based on comparison with tested systems. Variance from tested systems must be carefully considered to ensure that modifications do not invalidate forced entry test-based rating and/or acceptance. Most often, any structural changes to the system, including geometric and material variation, as well as connection detailing require retesting or certification of the modified system.

Design for ballistic protection is typically performed by specifying the use of components that have been tested according to the available test standards discussed in Chapter 10. However, for steel or other metal components, design thickness can be estimated using design methods found in UFC 4-023-07 (DoD 2008) and DOE/TIC-11268. The UFC document also provides geometric design guidance to limit sight lines to protected spaces and means of defeating high caliber ballistic threats. Testing is still necessary in most cases to certify a particular component or element can provide the necessary ballistic resistance.

**4.10.1.1 Forced Entry Resistance.** In general, forced entry protection is achieved by utilizing layers of materials that are difficult to cut, break, or remove with hand or power tools and are appropriately secured to the building structure. Attachments should be located on the interior to reduce the ability of adversaries to defeat them. The ability of a building surface to allow for adequate delay time against a forced entry depends on many factors including attack tools, number of hits and receiving element material strength, surface thickness, solidity ratio, and reinforcement configuration. RC, metal security mesh, and polycarbonate systems can provide a notable amount of forced-entry resistance. Reducing the spacing of reinforcement and mesh sizes tends to increase resistance to forced entry.

Design for forced entry typically focuses on providing materials that are difficult to penetrate with hand and/or power tools of concern and locating vulnerable hardware such as anchors, fasteners, hinges, and latches on the protected side of the component to increase the time it would take to make a passable opening in the component. Standardized delay time ranging from 5-, 15-, and 60-min corresponds to targeted LOPs. The level of forced entry resistance required depends on the established design basis threats and LOP desired for the facility.

UFC 4-020-02FA (DoD 2005) provides information relevant to the tactics and protection strategies for forced entry. For medium to very high levels of protection, the UFC requires the use of wall construction that provides the delay time (i.e., minimum to maximum response time) corresponding to the threat severity level (i.e., hand/power tools, thermal, and explosives). Refer to Chapter 2 for further discussion of design basis forced-entry threats and tactics.

**4.10.1.2 Ballistic Resistance.** The ability of a building surface to provide adequate resistance to ballistic attack depends on many factors including the ballistic attack characteristics, the surface's material strength, thickness, solidity ratio, and reinforcement configuration. Ballistic and fragment penetration resistance is usually achieved through the use of one or more layers of material that can adequately resist projectiles of the desired caliber. Materials can include specialty glass, composite fibers, magnesium, ceramics, polymers (e.g., polycarbonate and lexan), steel, aluminum, and titanium. Typically, the determination of ballistic rating for a specific construction is determined through testing; however, there is not enough testing information available for public use to guide that determination. Few published resources provide guidance to Physical Security professionals regarding the specification of ballistic resistance.

UFC 4-023-07 (DoD 2008) provides comprehensive coverage of protective design measures for resistance to direct fire weapons and correlates threat level to weapon's caliber and provides recommendations for using various construction materials to achieve different levels of protection. The UFC provides guidance based on existing data and calculations for construction required to resist typical ballistics threats. The current version of this document is available for public release through the Whole Building Design Guide website. Various chapters of UFC 4-020-02FA (DoD 2005) provide similar recommendations for minimum thickness of various protective materials for different threat severity levels (i.e., low to very high). UL 752 identifies 9 distinct ratings (i.e., protection, levels 1 to 8 + 12-gauge) that correspond to ammunition calibers ranging from 9 mm full metal jacket bullet to 12-gauge lead slug.

As previously discussed in Chapter 2, Sandia National Laboratories published a summary of empirical penetration equations that can be used to predict penetration depth for soil, rock, and concrete. The US Army has also developed the Thor equations that can describe ballistic penetration for various metals. The necessary penetration resistance depends on the design basis ballistic threats of concern and the desired LOP for the facility.

