A look at some of the major changes to design requirements, including new structural integrity provisions, in the 2016 *Specification*.

specwise

STRUCTURAL INTEGRITY—AND REORGANIZATION

BY RAMON GILSANZ, SE, PE, SANAZ SAADAT, PE, PhD, STEVEN J. FENVES, PhD, ARVIND GOVERDHAN, PhD, JEROME F. HAJJAR, PE, PhD, AND CARLO R. LINI, PE

THE 2016 *SPECIFICATION FOR STRUCTURAL STEEL BUILDINGS* (ANSI/AISC 360-16), now available at www.aisc.org/specifications, includes important improvements over the last edition that reflect ongoing advances in the world of steel construction.

Here, we'll review some of the more significant changes to Chapter B, specifically Section B3. These include the addition of new provisions for structural integrity and revisions to the charging language for ponding provisions, as well as a reorganization of the initial sections of the chapter. A comparison between the new structural integrity provisions in the *Specification* and requirements in other design standards is also provided.

Design Requirements

The opening sections of Chapter B on Design Requirements, Sections B1 through B3, have traditionally served to provide directions to the rest of the *Specification* through provisions commonly referred to as "charging language." Over the years, these sections have been growing and shrinking as provisions are added throughout the *Specification*, sending tentacles in different directions, encapsulating new material and dropping material that is no longer applicable. For example, in prior editions, provisions for Types of Construction were dropped, as were explicit listing of loads and load combinations; the chapter instead refers to requirements stipulated in the applicable building code, or in the absence of one, ASCE 7. On the other hand, since the 2005 AISC *Specification*, these sections have introduced the two parallel design bases of load and resistance factor design (LRFD) and allowable strength design (ASD).

The revised Sections B1 through B3 provide no new material except for the structural integrity provisions described below, but do present an improved logical and consistent organization and wording of the relevant material, essentially as follows:

- General Provisions
- Loads and Load Combinations
- Design Basis
  - Design for Strength
    - Design of Connections and Supports
    - Design of Diaphragms and Collectors
    - Design of Anchorages to Concrete
  - Design for Stability
  - Design for Serviceability
  - Design for Structural Integrity
  - Design for Ponding
  - Design for Fatigue
  - Design for Fire Conditions
  - Design for Corrosion Effects

The reorganization of Section B3 is expected to remain appropriate for future editions of the *Specification* and will better accommodate potential future additions to this section as they may arise.






Ramon Gilsanz is a partner with Gilsanz Murray Steficek, **Sanaz Saadat** is a senior engineer with Gilsanz Murray Steficek, **Steven J. Fenves** is professor emeritus at Carnegie Mellon University, **Arvind Goverdhan** is the owner of Stanley D. Lindsey and Associates and vice chair of AISC Task Committee 3 on Loads, Analysis and Systems, **Jerome F. Hajjar** is the CDM Smith Professor and department chair in the Department of Civil and Environmental Engineering at Northeastern University and the chair of AISC Task Committee 3 and **Carlo Lini** is an advisor in AISC's Steel Solutions Center and secretary of AISC Task Committee 3.

Design for Ponding

The 2005 AISC *Specification* introduced a safe harbor for ponding that appeared to preclude the need to ensure adequate strength and stability through structural analysis under certain conditions. Earlier editions of the *Specification* "required *sufficient* slope towards points of free drainage or adequate individual drains to prevent the accumulation of rainwater." In the 2005 AISC *Specification*, the term *sufficient* slope was replaced by the phrase "slope of ¼ in. per ft (20 mm per meter) or greater."

Fisher and Pugh present an example that shows a ¼ in. per ft roof slope does not always result in sufficient slope to free drainage. As a result, the safe harbor limit of a "slope of ¼ in. per ft (20 mm per meter) or greater" has been deleted, and the 2016 AISC *Specification* states: "The roof system shall be investigated through structural analysis to ensure strength and stability under ponding conditions, unless the roof surface is configured to prevent the accumulation of water."

Structural Integrity

Disproportionate collapse can be described as a sequence of failures as a result of an initial damage to a relatively small portion of the structure. The extent of the failures is disproportionate to the damage that initiated the collapse.

The initiating damage can be caused by abnormal loading events that are not considered routinely in design. These loads can be categorized as pressure loads (such as gas-related explosions, bomb explosions, tornado wind pressures), impact loads (such as motor vehicle collision with building, missile impact), deformation-related loads (such as fire-induced deformations or foundation subsidence) and loads induced as a result of damages due to faulty practice.

