District Architecture Center

Catastrophic Collapse: Lessons Learned, After the Fall

May 3–July 27, 2022

Exhibition Summary

Building collapses are rare but can happen for a host of reasons: earthquakes, extreme weather, human error, or a combination of factors. Fortunately, the lessons we learn from building failures make us all safer. These lessons often lead to refinements in construction codes and maintenance protocols, and can even bring about critical retrofits of existing buildings.

We have chosen eight well documented structural failure case studies, highlighting how building safety has been improved in their wake. The exhibition concludes with some speculation as to what we may learn from the recent collapse of a condominium building in Surfside, Florida, in 2021.

Introduction

Buildings, bridges, and other infrastructure are essential elements of our daily lives. Architects and engineers work together to create structures that protect the public's health, safety, and welfare, applying widely accepted standards for design and construction integrity. But what happens when disaster strikes, and catastrophic collapse follows from structural failure?

The consequences of a collapse can include injuries and fatalities, loss of property, environmental degradation, and legal issues. Inevitably, any such event also calls into question the stability of similar structures. Expert analysis of every major collapse is vital to mitigate potential future risk.

This exhibition explores what we can learn when structures—bridges, buildings, and dams—fail.

Carrying the Load: How Buildings Stand Up

This section of the exhibition gives you a quick overview of specific terms used in engineering and construction that will help you understand the events that follow.

"For every action, there is an equal and opposite reaction."—Isaac Newton

Loads

Loads, typically divided into gravity and lateral loads, are forces that act on a building.

Gravity loads are forces acting on a structure due to Earth's gravitational pull. Gravity loads are typically absorbed by horizontal elements such as beams or slabs, then transferred to vertical elements such as columns or walls, which then transfer the loads to the foundation. There are two kinds of gravity loads:

> *Dead loads* are **predictable, knowable** forces including the structure's own weight, the weight of finishes such as flooring and ceilings, and other permanent items like large planters.

Live (imposed) loads are **less predictable** forces including the weight of people and temporary furnishings such as bookcases, chairs, and tables.

Lateral loads are forces that make a building sway from side to side, such as normal winds or traffic-induced vibrations. Lateral loads are typically absorbed by horizontal elements such as beams and floors, then transferred to vertical elements such as walls and braced frames, which transfer the loads to the ground. Lateral loads can be dramatically increased by:

Natural events, including earthquakes, hurricanes, and tornadoes.

Man-made events, including accidental or purposeful explosions.

A *load path* is the path that carries a load through a structure and into the earth. Disasters can occur when a structure's load path is interrupted.

Photo Credit
Courtesy of Perkins Eastman DC

Anatomy of a Structure
A structure is composed of many elements that work together to ensure stability. A typical building is composed of a foundation, walls or columns, floors, and a roof. Explore the elements that make up a structure in the following section.

Slab/Floor
A slab is the floor of a structure or the main horizontal surface that people walk on, or automobiles drive on. A slab helps distribute the weight of the structure by connecting to the building's vertical elements like columns or walls. Historically, terra cotta and brick were commonly used as slabs. In modern construction, they are typically constructed of concrete or wood.

Photo Captions/Credits
Terracotta tile floor / Photo by Rustico Tile and Stone (CC BY 2.0)
Brick floor / Masoud Akbari, CC BY-SA 3.0, via Wikimedia Commons
Polished concrete floor / Intellicents, CC BY-SA 4.0, via Wikimedia Commons
Wood floor / Photo by Jurre Houtkamp on Unsplash

Beam
A beam is a narrow horizontal element supporting the underside of a slab or floor. Beams are typically used to stiffen a floor and help transfer loads to vertical supports. They can be made of steel, concrete, or wood.

Photo Captions/Credits
Beam / Photo by Jason Richard on Unsplash
A girder is a beam that supports other beams. / Pearson Scott Foresman, Public domain, via Wikimedia Commons
A joist is a closely spaced beam that spans between walls or girders. / Photo by ArmchairBuilder.com (CC BY 2.0)

A truss is a rigid frame composed of smaller structural units and often used for long spans or to create sloping roofs. / Photo by U.S Army Corps of Engineers Europe District (CC BY 2.0)

Column

A column is a vertical element supporting overhead beams, floors, or slabs. Columns transfer gravity and lateral loads from upper stories to the foundation. They are typically constructed of wood, masonry, steel, or concrete.