### 4.10.2 Levels of Protection and Performance Criteria

Levels of protection for ballistics and forced-entry range from low levels of protection to high levels of protection. At the lower levels of protection, the primary focus tends to be on blocking lines of sight of critical areas and targets. At medium to higher levels of protection, the criteria attempt to provide layers of penetration and hardening to mitigate or stop the design basis threats. Levels of Protection for Ballistic Resistance (BR) are predominantly based on the guidance provided in UFC 4-023-07 (DoD 2008). As an example, for a medium LOP, the objective is to prevent the projectile from perforating through the wall thickness and for it to be arrested within the wall without causing spalling on its inside (i.e., protected side) surface.

### 4.10.3 Analytical and Testing-Based Design Approaches

There are a limited set of design equations available for designing to mitigate ballistic and forced-entry tactics. As noted previously, there are a number of design equations available to mitigate ballistic threats available in UFC 4-023-07. For forced-entry resistance, acceptable protection is determined predominantly through testing. However, preliminary design strategies could be utilized to provide components and systems with strengths equivalent to components and systems that have already been tested.

Typically, the determination of forced-entry and/or ballistic resistance rating are determined through testing. Only limited testing/rating information are published and available for public use, therefore, physical security professionals may have to resort to other sources of guidance, which are mostly government provided such as the *DoS Compendium of Design Standards* and the UFC 4-020-02FA (DoD 2005) security engineering series. For further details about applicable certification and testing procedures for forced entry and ballistic resistance, refer to Chapter 10.

## 4.11 DESIGN, SPECIFICATIONS, AND CONSTRUCTABILITY CONSIDERATIONS

Protective design is most effectively applied as enhancements to a structural design that satisfies conventional gravity, wind, and seismic loading. By starting with a code-compliant design, the opportunities for an integrated design and the cost of protection are most easily identified. In this manner, blast-specific detailing requirements and constructability considerations can be addressed in collaboration with the structural engineer for the project.

### 4.11.1 Design Issues

**4.11.1.1 Proof of Concept.** It is essential for a successful design that the blast consultant, working for the design team, perform proof-of-concept calculations on delegated design elements (i.e., façade systems, prefabricated trusses, etc.) to properly represent the intended design concept in the drawings and prove that an acceptable design solution is achievable. This proof-of-concept effort is very useful when reviewing contractor submissions and requests for changes.

**4.11.1.2 Structural Engineer Duties.** The blast design engineer is responsible for providing all blast design-related information in the form of mark-ups to the code compliant design drawings and details, which are typically provided during the design development phase and back-checked during the construction documents phase. The Structural Engineer of Record (SEOR) is expected to continuously coordinate with the blast design engineer to ensure that he/she fully understand the project-specific blast protection requirements and their impacts on the structural design. Ultimately, the SEOR is responsible for incorporating all aspects of the blast-resistant design (i.e., notes, markups, details, and specifications) into the structural design package.

**4.11.1.3 Coordination with Other Design Disciplines.** For engineering projects involving blast-resistant design, it is the design manager responsibility to ensure that all disciplines of his design team are effectively coordinating with the blast design engineer to clearly understand the potential impacts on their design efforts. This coordination effort is very important to avoid potential design and construction problems that may arise at later times primarily because of the lack of understanding and/or coordination.

### 4.11.2 Performance Specifications

In general, blast hardening (i.e., enhancement or strengthening) is most effectively prescribed by the blast consultant for incorporation into design drawings; however, there may be elements of the design, such as pre-manufactured trusses, that are delegated to contractors and their subs. In addition, steel beam reaction forces may be tabulated or defined in a note that contains an equation for different boundary conditions. The detailing of steel connections is most frequently performed by the steel fabricator and the notes should include all instructions required to prevent brittle modes of failure.

Performance specifications for the delegated design of stud wall systems and light gage construction must provide all the information needed to perform the dynamic analyses. Other important blast-resistant building components that are typically described using performance specifications are glazing, curtain walls, windows, doors, and louvers. In this case, the design criteria and performance requirements of these specialty components are conveyed to the manufacturers who are responsible for designing, fabricating, and sometime testing blast-resistant products that meet the design intent. Therefore, it is of the utmost importance for the design team to work with the blast engineer to develop performance specifications that properly document the project-specific requirements for each component in a clear and complete manner.

