

Lightning Protection Systems for Concrete Structures

by Jennifer Morgan and Michael Chusid

Lightning is an electrical discharge between the atmosphere and earth that transmits tens of thousands of amperes of current. The electric potential can be in the millions of volts, so lightning will surge through anything it hits, including concrete structures, through the path of least resistance to the ground. When struck, concrete's electrical resistance generates instantaneous and extreme heat that can vaporize moisture in the concrete, causing violently expansive forces that can spall or fracture the concrete. Further, the heat generated during the strike can melt siliceous minerals, creating weaknesses in the concrete.

Lightning can ignite fires or spark explosions that can devastate a structure. Strikes can also cause chunks of concrete to fall or become airborne missiles that can injure people and damage lower portions of a structure (Fig. 1). Longer-term effects can include aggravation of weaknesses in previously distressed structures, including acceleration of corrosion. Nonstructural consequences of lightning can include damage to building contents, damage to circuits in equipment and building systems, and even electrocution of building occupants.

A 2008 compilation by the National Lightning Safety Institute included estimates of the annual damage caused by lightning.¹ In the United States alone, the data support an estimate of \$5 to 6 billion of damage. The economic ramifications of this puts lightning damage on par with major hurricanes, floods, and other catastrophic meteorological events.

The scope of this mayhem is not widely acknowledged because individual lightning strikes seldom garner the media attention given to regional disasters; yet lightning's impact on affected businesses, communities, and infrastructure can be just as grave. The true magnitude of lightning damage is also underestimated because damage, especially to electronic components, is often misattributed.



Fig. 1: Lightning frequently attaches to buildings at rooftop corners where, according to a rolling sphere analysis, the building is more vulnerable. Although the lightning strike that hit this building resulted in a small area of damage at the point of entry, the building's electrical systems were damaged and flying debris endangered people on the patio below. The building did not include a strike termination device within 24 in. (0.6 m) of the corner, as is required in nationally recognized standards for lightning protection systems (photo courtesy of East Coast Lightning Equipment, Inc.)

Further, the incidence of lightning-related damage may be increasing as climate change impacts the distribution and intensity of thunderstorms. Lightning protection must, therefore, be included in sustainability and resilience planning for buildings and communities.

Fortunately, lightning protection systems are effective and economical when designed and installed in accordance with standards and documents issued by the National Fire

Protection Association (NFPA), UL (formerly known as Underwriters Laboratories), the Canadian Standards Association (CSA), and the Lightning Protection Institute (LPI). These documents include:

- NFPA 780²;
- UL 96A³;
- CSA B72⁴; and
- LPI 175.⁵

Lightning Risk Assessment

The design process for a lightning protection system typically begins with a lightning risk assessment conducted using protocols specified in NFPA 780. A lightning protection system should be used when a structure's vulnerability to lightning is greater than the tolerable risk.

Factors affecting vulnerability include the region's topography and annual lightning flash density (strikes/km²) as well as the structure's projected area, height, and proximity to taller structures or trees.

Risk, the other side of the assessment equation, is affected by the conductivity and combustibility of roofing and the structural system (the latter is a factor in favor of concrete); value and combustibility of the contents; ease of evacuation; the owner's assessment of the need for operational continuity; and environmental hazards that may precipitate from a lightning strike.

Reference 6 provides a risk calculator based on NFPA's simplified risk assessment protocols (Fig. 2). This tool can be used to generate a report with recommendations for a lightning protection system for a structure, and the report can be shared with the building owner as well as serve as the basis for decision-making.

Regardless of calculated risk, however, NFPA 780 calls for a lightning protection system if a project will have or contain:

- Assembly occupancy (the presence of large crowds);
- A need for continuity of critical services;
- A location with a high lightning flash frequency;
- Tall, isolated structures;
- Explosive or flammable building contents;
- Contents with irreplaceable cultural heritage; or
- Regulatory or insurance requirements for such a system.