Photo Captions/Credits

Wood columns / Photo by Daniel Lorentzen on Unsplash
Stone columns / Photo by Claire Anderson on Unsplash
Steel columns / Photo by Yusuf Onuk on Unsplash
Concrete columns / Photo by Luca Rossato (CC BY-NC-ND 2.0)

Wall

A wall is a continuous vertical element designed to separate areas on a floor. Usually, walls connect to each other to enclose space. A *bearing wall* transfers loads from upper stories to the foundation. Walls may be constructed of many materials, among them wood, concrete, brick, concrete masonry units (CMU), and gypsum board.

Photo Captions/Credits

Wood wall / Photo by Ralph (Ravi) Kayden on Unsplash
Concrete masonry unit (CMU) wall / Myotus, CC BY-SA 4.0, via Wikimedia Commons
Concrete wall / Photo by Wells Chow on Unsplash
Brick wall / Photo by Drew Coffman on Unsplash
A non-load-bearing wall doesn't support a floor and is just used to separate spaces. / Franka Molitora, CC BY-SA 3.0, via Wikimedia Commons
A bearing wall is designed to carry gravity loads, as indicated here by rose-colored shading. / Cooper Hewitt, Smithsonian Design Museum, Public domain, via Wikimedia Commons

Frame

A frame is a series of beams and columns rigidly connected to resist lateral loads. Frames resist lateral forces and may also carry gravity loads. They are usually constructed of concrete, steel, or wood.

Photo Captions/Credits

A shear wall helps to brace a building against lateral forces, minimizing swaying to reduce the damage these forces might have on the building and its contents. / Used with permission from *Fine Homebuilding* magazine © 2011, The Taunton Press, Inc.
A braced frame has diagonal elements connecting the top and bottom of adjacent columns. Diagonal braces create triangles that stiffen the building and help resist lateral loads. / Encyclopedia Britannica, Public domain, via Wikimedia Commons
A rigid frame is the load-resisting skeleton designed with interconnected members that resist movements by mostly rigid connections. / Legacy Building Solutions, CC BY-SA 4.0, via Wikimedia Commons

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Who is Responsible for Your Safety?

To protect the health, safety, and welfare of the public, all US states and territories require practicing architects and engineers to be licensed (or "registered"). Most jurisdictions require that all but the smallest private structures be designed by an architect or engineer, and only licensed professionals may sign, seal, and submit construction drawings to a public authority for approval.

To obtain an architectural license, a person must have an accredited professional degree, complete a supervised internship, and pass a rigorous six-part exam. Once licensed, architects are required to fulfill continuing education credits to renew their licenses. In Washington, DC, the requirement is 24 credit hours every two years.

To become a licensed engineer, a person must complete a four-year college degree, work under a Professional Engineer for at least four years, and pass two intensive competency exams. Then, to retain their licenses, professional engineers must continually maintain and improve their skills throughout their careers.

Photo Captions/Credits

This infographic compares architects and engineers, revealing their thought processes, design approaches, and areas of expertise. / Courtesy of the NewSchool of Architecture and Design
Architect at work / Photo by Daniel McCullough on Unsplash
Engineers at work / Photo by This is Engineering (CC BY-NC-ND 2.0)

The Importance of Regulatory Agency Review

Before a structure is built, local regulatory agencies review the plans for compliance with the building code and periodically inspect the structure while it is under construction to ensure that it is being built in accordance with approved plans.

Safe construction requires a team of building professionals working in partnership with governmental authorities. Private sector and government agency inspections are critical to the process. Building codes change frequently, therefore building inspectors must keep up to date on the latest additions or deletions to the code. A building inspector is typically certified in one or more disciplines, either as a commercial or residential building inspector, or as a plumbing, electrical, or mechanical inspector.

Photo Caption/Credit

This infographic highlights the relationship between private sector partners and the government to keep building occupants safe. / Courtesy of the Department of Consumer and Regulatory Affairs

Construction Types

The most common construction types are wood, masonry, steel, and concrete. As new technologies emerge, other construction types evolve.

Wood

Wood is a renewable resource admired for its natural beauty. In buildings, wood may be used structurally as columns and beams, or it may be used as a substrate or finishing material such as flooring, sheathing, and roofing. Wood is naturally prone to defects such as splitting and warping, not to mention the potential for destruction by fire. Moisture and other environmental factors affect the aesthetic and structural properties of wood.