### 4.11.3 Constructability Considerations

The SEOR is responsible for integrating blast hardening of structural components into their design documents and verifying constructability. Aside from dimensional conflicts that are resolved with the project team, constructability concerns often relate to the spacing of reinforcing bars within concrete sections, the steel connection details required to develop the member reaction forces and the welding of thick plate sections. The proposed protective design for design-build projects or projects with construction management and design assist services receive guidance from a contractor or fabricator's perspective. In general, this should reduce the number of RFI or change orders during construction. Other projects rely on the experience and expertise of the SEOR, with more extensive construction administration services likely to occur.

## REFERENCES

ACI (American Concrete Institute). 2004. *ACI detailing manual-2004*. ACI SP-66. Farmington Hills, MI: ACI.

ACI. 2005. *Tilt-up concrete construction guide*. ACI 551.1R-05. Farmington Hills, MI: ACI.

ACI. 2013. *Building code requirements and specification for masonry structures and companion commentaries*. ACI 530.1-13. Farmington Hills, MI: ACI.

ACI. 2014a. *Building code requirements for structural concrete and commentary*. ACI 318-14. Farmington Hills, MI: ACI.

ACI. 2014b. *Report for the design of concrete structures for blast effects*. ACI 370R-14. ACI 370 Committee on Design for Blast and Impact. Farmington Hills, MI: ACI.

AISC (American Institute of Steel Construction). 2013. *Design of blast resistant structures*. AISC Design Guide 26. Chicago: AISC.

AISC. 2015. *Specification for structural steel buildings*. ANSI/AISC 360-10, 4th printing. Chicago: AISC.

AISI (American Iron and Steel Institute). 2012a. *North American standard for cold-formed steel framing—General provisions*. AISI S200-12. Washington, DC: AISI.

APA (The Engineered Wood Association). 2020. *Standard for performance-rated cross-laminated timber*. ANSI/APA PRG 320-2019. Tacoma, WA: APA.

ARA. 2018. *Dynamic component modeling software (DCMS)*. Vicksburg, MS: ARA.

ASCE. 2010. *Design of blast-resistant buildings in petrochemical facilities*. ASCE Task Committee on Blast-Resistant Design. Reston, VA: ASCE.

ASCE. 2011. *Blast protection of buildings*. ASCE 59-11. Reston, VA: ASCE.

ASTM. 2014. *Standard test method for timed evaluation of forced-entry-resistant systems*. Active standard by subcommittee F12.10. ASTM F3038-14. West Conshohocken, PA: ASTM.

AWC (American Wood Council). 2015a. *National design specification for wood construction*. ANSI/AWC NDS. Leesburg, VA: AWC.

AWC. 2015b. *National design specification—Design values for wood construction*. ANSI/AWC NDS Supplement. Leesburg, VA: AWC.

AWC. 2015c. *Special design provisions for wind and seismic* ANSI/AWC SDPWS. Leesburg, VA: AWC.

Bellettia, B., J. C. Walraven, and F. Trapani. 2015. "Evaluation of compressive membrane action effects on punching shear resistance of reinforced concrete slabs." *Eng. Struct*. 95 (July): 25–39.

Bewick, B., C. O'Laughlin, and E. B. Williamson. 2013. "Evaluation of conventional construction techniques for enhancing the blast resistance of steel stud walls." *ASCE J. Struct. Eng*. 139 (11): 1992–2002.

Biggs, J. M. 1964. *Introduction to structural dynamics*. New York: McGraw-Hill.

Botte, W., R. Caspeele, D. Gouverneur, and L. Taerwe. 2014. "Influence of membrane action on robustness indicators and a global resistance factor design." In *Proc., IABMAS 2014—Bridge Maintenance, Safety, Management and Life Extension*, Shanghai, China, July 7-11. Boca Raton, FL: CRC Press. pp. 2038–2046.

Braimah, A. 2013. "*Blast Load Effects on Historic Masonry Buildings." Technical Report DRDC CSS CR 2013-045. North York, ON: Defence Research and Development Canada (DRDC)*.

Browning, R. S., J. S. Davidson, and R. J. Dinan. 2008. *Resistance of multi-wythe insulated masonry walls subjected to impulse loads—Vol. 1*. Rep. AFRL-RX-TY-TR-2008-4603. Patterson Air Force Base, OH: Air Force Research Laboratory

Browning, R. S., R. J. Dinan, and J. S. Davidson. 2014. "Blast resistance of fully grouted reinforced concrete masonry veneer walls." *J. Perform. Constr. Facil* 28 (2) 228–241.

