemical and other industries has evolved on two fronts, namely: (1) hazard analysis and explosion modeling, and (2) structural responses. The following describes the evolution in chronological order:

1. Equivalent static loads and conventional static design methods (Bradford and Culbertson 1967).
2. Blast loading derived using TNT equivalence and simplified dynamic design methods that take into account dynamic characteristics and ductility of structural components (Forbes 1982).
3. More complex and rational methods involving VCE models to characterize the blast loading (Pierorazio et al. 2005) and nonlinear multi-degree-of-freedom dynamic models to analyze the building structure.
4. High-fidelity physics-based numerical methods such as computational fluid dynamics (CFD), turbulent combustion models to simulate blast loading, and dynamic nonlinear finite-element (FE) models for structural response.

It should be noted that current practices within the industry include or refer to some (or all) of the approaches described previously.

1.2 PURPOSE AND SCOPE

This report is intended to provide guidelines on the various methods available for the structural analysis and design of blast-resistant buildings, both new and existing, at industrial facilities. It provides the basic considerations, principles, procedures, and details for structural analysis and design of buildings to resist blast overpressure effects. Evaluation and retrofit of existing buildings are also included. The guidelines do not address considerations regarding protection of buildings from potential thermal hazards and toxic gas or smoke ingress that may or may not accompany a VCE. However, some applicable industry references are listed subsequently, and further context is provided in Chapter 2, "General Considerations."

The report focuses primarily on "how to" design, evaluate, and retrofit buildings for blast resistance once the blast loading is defined for a postulated explosion scenario. Chapter 2, "General Considerations," discusses the basic philosophy and general considerations involved in establishing design requirements for blast resistance of buildings to resist the effects of accidental explosions in energy and industrial facilities. Chapter 3, "Determination of Loads," describes the types of explosions that may occur and the general characteristics of the resulting blast load

but does not prescribe values for design. The chapter provides a brief review of the approaches used in the industry to quantify blast loads for design purposes and gives typical examples of such loads. In Chapter 4, "Types of Construction," the types of building construction appropriate for various levels of blast resistance are discussed. The dynamic ultimate strength design criteria, including the dynamic material properties and deformation limits applicable to blast-resistant design, are covered in Chapter 5, "Dynamic Material Strength and Response Criteria."

The methods and procedures for blast-resistant design can vary considerably in terms of complexity, accuracy, cost, and efficiency from a simple conventional static design approach to a transient nonlinear, multi-degree-of-freedom dynamic design methods to a combination of CFD and finite-element analysis. To assist engineers in striking a balance among these, Chapter 6, "Dynamic Analysis Methods," provides a discussion of the various blast-resistant analysis methods, while identifying the main features, advantages, and disadvantages of each method. Chapter 7, "Design Procedures," outlines recommended procedures and provides aids for the design of the typical components of reinforced concrete, reinforced masonry, and structural steel buildings. Chapter 7 also provides some typical structural details for doors and frames, wall penetrations, and connections for steel and reinforced concrete components. Blast protection considerations for nonstructural items such as interior details, windows, openings, and HVAC ductwork are covered in Chapter 8, "Ancillary and Architectural Considerations." Chapter 9, "Evaluation and Upgrade of Existing Buildings," provides some practical measures for upgrading masonry and metal buildings, which represent some of the most common types of building construction for plants in the energy industry. Design examples are provided in Chapter 10, "Shear Wall Building Design Example," Chapter 11, "Metal Building Design Example," and Chapter 12, "Masonry Retrofit Design Example," to illustrate the use of these procedures in the design of typical buildings for blast resistance.

1.3 RELATED INDUSTRY GUIDELINES, SPECIFICATIONS, AND CODES

The design practices used by some operating companies and contractors are based on a number of existing documents dealing with this subject, including

1. PIP STC01018 (PIP 2014), *Blast Resistant Building Design Criteria*.
2. ACI 370R-14 (ACI 2014), *Report for the Design of Concrete Structures for Blast Effects*.
3. CIA (2020), *Guidance for the Location and Design of Occupied Buildings on Chemical Manufacturing and Similar Major Hazard Sites*.
4. UFC 3-340-02 (US DoD 2014), *Structures to Resist the Effects of Accidental Explosions*.
5. ASCE 59-22 (ASCE 2022), *Blast Protection of Buildings*.