Photo Captions/Credits

Trees are logged from forests. / Photo by Gene Gallin on Unsplash

Cross-laminated timber (CLT) is a prefabricated wood panel engineered for strength, dimensional stability, and rigidity. Popular in Europe, with growing acceptance around the globe, CLT offers exceptional sound, fire, seismic, and thermal performance. / Photo by Oregon Department of Forestry, cropped from original (CC BY 2.0)

Heavy timber construction relies on large wooden timbers, sawn or glue-laminated with mortice and tenon joinery and metal fasteners, and is used primarily in barns, lodges, factory buildings, and places of worship. / Photo by slocumjoseph (CC BY-NC 2.0)

A wood frame is an economical method of construction used to assemble walls and roofs in combination with beams, columns, and joists in residential and small commercial buildings. The wood is typically treated to prevent decay and termite damage. / Photo by Josh Olalde on Unsplash

Masonry

Masonry involves stacked units of material such as stone, brick, and concrete. While bricks and concrete masonry units are man-made and molded into shape with specific sizing, stone is natural and must be extracted from the land before it is cut or carved into the desired shape and size. Each masonry material requires a different laying technique. While masonry can resist fire and moisture better than wood, it does not withstand earthquakes without significant reinforcement.

Photo Captions/Credits

Stone is quarried from the earth. / Photo by Mariana Proença on Unsplash

Typical stones used in buildings are granite, limestone, marble, and slate. Granite is nonporous and durable, and often used in contact with the ground or in areas exposed to severe weather. Limestone is porous and used as a finished surface above the ground. Marble, a recrystallized form of limestone, is typically used for decoration. Slate is a dense, hard stone often used for roofing. / Qurren, CC BY-SA 4.0, via Wikimedia Commons

A brick, made of clay, is molded into hand-sized shapes and fired to harden. After the drying process, experienced masons bond bricks with cement-based mortar, laying them in various positions to create visual interest through color and pattern. / Photo by Waldemar Brandt on Unsplash

A concrete masonry unit (CMU), manufactured with different densities and often hollow, is molded into various sizes and may have different colors and textures. Their hollow centers are typically reinforced with steel and grout. / Photo by U.S. Pacific Fleet (CC BY-NC 2.0)

Steel

Steel, which became very common during the Industrial Revolution, is manufactured into repetitive elements such as beams and columns. Steel's strength and stiffness make it well suited to tall buildings and long-span structures such as bridges. Steel is susceptible to corrosion from prolonged moisture and damage from intense fire.

Photo Captions/Credits

Steel is manufactured in a factory. / Photo by Ken (CC BY-NC-ND 2.0)

Structural steel is steel made of iron optimized for structural purposes with the precise amount of carbon and other elements. Steel members are connected with angles, plates, or tees through bolts and welding. / University of Washington, Public domain, via Wikimedia Commons

Light-gauge steel consists of steel members such as studs, joists, and rafters, assembled in much the same way as wood in light-frame construction. Steel members may be sheathed, insulated, and finished similarly, but unlike wood, they have punched holes to allow for bracing, piping, and wiring to pass through them. / P199, Public domain, via Wikimedia Commons

Concrete

Concrete is used around the globe as a paving and construction material in sidewalks, highways, and buildings. Relatively inexpensive, concrete is usually reinforced with steel to resist bending forces, and must be molded or cast into the desired form. Concrete is resistant to fire, rust, and rot, though it is brittle and subject to cracking. Concrete also creates an impervious surface, which is less ideal in conditions with substantial storm water run-off—because it cannot absorb much water, it can increase a community's risk of flooding.

Photo Captions/Credits

Workers pouring concrete / Photo by Oregon Department of Transportation (CC BY 2.0)

Reinforced concrete contains steel bars or wire mesh embedded into the mixture to resist tensile (stretching) forces while the concrete itself resists compressive (gravity) forces. / Metropolitan Transportation Authority of the State of New York, CC BY 2.0, via Wikimedia Commons

Post-tensioned concrete is concrete with high-strength steel strands—called tendons— tensioned on site using a hydraulic jack. Here, a worker threads steel strands in preparation for post-tensioning. / Photo by Washington State Dept of Transportation (CC BY-NC-ND 2.0)

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Catastrophic Collapses

1. 1889 South Fork Dam / Johnstown, PA
7. 2005 New Orleans Levees/Floodwalls / New Orleans, LA

2. 1922 Knickerbocker Theatre / Washington, DC

3. 1940 Tacoma Narrows Bridge / Tacoma, WA
9. 2021 Western Kentucky Tornado

4. 1981 Hyatt Regency Hotel / Kansas City, MO

5. 1994 Northridge Meadows Apartments / Los Angeles, CA

6. 2001 World Trade Center / New York, NY

8. 2021 Champlain Towers South / Surfside, FL

The following panels explore some of our nation's most catastrophic structural disasters—from the South Fork Dam and Tacoma Narrows Bridge to the Northridge Meadows apartments and the World Trade Center. Each catastrophic collapse offers a story with lessons learned that improved the way we design buildings today.