Bruhl, J., and A. H. Varma. 2018. "Experimental evaluation of steel–plate composite walls subject to blast loads." *J. Struct. Eng*. 144 (9): 04018155.

Bryant, L., J. Erekson, and K. Herrle. 2013. "Are you positive about negative phase?" In *Proc., Structures Congress 2013*, 103–114. Reston, VA: ASCE.

Chen, L. 2018. "Non-dimensional pressure–impulse diagrams for blast-loaded reinforced concrete beam columns referred to different failure modes." *Adv. Struct. Eng*. 21 (14): 396–414.

Consunji, A. C., J. M. Nickerson, C. M. Newberry, C. J. Naito, and J. S. Davidson. 2015. "Peak transient shear and connection demand prediction for the blast load design of slender precast panels." In *Proc., 3rd Int. Conf. on Protective Structures*. Organized by the International Association for Protective Structures (IAPS) at the University of Newcastle, Australia.

Cramsey, N., and C. J. Naito. 2007. "Analytical assessment of the blast resistance of precast, prestressed concrete components." *PCI J*. 52 (6): 67–80.

Davidson, J. S., J. M. Hoemann, H. H. Salim, J. S. Shull, R. J. Dinan, M. I. Hammons, and B. T. Bewick. 2011. *Full-scale experimental evaluation of partially grouted, minimally reinforced CMU walls against blast demands*. Rep. AFRL-RX-TY-TR-2011-0025. Patterson Air Force Base, OH: Air Force Research Laboratory.

DoD (US Department of Defense). 2002. *Design and analysis of hardened structures to conventional weapons effects*. UFC 3-340-01. Washington, DC: DoD.

DoD. 2004. "Basic guidelines for hardening of new chemical military facilities." UFC 3-340-13. Washington, DC: DoD.

DoD. 2005. *Security engineering: Concept design*. UFC 4-020-02FA. Washington, DC: DoD.

DoD. 2008. *Design to resist direct fire weapons effects*. UFC 4-023-07. Washington, DC: DoD.

DoD. 2012. *Minimum antiterrorism standoff distances for buildings.* UFC 4-010-01. Washington, DC: DoD.

DoD. 2014. *Structures to resist the effects of accidental explosions, with change* 2. UFC 3-340-02. Washington, DC: DoD.

Dusenberry, D. O. (Ed.) 2010. *Handbook for blast-resistant design of buildings*. Hoboken, NJ: Wiley.

Dwight, J. 1999. *Aluminum design and construction*. 1st ed. New York: E & FN Spon.

FEMA 277. 1996. "The Oklahoma City Bombing: Improving building performance though multi-hazard mitigation." US Federal Emergency Management Agency- Mitigation Directorate, August 30. Washington, DC: FEMA.

GSA (US General Service Administration). 2011. *GSA interpretation of the ISC (FOUO)*. Washington, DC: GSA.

Hoemann, J. M., J. S. Shull, H. H. Salim, B. T. Bewick, and J. S. Davidson. 2014. "Performance of partially grouted, minimally reinforced CMU cavity walls against blast demands. II: Performance under impulse loads." *J Perf. Constr. Facil*. 29(4). https://doi.org/10.1061/(ASCE)CF.1943-5509.0000509

Huang, X., H. Bao, Y. Hao, and H. Hao. 2017. "Damage assessment of two-way RC slab subjected to blast load using mode approximation approach." *Int. J. Struct. Stab. Dyn*. 17 (1): 1750013.

Jacques, E. 2014. "RCBlast version 0.5.1 computer program." Accessed February 19, 2021. http:/www.rcblast.ca.

Johnson, C. F. 2013. "Concrete masonry wall retrofit systems for blast protection." Ph.D. thesis, Texas A&M University, Dept. of Civil and Environmental Engineering.

K&C (Karagozian & Case). 2013. *CBARD: Column blast analysis and retrofit design*. Glendale, CA: K&C.

Langdon, G. S., and G. K. Schleyer. 2004. *Scale testing of profiled stainless steel blast walls*. Structures under Shock and Impact VIII. Southampton, UK: WIT Press.