There are various strategies for reducing the disproportionate collapse vulnerability of the structure that can generally be categorized into event control, direct design and indirect design methods. For the disproportionate collapse to happen, several events have to occur in sequence. The first is the occurrence of the damaging event; second, the damaging event has to create local damage; and finally, the local damage has to extend through the structure to cause the disproportionate collapse.

The probability of collapse as explained above can be defined mathematically using the following equation:

$$P(C) = P(C \mid LD)\, P(LD \mid H)\, \lambda_H \qquad (1.1)$$

in which $P(C)$ is the probability of structural collapse, $P(C \mid LD)$ is the probability of collapse conditioned on the local damage, $P(LD \mid H)$ is the probability of local damage given the occurrence of the potentially damaging event H, and λ_H is the probability of occurrence of event H.

Event control methods are safety measures that reduce the probability of the damaging event or reduce the effect of the event.

Structural methods are divided in direct design methods and indirect design methods.

Direct design methods are structural measures that reduce the probability of local damage or the progress of the local damage through the structure. These methods explicitly consider the resistance to disproportionate collapse in the design and are categorized into the specific local resistance method and the alternative load path method.

The specific local resistance approach reduces the probability of local damage in the structure due to the occurrence of a damaging event. Critical structural elements are designed to have sufficient strength to resist the specified levels of threat.

The alternative load path method reduces the probability that the local damage extends through the structure. The structural system is designed to develop an alternative load carrying path following the loss of the primary load bearing component.

Indirect methods are prescriptive approaches to improve the structures resistance against disproportionate collapse through minimum levels of strength, continuity and ductility. General structural integrity provisions in various design standards are examples of the indirect methods. Providing integrated system of ties, ductile detailing, redundant structural systems, catenary action of the floor slab, etc. are among the suggestions or requirements that are listed in the current design standards to improve the structural integrity.

New Provisions for Structural Integrity

The 2016 AISC *Specification* has expanded the structural integrity provisions applicable to connection design in Section B3.9. As stated in Section B3.9, these provisions should be considered where required by the applicable building code. Reference is made to Section 1615 of the *International Building Code*, which assigns these requirements to high-rise buildings in risk category III or IV. These new provisions include providing a minimum specified nominal tensile strength for column splices, beam and girder end connections and end connections of members bracing columns:

a) Required minimum nominal tensile strength for a column splice is equal to the total gravity load (dead plus live loads) for the area tributary between the column splice and the splice or base immediately below. If live load reduction is to be used, it should be the same as that used for the design of the connections of the floor members framing to the column.
b) Required minimum nominal tensile strength for beam and girder end connections is two-thirds of the required vertical shear strength according to section B3.1 (LRFD) or the required vertical shear strength according to section B3.2 (ASD) for design, but should not be less than 10 kips in either case.
c) Required minimum nominal tensile strength for end connections of members bracing columns is 1% of two-thirds of the required column axial strength at that level for design according to LRFD, or 1% of the required column axial strength at that level for design according to ASD.

These requirements are specified to be evaluated independently of other strength requirements.

References

[1] AISC (2016). *Specification for Structural Steel Buildings*, ANSI/AISC 360-16, American Institute of Steel Construction, Chicago, Illinois.

[2] American Society of Civil Engineers (2010). *Minimum Design Loads for Buildings and Other Structures*, ASCE 7-10, American Society of Civil Engineers, Reston, Virginia.

[3] Fisher, J.W. and Pugh, C.W. (2007). "Technical Digest 3: Structural Design of Steel Joist Roofs to Resist Ponding Loads," Steel Joist Institute, Myrtle Beach, South Carolina.

[4] Leyendecker, E. V. and Ellingwood, B. R. (1977). "Design Methods for Reducing the Risk of Progressive Collapse in Buildings," Building Science Series 98, National Bureau of Standards, Washington, DC.

[5] Leyendecker, E. V. and Burnett, E. F. P (1976). "The Incidence of Abnormal Loading in Residential Buildings," Building Science Series 89, National Bureau of Standards, Washington, DC.

[6] Ellingwood, B.R., Smilowitz, R., Dusenberry, D.O., Duthinh, D., Carino, N. (2007). "Best Practices for Reducing the Potential for Progressive Collapse in Buildings", NISTIR 7396, National Institute of Standards and Technology, Technology Administration, U.S. Department of Commerce, Gaithersburg, Maryland.

[7] International Code Council (2015). *International Building Code*, International Code Council, Inc., Country Club Hills, Illinois.