We encourage you to explore additional content by scanning (using your smartphone camera) the QR codes you see throughout the exhibition. Content may include personal accounts, news reports, or engineering analysis related to each disaster. Caution: some videos may be disturbing, so viewer discretion is advised.

Water

South Fork Dam

Casualties: 2,209 killed **Where:** Johnstown, PA **When**: May 31, 1889

What

The South Fork Dam was an earthen and rock-filled structure in western Pennsylvania that was 72 feet high, 918 feet long, and 220 feet wide at the base. It had a history of partial failures in 1847 and 1862. When the structure fully collapsed in May 1889, it sent 20 million tons of water into Johnstown, which was 14 miles away from the dam. The wave of water measured 35 to 40 feet high and approached the town at about 40 miles an hour. The flood destroyed four square miles of the town. The resulting pile of debris covered 30 acres. Property damage amounted to $17 million, and 99 entire families died.

Why

The dam failed because it was never fully repaired after the previous partial failures. This had fatal consequences in 1889 when a heavy storm pounded the dam.

How did this change the way structures are designed?

Dam design has changed since this flood both to protect the structure itself and to anticipate and mitigate potential flooding should the structure fail. Mathematical calculations—such as probable maximum precipitation (PMP) estimates—are now used in designing a dam to model a watershed's response to extreme precipitation. Computer models can also simulate water runoff and dam failure flood waves. These advances provide engineers with the ability to perform sophisticated evaluations of dam designs and more precisely evaluate risks.

Photo Captions/Credits

On May 31, 1889, the South Fork Dam failed after days of heavy rain, unleashing 20 million tons of water on the town of Johnstown below. Like other houses, the John Schultz House, pictured here, was destroyed. / Unknown author, Public domain, via Wikimedia Commons

People pose on rooftops of buildings damaged by the Johnstown Flood. / Courtesy of the Johnstown Flood Museum Archives, Johnstown Area Heritage Association

Main Street after the flood. / E. Benjamin Andrews, Public domain, via Wikimedia Commons

The Great Conemaugh Valley Disaster, Flood and Fire at Johnstown, Pa. Lithograph, published by Kurz and Allison, 1890 / Unknown artist, Public domain, via Wikimedia Commons

Area marked by wooden walkways, as it appears today, where the dam collapsed in 1889. / David Brossard, CC BY-SA 2.0, via Wikimedia Commons

Story of the Johnstown Flood; Duration: 25 min 57 sec / Video via James Zollweg on YouTube

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Water

New Orleans Levees/Floodwalls

Casualties: 1,577 killed **Where:** New Orleans, LA **When:** August 29, 2005

What

Hurricane Katrina was a Category 5 storm that pushed water from the Gulf of Mexico toward New Orleans, sending the contents of the ocean spilling down into a metropolis that for the most part sits below sea level. The result was catastrophic: the city filled up with water like a bowl, trapping thousands of residents in their homes.

In all, levees and floodwalls in New Orleans and surrounding areas were breached in more than 50 locations, flooding 80 percent of the city and fully 95 percent of nearby St. Bernard Parish. Water depths were up to 15 feet in areas including parts of the Lower 9th Ward, New Orleans East, and the well-to-do Lakeview neighborhood.

Why

If water gets into New Orleans, which is surrounded by levees, it has nowhere to go unless it is pumped out mechanically. The city's already low elevation was exacerbated by early development that entailed draining adjacent swamplands, resulting in soil subsidence. The city now lies up to six feet below sea level and is continuing to sink.

In the immediate aftermath of Hurricane Katrina, the U.S. Army Corps of Engineers claimed the massive storm had overwhelmed the levee system, which had been designed to protect the region from a Category 3 storm or below. Yet later investigations revealed that some of the city's levees failed even at water levels far below what they had been expected to withstand.

How did this change the way structures are designed?

The New Orleans levee system, rebuilt at a cost of $14 billion after Katrina, includes flood walls more deeply rooted in the ground and with foundations designed to prevent overturning, which should keep them standing even if water goes over them. The Army Corps of Engineers also erected a massive storm surge barrier around the adjacent Lake Borgne and closed a canal outlet between the Mississippi River and the Gulf of Mexico, which had funneled storm surge into the city during Katrina.