Lightning Protection Components

A lightning protection system provides a network of low-resistance paths that allow lightning to safely pass through a building. The paths must be in accordance with national standards and, except as otherwise allowed, components must be listed for compliance with ANSI/CAN/UL 96.⁷

Components are typically made of highly conductive copper, copper alloy, or aluminum, and they should be selected based on compatibility with adjacent materials. For example, copper cannot be in contact with steel or aluminum due to galvanic action, and aluminum should not be embedded in concrete due to its alkalinity.



Fig. 2: Online apps are available for conducting lightning risk assessment in accordance with NFPA 780 protocols. The user sketches the building's horizontal projected area, enters the height of each roof area, and answers seven multiple-choice questions based upon information that is usually available early in the design process. The app calculates the building's vulnerability and risk and prepares a report indicating whether a lightning protection system is recommended (illustration courtesy of East Coast Lightning Equipment, Inc.)

While rainwater flowing over exposed copper can stain concrete, this is seldom a problem with lightning protection systems; rainwater passing over vertical down conductors drains quickly, without much opportunity for copper ions to cause stains. Moreover, good practice calls for exposed conductors to be installed in corners or along other architectural edges where the conductors will be less visible. Still, further considerations may be prudent in damp locations where marine or polluted atmospheres are likely to accelerate staining. The concrete can be treated with water repellants, or the conductors can be plated with tin or nickel to enhance corrosion resistance. Plating can also be used for aesthetic reasons where a bright finish is preferable to the natural or patinated color of copper.

Note that products designed for use in normal electrical power systems are undersized and unsuitable for use in lightning protection systems. Specifiers are also advised to be skeptical of lightning protection devices that are claimed to allow greater spacing than permitted under NFPA 780.

A Complete System

A complete lightning protection system includes five primary types of components plus numerous fasteners, clamps, and other accessories (as shown in Fig. 3).

Strike terminations

Air terminals, formerly called lightning rods, rise at least 10 in. (254 mm) above other building elements to provide a contact point for lightning discharges. NFPA 780 requires air

Typical Commercial Lightning Protection System

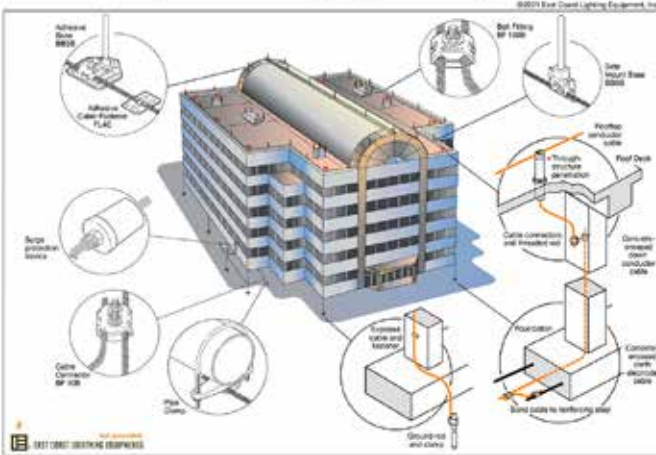


Fig. 3: A lightning protection system must create a network of paths that can safely conduct lightning through a building without causing damage. Components must be listed by UL for specific use in lightning protection systems (illustration courtesy of East Coast Lightning Equipment, Inc.)

terminals to be located at no more than 20 ft (6 m) on-center along ridges, parapets, and other high points on a building. Large roofs also require air terminals located 50 ft (15 m) on center in the field of the roof. A “rolling sphere” analysis per Section 4.8.3 of NFPA 780 will determine where air terminals are also required on rooftop equipment, along eaves, and at building appurtenances. Note, however, that permanent exterior metal components (such as those as shown in Fig. 4) can also be used as strike termination devices if they meet requirements set forth in NFPA 780.

Conductors

Braided or twisted multistrand cables are typically used as lightning conductors to interconnect air terminals and as down conductors to ground. Down conductors are spaced not more than 100 ft (30 m) around the building perimeter; a minimum of two down conductors are required for a building. Tall concrete structures also require intermediate-level conductor loops around their perimeters (Fig. 5).