Langdon, G. S., and G. K. Schleyer. 2005a. "Inelastic deformation and failure of profiled stainless steel blast wall panels. Part I: Experimental investigations." *Int. J. Impact Eng*. 31 (4): 341–369.

Langdon, G. S., and G. K. Schleyer. 2005b. "Inelastic deformation and failure of profiled stainless steel blast wall panels. Part II: Analytical modeling considerations." *Int. J. Impact Eng*. 31 (4): 371–399.

Langdon, G. S., and G. K. Schleyer. 2006. "Inelastic deformation and failure of profiled stainless steel blast wall panels. Part III: Finite element simulations and overall summary." *Int. J. Impact Eng*. 32 (6) 988–1012.

Louca, L. A., and J. W. Boh. 2004. *Analysis and design of profiled blast walls*. Research Rep. 146. Technical Rep. Prepared by Imperial College of London for the Health and Safety Executive (HSE), London.

Louca, L. A., and J. Friis. 2001. *Modelling failure of welded connections to corrugated panel structures under blast loading*. Technical Rep. Prepared by Imperial College of London for the Health and Safety Executive (HSE), London.

LSTC (Livermore Software Technology Corporation). 2012. *LS-DYNA: A FEM program for nonlinear dynamic analysis of the inelastic structures*. Livermore, CA: LSTC.

Mark, K., M. K. Weaver, C. M. Newberry, L. Podesto, and C. O'Laughlin. 2018. "Blast testing of loaded cross-laminated timber structures." In *Proc. 2018 ASCE Structures Congress*, April 19–21, 2018, Fort Worth, Texas. Reston, VA: ASCE.

McDonald, B., H. Bornstein, G. S. Langdond, R. Curry, A. Daliria, and A. C. Orificia. 2018. "Experimental response of high strength steels to localised blast loading." *Int. J. Impact Eng*. 115: 106–119.

Naito, C., M. Beacraft, J. Hoemann, J. Shull, H. Salim, and B. Berwick. 2014. "Blast performance of single-span precast concrete sandwich wall panels." *J. Struct. Eng*. 140(12): December.

Naito, C., J. Hoemann, M. Beacraft, and B. Bewick. 2012. "Performance and characterization of shear ties for use in insulated precast concrete sandwich wall panels." *J. Struct. Eng*. 138 (1): 52–61.

Naito, C., J. Hoemann, J. Shull, M. Beacraft, B. Bewick, and M. Hammons. 2011a. *Dynamic performance of non-load bearing insulated concrete sandwich panels subject to external demands*. Airbase Technologies Division Technical Rep. AFRL-RX-TY-TR-2011-0039. Patterson Air Force Base, OH: Air Force Research Laboratory.

Naito, C., J. Hoemann, J. Shull, A. Saucier, H. Salim, B. Bewick, and M. Hammons. 2011b. *Precast/prestressed concrete experiments performance on* *non-load bearing sandwich wall panels*. Wright-Patterson Air Force Base, OH: Air Force Research Laboratory.

Naito, C. J., and C. Oswald. 2015. "PCI design handbook: Appendix A: Blast-resistant design of precast, prestressed concrete components." *PCI J*. 59 (1): 137–159.

NCMA (National Concrete Masonry Association). 2014. *Design of concrete masonry walls for blast loading*. TEK 14-21A. Herndon, VA: NCMA.

Nickerson, J. M., P. A. Trasborg, and C. J. Naito. 2015. "Finite element evaluation of blast design response criteria for load-bearing precast wall panels." *Int. J. Prot. Struct*. 6 (1): 155–174.

Nickerson, J. M., P. A. Trasborg, C. J. Naito, C. M. Newberry, and J. S. Davidson. 2014. "Finite element assessment of methods for incorporating axial load effects into blast design SDOF analyses of precast wall panels." *J. Perform. Constr. Facil* 29 (5): B4014006.

Nickerson, J. M., P. A. Trasborg, C. M. Newberry, C. J. Naito, and J. S. Davidson. 2013. "Blast design considerations for load-bearing PC/PS sandwich panels used in multi-story total precast construction." In *Proc. 10th Int. Conf. on Shock & Impact Loads on Structures*. ASCE, November 25–26, 2013, Singapore.