Photo Captions/Credits

Commissioned officers of the National Oceanic and Atmospheric Administration (NOAA) Corps flew more than 100 hours surveying Hurricane Katrina's devastation. / Commander Mark Moran of the NOAA Aviation Weather Center with Lt. Phil Eastman and Lt. Dave Demers of the NOAA Aircraft Operations Center, Public domain, via Wikimedia Commons

Sectional diagram (not to scale) showing elevation differences between the land and water in one area of New Orleans / Alexdi at English Wikipedia, CC BY-SA 3.0, via Wikimedia Commons

The Inner Harbor Navigation Canal Lake Borgne Surge Barrier / Ray Devlin, CC BY 2.0, via Wikimedia Commons

How New Orleans Sank Below Sea Level; Duration: 7 min 55 sec / Video via Grist on YouTube

Snow

Knickerbocker Theatre

Casualties: 98 killed; 133 injured **Where:** Washington, DC **When:** January 28, 1922

What

The Knickerbocker Theatre, built in 1917, once stood at the southeast corner of 18th Street and Columbia Road, NW—the crossroads of today's Adams Morgan neighborhood. It was a grand entertainment palace with a seating capacity of 1,700, making it one of the largest and most modern of the many Washington-area neighborhood theaters.

On the night of January 28, 1922, following a two-day blizzard that brought two feet of wet, heavy snow, the Knickerbocker was screening a silent film, *Get-Rich-Quick Wallingford*, when the weight of that snow caused the roof to collapse suddenly onto filmgoers and the theater's orchestra.

Why

The investigation into the disaster showed that during the building's construction, lightweight steel had been substituted for the approved heavier steel due to shortages of the latter following the country's engagement in World War I, combined with a desire to keep the building's construction on schedule. The lighter steel gradually weakened with the building's seasonal expansion and contraction from summer to winter. In addition, beams were inadequately connected: they rested on only two inches of masonry within the walls, rather than the required eight inches. The weight of the snow that fateful night pushed the weakened structure beyond its limit, causing the entire roof to come down.

How did this change how structures are designed?

The collapse led to calls for the city's building code to be updated to include the use of adequate steel I-beams and better supports for roofs. Continuing education requirements were called for to make sure architects were keeping up with the latest materials and methods. As a result, architects are required to complete continuing education courses to maintain their licenses.

Photo Captions/Credits

The roof of the Knickerbocker Theatre collapsed on January 28, 1922, under the weight of 28 inches of snow. / Courtesy of the Library of Congress, LC-DIG-npcc-22642 (digital file from original) [signature image]
The Knickerbocker Theatre as it appeared in October 1917. / Unknown author, Public domain, via Wikimedia Commons
Interior of the Knickerbocker Theatre as it appeared in October 1917. / National Photo Company Collection, Public domain, via Wikimedia Commons
Inside the theater showing debris and damage caused by the roof collapse. / Courtesy of the Library of Congress, LC-DIG-npcc-05700 (digital file from original)
Officials surveying damage inside the theater. / Courtesy of the Library of Congress, LC-DIG-npcc-22645 (digital file from original)
Newsreel footage of the Knickerbocker Theatre disaster (no sound); Duration: 3 min 30 sec / Video via Jeff Krulik on Youtube

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Wind

Tacoma Narrows Bridge

Casualties: 0 **Where:** Tacoma, WA **When:** November 7, 1940

What

At the time of its construction, the Tacoma Narrows Bridge was the third-longest suspension bridge in the United States. Because of the expectation of light traffic on the bridge, it was designed with only two lanes and was just 39 feet wide. Consequently, designers thought they could replace the deep trusses traditionally used in a suspension bridge with smaller steel girders. The roadbed was also shallower than normal, and the span moved in the wind from the day it opened.

Why

The bridge's slender elegance and light construction actually made it aerodynamic—an undesirable quality in a stationary structure—which led to its catastrophic collapse only four months after it was dedicated. The bridge became famous as "the most dramatic failure in bridge engineering history." The sunken remains of "Galloping Gertie," as the bridge was nicknamed during its brief existence, now form an artificial reef that was placed on the National Register of Historic Places in 1992 to protect it from salvagers.

How did this change how structures are designed?

Following the incident, engineers took extra caution to consider aerodynamic principles into their designs using wind-tunnel testing of structural models. A key consequence of the failure was that suspension bridges reverted to deeper and heavier truss designs, including the replacement Tacoma Narrows Bridge (1950), until the development in the 1960s of box girder bridges with an airfoil shape such as the Severn Bridge in Great Britain, which provided the necessary stiffness while reducing torsional forces.