Fig. 4: Exterior metal railings and posts such as these on One Bennett Park, Chicago, IL, USA, can be used as strike termination devices (photo courtesy of Robert A.M. Stern Architects)



Fig. 5: To help equalize the electrical potential throughout the building, NFPA 780 requires that tall reinforced concrete structures include loop conductors, interconnected with down connectors, at vertical intervals not exceeding 200 ft (60 m) (photo courtesy of Boston Lightning Rod Co., Inc.)



Fig. 6: A conduit will serve as part of a through-roof penetration device connecting lightning conductors on the roof to down conductors below (photo courtesy of HLP Systems, Inc.)

Conductors can be installed in direct contact with combustible materials and do not require thermal or electrical protection. Weather-resistant, through-structure penetration devices may be required where conductors pass through roofing or walls (Fig. 6). Copper lightning conductor cables can be embedded in concrete, pulled through conduits in the concrete, or mounted on concrete surfaces. Embedment conceals conductors to meet aesthetic considerations, and it provides a secure, permanent installation that is protected against damage and theft. However, the process of embedding conductors requires close coordination with the lightning protection installer and other subtrade contractors (Fig. 7).

Conductors can also be concealed in conduit; however, cables in conduit are vulnerable to theft. On some construction projects, the number of jobsite visits by the lightning protection installer may be reduced if conduit is installed by electricians when they install other conduit. The lightning protection installer can pull the cables later, although this can be problematic if conduits are knocked out of alignment or blocked by concrete.

Conductors can be mounted on the interior or exterior surface of walls when installing systems on existing structures, when aesthetics are not paramount, or when embedded installation isn't practical. In such cases, however, conductors within 6 ft (1.8 m) of grade must be enclosed in conduit for protection.

On precast concrete structures, conductors can often be run between panel joints where they are concealed and protected.

While reinforcing bars can also be used to create conductive paths, this is not ideal. The bar placers and the



(a)



(b)



(c)

Fig. 7: Embedment of conductors requires close coordination between subtrade contractors: (a) a copper-clad steel ground rod, in the foreground, has been welded to a copper conductor cable that has been pulled through conduit for subsequent encasement in a concrete footing and column (photo courtesy of Mr. Lightning); (b) a copper cable ground loop has been placed in a footing form and routed through a conduit for subsequent connection to a steel column that will serve as a down connector extending to the roof level (photo courtesy of Lightning Protection Systems, Inc. of Tampa); and (c) lighting conductor cables and conduit have been installed along with reinforcing bars, post-tensioning tendons, and electrical conduit in a column joint (photo courtesy of Guardian Lightning Protection)

lightning protection installers may have conflicting priorities that can make it difficult to assign responsibility and ensure performance. Also, rough handling of reinforcing bars and the force of placing concrete can jostle bars sufficiently to disrupt electrical continuity between bars. However, if reinforcing bars are to be used for lightning protection, members must be at least 1/2 in. (12.7 mm) in diameter and adjacent bars must be joined by welding or UL-approved clamps. Mill scale, rust, and nonconductive coatings must be removed before making splices, and bar bends must have 8 in. (203 mm) or larger radii.

Grounding

Each down conductor must be connected to a ground electrode. In most buildings, these electrodes are copper-clad steel ground rods driven 10 ft (3 m) into the earth (Fig. 7(a)). Alternatively, the electrode can be a copper conductor cable installed as a ground loop around the building's foundation or embedded in the concrete foundation itself (Fig. 7(b)). On this topic, NFPA 780 states:

“4.13.3 Concrete-Encased Electrodes. Concrete-encased electrodes shall be used only in new construction.

4.13.3.1 The electrode shall be located near the bottom of a concrete foundation or footing that is in direct contact with the earth and shall be encased by not less than 2 in.

(50 mm) of concrete.

4.13.3.2* The encased electrode shall consist of one of the following:

(1) Not less than 20 ft (6 m) of bare copper main-size conductor; and

(2) At least 20 ft (6 m) of one or more steel reinforcing bars or rods not less than 1/2 in. (12.7 mm) in diameter that have been effectively bonded together by welding, structural mechanical coupling, or overlapping 20 diameters and wire tying.