Orbovic, N., J. Grimes, K. El-Domiaty, and J. Florek. 2017. "ASME blast tests on Pre-stressed concrete slabs." In *Trans., SMiRT-24, International Association for Structural Mechanics in Reactor Technology (IASMiRT)*, August 20–25, 2017, Busan, South Korea.

Oswald C., and M. Bazan. 2014. "Performance and blast design for non-load bearing precast concrete panels." In *Proc., 2014 ASCE Structures Congress*, 143–154. April 3–5, 2014, Boston. Reston, VA: ASCE.

Oswald, C., and W. Zehrt. 2010. "Update to UFC 3-340-02 for blast resistant design of masonry components." In *Proc., 34th Department of Defense Explosives Safety Board Seminar*, Portland, Oregon, July 13-15.

Panedpojaman, P. 2012. "Modified quasi-static, elastic–plastic analysis for blast walls with partially fixed support." *Eng. J*. 16 (5): 45–56.

PCI. 2010. *PCI design handbook—Precast and prestressed concrete*. 7th ed. Chicago: PCI.

PCI (Precast/Prestressed Concrete Institute). 2014. "PCI design handbook: Appendix A: Blast-resistant design of precast, prestressed concrete components." *PCI J.*, Winter, 137–159.

Ritchie, C. B., J. A. Packer, M. V. Seica, and X. L. Zhao. 2017. "Behavior of steel rectangular hollow sections subject to blast loading." *J. Struct. Eng*. 143 (12): 04017167.

Sagaseta, J., P. Olmati, K. Micallef, and D. Cormie. 2017. "Punching shear failure in blast-loaded RC slabs and panels." *Eng. Struct*. 147: 177–194.

Shin, J., A. S. Whittaker, and A. J. Aref. 2015. "Near-field blast assessment of reinforced concrete components." *Int. J. Prot. Struct*. 6 (3): 487–508.

Smith, N. L. 2014. "Response of two-way reinforced masonry infill walls under blast loading." M.Sc. thesis, McMaster University, Dept. of Civil Engineering.

UL (Underwriters Laboratories). 2005. "Standard for bullet reisitant equipment." UL Standard. UL 752, Edition 11.

USACE ERDC (US Army Corps of Engineers Engineer Research and Development Center). 2005. *ConWep: Conventional weapons effects*. Vicksburg, MS: USACE ERDC.

USACE PDC (US Army Corps of Engineers Protective Design Center). 2006. *Single degree of freedom structural response limits for antiterrorism design*. Technical Rep. PDC-TR 06-08. Washington, DC: USACE PDC.

USACE PDC. 2008a. *Component explosive damage assessment workbook*. CEDAW v2. Washington, DC: USACE PDC.

USACE PDC. 2008b. *Methodology manual for the single degree of freedom blast effects design spreadsheets (SBEDS)*. PDC-TR 06-01 Rev 1 with Appendices. Technical Rep. Washington, DC: USACE PDC.

USACE PDC. 2012. *Methodology manual for the single degree of freedom blast effects design spreadsheets (SBEDS)*. PDC-TR 06-01 Rev 2 with Appendices. Technical Rep. Washington, DC: USACE PDC.

USACE PDC. 2015a. *Single degree of freedom blast effects design spreadsheets (SBEDS)*. SBEDS v5.1. Washington, DC: USACE PDC.

USACE PDC. 2015b. *Single-degree-of-freedom blast effects design spreadsheets for windows*. SBEDSW v1.1.1. Washington, DC: USACE PDC.

USACE PDC. 2018. *Analysis guidance for cross-laminated timber construction exposed to airblast loading*. PDC-TR 18-02. Washington, DC: USACE PDC.

Viau, C., and G. Doudak. 2016. "Investigating the behavior of light-frame wood stud walls subjected to severe blast loading." *J. Struct. Eng*. 142 (12): 04016138.

Yu, W. W., and R. A. LaBoube. 2010. *Cold-formed steel design*. 4th ed. Hoboken, NJ: Wiley.

Zapata, B. J. 2012. "Full-scale testing and numerical modeling of a multi-story masonry structure subjected to internal blast loading." Ph.D. thesis, University of North Carolina-Greensboro¸ Dept. of Civil and Environmental Engineering.