Photo Captions/Credits

The Tacoma Narrows Bridge collapsed on November 7, 1940, due to high winds. / Courtesy of the Library of Congress, LC-USZ62-46682 (b&w film copy neg.)
Program cover for the opening ceremonies of the Tacoma Narrows Bridge and McChord Field (USAAF)—now McChord AFB—at Joint Base Lewis-McChord in Lakewood, WA / Tacoma Narrows Bridge - McChord Field Celebration Committee, Norton Clapp, General Chairman; Prepared by Shannon Brothers; Published by Johnson-Cox Company, Tacoma, WA, Public domain, via Wikimedia Commons
A man is photographed running off the Tacoma Narrows Bridge during the collapse. / University of Washington Libraries, Special Collections, UW20731
Diagram showing the impact of wind on the Tacoma Narrows Bridge due to its design. / BedrockPerson, CC BY-SA 4.0, via Wikimedia Commons
Collapse of the Tacoma Narrows Bridge (narrated); Duration: 2 min 35 sec / Video via Time Capsule Project on YouTube

Wind

Western Kentucky Tornado

Casualties: 56 killed; 500+ injured **Where:** Western Kentucky **When:** December 10, 2021

"It's not normal to get a tornado in December, but then it's not normal for it to be 73 degrees at night."
—Tim Wetherbee, Mayfield Resident

What

A rare December tornado with winds up to 190 mph hit western Kentucky and shredded 15,000 buildings in less than three hours. The property damage is estimated at $3.6 billion.

The city of Mayfield, as an example, was almost completely leveled. The courthouse had its roof torn off and its clock tower toppled. The post office, city hall, fire station, and police station were also significantly damaged or destroyed. Three large churches were destroyed in downtown Mayfield, including the First Presbyterian Church, a substantial and well-built brick structure. The First United Methodist Church sustained collapse of its sanctuary, which was constructed with very thick masonry exterior walls. Twenty-two people were killed in and around Mayfield, with hundreds more injured, many severely. Only large piles of bricks and lumber remained in the hardest-hit portions of the downtown area, and streets were left buried under debris.

Why

This was a particularly long-lasting storm at an unusual time of year. In addition, Kentucky is well east of the traditional "tornado alley," the states where tornadoes are most frequent. Scientific studies show that this eastward movement of the tornado-prone zone is caused by climate change. If this trend continues, tornadoes may reach areas of greater population densities with higher likelihood of casualties and significant property damage.

How did this change how we design structures?

This event is so recent that there hasn't been time to make changes to building design standards yet. However, for many years the Federal Emergency Management Agency (FEMA) has recommended that jurisdictions within tornado zones adopt codes that include safe rooms. Safe rooms can be located anywhere on the first floor of a home, in a basement, or outside the main building. When designed to meet the standards set forth by the International Code Council, the National Storm Shelter Association (NSSA), and FEMA, a safe room will stand up to the most intense tornadoes and hurricanes with winds up to 250 mph, which could significantly reduce injury and loss of life if not property damage.

Photo Captions/Credits

Aerial view of Mayfield, KY, showing devastation from the tornado. / State Farm, CC BY 2.0, via Wikimedia Commons
Using radar, this graphic depicts debris that was lofted into the air as high as 30,000 feet over Mayfield, KY. / Highteeld99, CC BY-SA 4.0, via Wikimedia Commons [share; adapt]
FEMA drone footage showing devastation in Mayfield after the tornado; Duration: 5 min 34 sec / Video via WHAS11 on YouTube

Human Error
Hyatt Regency Hotel

Casualties: 114 killed; 216 injured **Where** Kansas City, MO **When:** July 17, 1981

What
Approximately 1,600 people gathered in the atrium of the Kansas City Hyatt Regency Hotel for a tea dance on the evening of July 17, 1981. Above the atrium were three suspended walkways, or “skybridges.” The fourth-floor walkway was directly over the second-floor walkway. At 7:05 that evening, about 40 people were on the second-floor walkway with an additional 16 to 20 on the fourth-level walkway directly above. Guests heard popping noises and a loud crack moments before the fourth-floor walkway dropped several inches, paused, then fell completely onto the second-floor walkway. Both walkways then fell to the crowded lobby floor.

Why
The original design called for the fourth- and second-floor skybridges to be suspended from continuous rods stretching from the roof structure. After the contractor deemed it too difficult to build the walkways in that fashion, a design change was made during construction, resulting in the use of one set of rods from the ceiling to the fourth-floor walkway and then another set of rods suspending the second-floor walkway from the fourth-floor walkway. The fourth-floor walkway was thus carrying the weight of the lower walkway as well as its own. An investigation concluded that the fourth-floor walkway would have failed even under one-third of the weight it held that night.

How did this change how we design structures?
Today, steel connections in a project that is under construction are required by code to be checked by a third-party engineer. A third-party engineer is a professional engineer unaffiliated with a project who is there to verify the work, making sure structures are designed and constructed properly.