4.13.3.3 A test or connection point shall be provided on each concrete-encased electrode to enable periodic maintenance and testing of the ground system...”

As indicated by the asterisk, explanatory material on Section 4.13.3.2 can be found in Appendix A of the standard. The appendix includes the caveat that “Each installation should be evaluated to determine the need for any additional corrosion protection.” Relying on the electrical continuity of reinforcing bars in foundations is subject to the same considerations affecting use of reinforcing bars as above-grade conductors.

Bonding

Lightning can side flash (arc) from one building system to another as it seeks a path to ground. To prevent this, the mechanical, electrical, and plumbing systems as well as



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reinforcing bars and structural steel sections must be interconnected with the lightning protection system to equalize the systems' electrical potential. Conductor cables are typically used for these bonding connections.

Surge protective devices

Lightning can travel through power, data, and other electrically conductive lines. Surge protective devices are located where lines enter a building to interrupt sudden power spikes caused by lightning.

Accessories

A variety of connectors, fasteners, and accessories are also required to install a complete system. Of particular concern to concrete construction are through-structure penetration devices used at roof decks (Fig. 6) and exterior walls.

Project Considerations

The cost of installing lightning protection is modest in comparison to many other safety and security systems, and life-cycle costs are attractive because a lightning protection system will last the life of a structure with minimal maintenance. On large or complex projects, an experienced lightning protection system designer should be consulted early in project, and a preconstruction meeting should be held to expedite coordination.

We recommend that the design and specification of a lightning protection system should include, as a minimum:

- Compliance with NFPA 780 and related industry standards;
- Delegation of lightning protection system design to a firm employing an LPI-certified Master Designer or Master Installer/Designer;
- Installation by a lightning protection firm employing LPI-certified individuals; and
- Certification of the installation by the Lightning Protection Institute-Inspection Program (LPI-IP).⁸

The lightning protection contractor may have to be on the jobsite to make grounding and bonding connections before the first foundation elements are placed, as required to install conductors as a structure rises, and when necessary to create bonded connections as building equipment and systems are installed. The lightning protection contractor will also be one

of the last subtrade contractors on the jobsite, ensuring that work performed by others is within the lightning protection system's zone of protection and the project is ready for LPI-IP inspection.

Individuals and companies looking to increase their understanding of lightning protection systems can participate in AIA-certified continuing education programs available from the Lightning Safety Alliance.⁹

Finally, note that most lightning-related injuries and deaths occur outdoors. When on a construction site, you and your team must take cover in an enclosed building or hard-topped vehicle at the first indication of thunder and lightning, then remain indoors until 30 minutes after all lightning activity has ceased. As the National Weather Service advises, "When thunder roars, go indoors."

References

1. www.lightningsafety.com/nlsi_lls/nlsi_annual_usa_losses.htm, accessed Sept. 30, 2021.
2. NFPA 780, Standard for the Installation of Lightning Protection Systems, NFPA, Quincy, MA, Apr. 2019, 111 pp.
3. UL 96A, Standard for Installation Requirements for Lightning Protection Systems, UL LLC, Mar. 2016, 63 pp.
4. CSA B72, Installation Code for Lightning Protection Systems, CSA Group, Jan. 2020, 85 pp.
5. LPI 175, Standard for the Design – Installation – Inspection of Lightning Protection Systems, LPI, Jan. 2020.
6. www.bit.ly/LightningRisk, accessed Sept. 30, 2021.
7. ANSI/CAN/UL 96, Standard for Lightning Protection Components, UL LLC, Jun. 2016, 26 pp.
8. www.lpi-ip.com, accessed Sept. 30, 2021.
9. www.lightningsafetyalliance.com/education.html, accessed Sept. 30, 2021.

Selected by the editors for reader interest.



Jennifer Morgan is Co-Owner of East Coast Lightning Equipment, Inc., and Education Coordinator of the Lightning Safety Alliance.



Michael Chusid is a licensed architect and a Fellow of the Construction Specification Institute. He has published many papers on integrating lightning protection into buildings. He is also the author of several papers previously published in *Concrete International*.

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