[8] U.S. Army Corps of Engineers, Naval Facilities Engineering Command, Air Force Civil Engineer Support Agency, 2013, "Unified Facilities Criteria (UFC), Design of Buildings to Resist Progressive Collapse", UFC 4-023-03, U.S. Army Corps of Engineers, Washington, DC.

[9] Main, J. A. (2014). "Composite Floor Systems under Column Loss: Collapse Resistance and Tie Force Requirements", *Journal of Structural Engineering*, ASCE, Vol. 140, No. 8.

[10] Stevens, D. (2008). "Assessment and proposed approach for tie forces in framed and load-bearing wall structures." *Final Report, Prepared for Security Engineering Working Group*, Protection Engineering Consultants, Dripping Springs, Texas.

[11] AISC (2010). *Specification for Structural Steel Buildings*, ANSI/AISC 360-10, American Institute of Steel Construction, Chicago, Illinois.

[12] New York City (2014). *New York City Building Code*, International Code Council, Inc., New York City Department of Buildings, New York, NY.

Providing minimum tensile strength for connections and splices improves the continuity and ductility in the structure and reduces the chance of its failure when subjected to unanticipated tension loads caused by extraordinary events such as failure of an adjacent structural member, impact loads on columns, etc.

There is significant ongoing research, and as the results become available, future editions of the *Specification* may incorporate the newer findings. Currently, there is an effort to confirm what type of connections can carry the tie forces while undergoing rotations of 0.2 rad (11.3°) and the UFC 4-023-03 now requires that tie forces go through the floor and roof system.

The Section B3.9 provisions are in addition to the general structural integrity design requirements for fire conditions that were stated in the 2010 AISC *Specification*, Appendix 4, Section 4.2.4.1, and now appear in the 2016 AISC *Specification* Appendix 4, Section 4a. These provisions include requirements: to provide adequate strength and deformation capacity when subjected to fire within the prescribed limits of deformation; for the structural system to sustain local damage and remain stable as a whole; and for providing a continuous load path to transfer all forces to the final point of resistance.

Existing Structural Integrity Provisions

Presently, different codes contain provisions that relate to steel construction and address structural integrity. The AISC *Specification* was developed with knowledge of this prior work. Following is a summary of some of the integrity provisions found in two prominent building codes:

ASCE 7–10. Section 1.4 in ASCE 7-10 provides general structural integrity provisions including continuous load path, load combinations with notional loads for integrity checks, minimum lateral forces and connections to supports. Section 2.5 provides load combinations to be used for checking the structure for extraordinary events.

New York City Building Code (NYCBC). New York's code has similar, but in some cases more stringent, structural integrity provisions for steel structures compared to the new provisions in the 2016 AISC *Specification*. These provisions are stated in Section BC 2212:

a) Required minimum nominal tensile strength for column splice is equal to the largest design gravity load reaction applied to the column at any floor level located within four floors below the splice (Section 28.2-2212.2.1).

b) Required minimum nominal tensile strength for beam and girder end connections is the available vertical shear strength of the connection at either end, but not less than 10 kips. Shear force and axial tensile force need not act simultaneously for the connection design (Section 28.2-2212.2).

c) Required minimum nominal tensile strength for elements bracing compression members is 2% of the required compressive strength of the member being braced, but not less than 10 kips. Shear force and axial tensile force need not act simultaneously for the connection design. Where more than one element braces a compression member at a point in one direction, each element and connection should have a minimum available tensile strength equal to 1% of the required compressive strength of the member being braced, but not less than 10 kips (Section 28.2-2212.2).

According to NYCBC Section BC 2212, the only exemption from providing the abovementioned tie-force capacity requirements are one-story structures less than 5,000 sq. ft and not exceeding 15 ft in height, and structures in occupancy group category $R = 3$ (which are one- and two-family dwellings, as defined in Section 28.2-310.1.3) not more than three stories in height.

In addition, some minimum requirements for bolted connections and composite slab construction are provided in the same section.

NYCBC also provides additional structural integrity provisions including prescriptive requirements for specific cases of vehicular impact and gas explosions in Section BC 1615 as well as key element analysis for the buildings that qualify for this analysis as stated in Section BC 1616.

A Consistent Framework

Section B3 of the *Specification* has been reorganized to provide a consistent framework for introducing charging language and design requirements for the *Specification*. If water is impounded on a roof, design for ponding must be considered regardless of the roof slope. Also, additional provisions related to structural integrity have been included as a result of recent efforts by AISC to take steps towards reducing the possibility of disproportionate collapse with minimal additional cost to the project. As more research results become available, these structural integrity provisions may be developed further to more effectively control the risks associated with disproportionate collapse of structures due to unexpected loading events. ■