Photo Captions/Credits
On July 17, 1981, two skybridges in the lobby of the Hyatt Regency Hotel collapsed under the weight of people, due to a design change made during construction. / Dr. Lee Lowery, Jr., P.E., Public domain, via Wikimedia Commons
Infographic detailing the scene before and after the collapse. / Illustrations by Dave Eames for The Kansas City Star
View showing the fourth-floor walkway collapsed on top of the second-floor walkway. / Dr. Lee Lowery, Jr., P.E., Public domain, via Wikimedia Commons
Diagram showing the original design verses actual construction of the rod supporting the second- and fourth-floor walkways. / DTR, see also original creator at w:File:HRWalkway-01.jpg, Public domain, via Wikimedia Commons
Animation showing the collapsed skywalks at the Hyatt Regency Hotel; Duration: 1 min 9 sec / Video via KMBC 9 on YouTube

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Earthquake

Northridge Meadows Apartment Complex

Casualties: 16 killed **Where:** Los Angeles, CA **When:** January 7, 1994

What

A magnitude 6.7 earthquake on a previously unknown fault in the Northridge section of Los Angeles pancaked the 163-unit Northridge Meadows apartment building. In total the quake killed more than 60, injured more than 9,000, and caused damage amounting to over $20 billion. The largest loss of life was at Northridge Meadows. Residents reported that the terrifying shaking felt like someone had lifted the building up, then let it crash back down.

Why

Generally, older masonry structures are easily damaged by earthquakes. Masonry is strong against gravity forces, but the lateral motion of an earthquake can make unreinforced concrete columns break off in pieces. Walls and floors can then separate, causing a collapse.

The Northridge Meadows apartment buildings were “soft-story” buildings, like hundreds of similar buildings that collapsed throughout the Los Angeles area. These structures contain up to three stories over an open ground level with fewer walls than above. This level is typically reserved for parking. With fewer walls, the ground level is less stiff and has the potential to “pancake” when a building sways.

How has this changed the way we design structures?

Many cities have worked to reinforce existing structures since the Northridge Meadows collapse. Reinforcing material, like steel rods, can help stiffen the structure to better handle the lateral movement of an earthquake. Throughout California, soft-story buildings are being retrofitted with moment frames that help with lateral forces during a seismic event.

Photo Captions/Credits

At the Northridge Meadows apartments, the first story completely collapsed during the Northridge earthquake. / Photo by Kris Tacsik and Michael Swift, Northridge Earthquake Photo Collection, California State University Northridge

View of the Northridge Meadows apartment complex from the rear parking lot showing the first floor completely collapsed. / Photo by Kris Tacsik and Michael Swift, Northridge Earthquake Photo Collection, California State University Northridge

The collapse at the Northridge Meadows apartment complex resulted in the largest concentration of deaths in the Northridge earthquake. / Stickpen, CC0, via Wikimedia Commons

Like the Northridge Meadows apartments, the first floors of other buildings in the area completely collapsed. / Photo by Kris Tacsik and Michael Swift, Northridge Earthquake Photo Collection, California State University Northridge

Aftermath coverage of the 1994 Northridge Earthquake at the Northridge Meadows apartments; Duration: 7 min 11 sec / Video via SeattleThen on YouTube

Understanding the process of retrofitting soft-story buildings in LA; Duration: 4 min 55 sec / Video via Simpson Strong-Tie on YouTube

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Terrorism

World Trade Center

Casualties: 2,606 killed **Where:** New York, NY **When:** September 11, 2001

What

On the morning of September 11, 2001, two jet aircraft were intentionally crashed into the Twin Towers of the World Trade Center. The North Tower was first to be hit at 8:46 AM, and it collapsed at 10:46 AM. The South Tower was struck at 9:03 AM and fell at 9:59 AM. Several surrounding buildings were also damaged or destroyed by these collapses.

Why

The World Trade Center Twin Towers—then New York's tallest structures—were constructed with very lightweight modular elements that allowed them to be built more rapidly at reduced cost. Each of the buildings was designed with a dense ring of perimeter columns to resist lateral forces (swaying in the wind), connected at each floor to the rigid core. Because the primary supporting columns were on the exterior, the impact of the aircraft immediately compromised the structure. Although the building's engineer had anticipated the possibility of an airplane accidentally hitting one of the towers, the structures could not withstand the force of a modern, wide-body aircraft deliberately flown into them. Given the large number of columns destroyed on impact, each tower remained standing for a remarkably long time.

The buildings ultimately failed after the heat from raging fires, fed by tons of jet fuel, warped the structural steel. The joists supporting the floors failed, causing the perimeter columns to bow outward, at which point the floors above them began to fall. Each building collapsed in 30 seconds at a speed of more than 120 miles an hour.

How has this changed the way we design structures?

The Twin Towers were built without much structural redundancy—that is, there was very little in the way of back-up should a key beam or column be damaged or destroyed. Buildings today are more likely to include such systems in the wake of this tragedy. Materials such as fiber reinforced concrete can also help make a building more resistant to the force of a blast. Dozens of other changes in the building code for buildings of a certain height were also made after 9/11, including widening staircases to hasten evacuation and using thicker glass on lower levels.

Photo Captions/Credits

On September 11, 2001, terrorists deliberately flew planes into the Twin Towers. / Photo by Cyril Attias (CC BY-NC-ND 2.0)

On September 11, 2001, two airplanes were deliberately flown into the North and South towers of the World Trade Center. / Photo by Cyril Attias (CC BY-NC-ND 2.0) [share]

Firefighters among the rubble of the World Trade Center. / Photo by Beverly & Pack (CC BY 2.0)

Illustration of the World Trade Center floor and elevator arrangement of Towers One and Two. / MesserWoland, Public domain, via Wikimedia Commons

Simple diagram of the collapse of World Trade Center Tower One. / BedrockPerson, CC BY-SA 4.0, via Wikimedia Commons

How the World Trade Center Collapsed on Catastrophic Science; Duration: 4 min 6 sec / Video via UNSW on YouTube

Yet to be Determined

Champlain Towers South

Casualties: 98 deaths; 11 injuries **Where:** Surfside, FL **When:** June 24, 2021

What

The 12-floor concrete Champlain Towers South beachfront condominium partially collapsed at about 1:20 in the morning. The extent of the damage led to the deliberate demolition of the rest of the building 10 days later.

Why

It will be years before the exact causes of this collapse have been fully determined, but preliminary evidence points to a string of failures beginning with the building's design and construction and continuing through years of deferred maintenance. Engineers who have examined the original engineering drawings have noted that some of the columns appear to have been undersized, with inadequate space for steel reinforcement and insufficient concrete coverage to protect that steel from corrosion, in violation of building codes in effect at the time. There is also evidence that the building's pool deck was too thin, with poor water-proofing and inadequate slope to allow proper drainage.

Over the years, heavy planters had been placed inadvertently over weak points in the building, leading to visible cracks and even large chunks of concrete falling from columns and beams, thus exposing more reinforcement bars to the corrosive effects of moist air. According to a pending lawsuit, the construction of a large new condominium next door may also have weakened the perimeter wall of the Champlain Towers South building, where some forensic models indicate that the collapse sequence began.

How will this change the way we design structures?

The Miami-Dade County government passed a new law in early 2022 requiring all condominium and homeowner associations to make financial statements and structural safety reports available to the public. The hope is that such information will allow current residents and potential buyers alike to be warned of potential structural problems. Florida's building codes were already strengthened in the 1990s in the wake of Hurricane Andrew, so there is reason to believe that structures built since then would be less prone to disasters such as the one that brought down Champlain Towers South.

Photo Captions/Credits

Champlain Towers South partially collapsed on June 24, 2021. / Miami-Dade Fire Rescue Department, Public domain, via Wikimedia Commons

Champlain Towers South, as it appeared before the collapse. / Microsoft StreetSide, CC BY-SA 4.0, via Wikimedia Commons

Ground view of the collapse showing debris and workers searching for survivors. / Miami-Dade Fire Rescue Department. The original uploader was TheEpicGhosty at English Wikipedia., Public domain, via Wikimedia Commons

First-aid responders pick through rubble following the collapse. / IDF Spokesperson's Unit, CC BY-SA 3.0, via Wikimedia Commons

Tracking the fall of Champlain Towers South; Duration: 8 min 23 sec / Video via ABC News on YouTube

Final Thoughts
These building disasters have not only changed building codes and design standards, but they have also changed emergency preparedness in fundamental ways. The Johnstown Flood was the Red Cross's first effort in emergency response, with a team led by Clara Barton. The Hyatt Regency collapse caused Kansas City to revamp its emergency system. The Northridge Earthquake spurred California to develop a program to encourage residents to have an evacuation plan. The World Trade Center disaster led to better protection of emergency responders with improved communication, evacuation lighting, and equipment to mitigate smoke inhalation.

You may have noticed that we started our case studies with the statistics about people because as catastrophic as the property damage may be, we need to remember that lives were lost. It is the greatest responsibility the design profession has: to ensure the safety of building occupants.

Exhibition Credits

Catastrophic Collapse: Lessons Learned, After the Fall is organized by AIA|DC for the SIGAL Gallery.

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