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Resilience: Why Material Selection Matters

Understanding how the selection of structural framing materials impacts the resilience of buildings and communities

Sponsored by American Institute of Steel Construction

Resilience is the ability of an object or system to absorb and recover from an external shock, such as those caused by natural disasters (earthquakes, hurricanes, tornadoes, wildfires) or malicious acts (arson, terrorism).

While the primary purpose of building codes is to protect the health and safety of occupants during an extreme event, the design goal of a resilient structure is for it to withstand an extreme event with minimal damage. By doing so, the building will be able to maintain continuous function or be quickly repaired for a rapid return to service.

Resilience is a simple concept, yet it has complex implications for designers and builders. For some, resilience is viewed at the community level and refers to a community's ability to absorb and recover after a disaster. This could be measured by the ability to restore energy, transportation, clean water, and communication services to residents quickly after a disaster. As illustrated in the graphic below, communities become resilient

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Learning Objectives

After reading this article, you should be able to:

1. Define the architectural concept of resilience and explain its implications for occupant safety and building durability.
2. Discuss how material and framing system selection can impact resilience and health, safety, and welfare of occupants in the built environment.
3. List the attributes of framing materials that contribute to resilient framing systems and building performance.
4. Compare the durability, strength, and combustibility characteristics of structural steel and other common framing materials.

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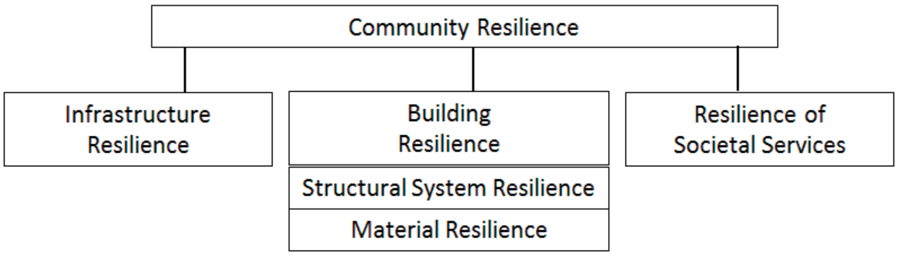
Often referred to as the "most resilient skyscraper on the West Coast," 181 Fremont in San Francisco utilizes external megabraces to resists shear demands in the office levels and standard buckling-restrained braces in the residential levels.

Rendering courtesy of Jay Paul Company

Community resilience is dependent on the resilience of multiple community assets.



by having an infrastructure, which includes buildings, that can withstand intense storms or disastrous events.

Facilities such as fire, police, health care, government entities, and designated shelters or residential units are of key concern for community resilience. To enhance community resilience, key decision makers must begin by selecting structural framing materials that can efficiently and effectively be used in the design and construction of resilient framing systems for critical structures. When measured against other framing materials, structural steel clearly satisfies those requirements.

THE FOUR RS OF RESILIENCE

The resilience of a community, building, or material is often characterized by four interconnected Rs: robustness, resourcefulness, recovery, and redundancy.

Robustness at the community level refers to the ability of critical services to maintain operations during and after an extreme event. Buildings that house vital services such as health care, power management, transportation, and communications must be able to maintain operation for a community during and after a disruption. For a building to be resilient, it also must be robust and able to withstand or recover rapidly from the extreme event. The building's robustness is a function of the integrity of the structural frame and, in turn, the strength of the framing material used in that frame.

Resourcefulness is the ability to prepare for and skillfully respond to a crisis or disruption. For a community, that means not only having contingency plans in place but also identifying and providing the resources needed to implement those plans. For a building, it means having as-built building plans available for rapid reference, structural engineers identified who are prepared to provide a rapid assessment of damage to the structural frame, and sources identified for materials that may be required to implement a repair. For example, structural steel is stocked at hundreds of steel service centers throughout the country for rapid delivery to a structural steel fabricator that can quickly fabricate the members required for the repair (see MacArthur Maze sidebar).

Recovery is the restoration of key operations as quickly and efficiently as possible after a disruption with the goal of a full return to normalcy within a short timeframe. It is impossible and impractical to design a building and structural frame to handle every potential extreme event. There will be times when even the most resilient of designs are stressed beyond the point of failure. In these cases, resilience is determined by the level of loss of functionality and the time required to resume full functionality. The level of recovery and the time required to accomplish it will be in direct relationship to the robustness, redundancy, and ease of repair of the structural system, as well as the availability of resources to complete the repair.

Redundancy in the community context refers to the provision of backup resources to support key functional components of the resilient community. If a key component such as the provision of health services at a local hospital is taken offline, then a backup for that service should be identified to provide the service. For a building, redundancy can best be seen as the ability of the structural framing system and the material from which the frame is constructed to provide additional load-carrying capacity and the ability of the frame to transfer loads to alternative load paths.

MACARTHUR MAZE

Photo courtesy of Scott Jones/Flickr

The rapid reconstruction of the MacArthur Maze illustrates the benefits of resilient design using readily available resources

The MacArthur Maze is a large freeway interchange at the east end of the San Francisco-Oakland Bay Bridge. On April 29, 2007, a tank truck carrying 8,600 gallons of gasoline overturned and caught fire beneath one of the ramps of the interchange. The petrochemical fire weakened the steel structure supporting the roadway, resulting in the collapse of the ramp connecting I-80 east to I-580. The original cost estimate for repair of the ramp was $10 million and a schedule that required the roadway to be out of service for several months, resulting in significant out-of-pocket costs to commuters and municipal agencies that provided free transportation on the local BART system. The State of California projected that the economic impact of the road closure was $6 million per day. Contrary to the initial cost and schedule estimates, the roadway was placed back in service on May 24, less than 30 days after the original accident, at cost below original budget estimates (the actual winning bid was $876,075 with an incentive of $200,000 per day if the work was completed before June 27). This rapid recovery after an extreme event was accomplished because the material and labor resources required for completing the project were immediately available. Engineers were prepared to address the design issues on an accelerated schedule, a contractor with significant experience in rebuilding damaged expressways had an existing relationship with Caltrans, and the material (steel) and fabrication resources were readily available to the project team.

Structural frames constructed using structural steel consistently receive high marks when measured using the four Rs thanks to the inherent resiliency of steel. When resiliency is required in a structure, structural steel is the ideal choice.

When developing emergency management and resilience plans, it is important to recognize that not all communities are alike. The stressors that could affect a community vary by location. For example, some communities may be located in areas prone to hurricanes, floods, and storm surges, while others are in places prone to snowstorms, wildfires, or tornados. Many areas are seeing an increase in storm intensity, hot and dry spells, and snow loads due to global climate change. Not all factors must be included when developing resiliency management plans and selecting building materials, but those stressors that have a measurable probability of impacting the local community must be considered.

EVALUATING RESILIENCE

When determining resilience as it relates to the four Rs, a defined resilience scale is key. Without an appropriate scale, it is difficult for decision makers to determine ways to efficiently and effectively compare alternative approaches. The evaluation of resilience is a developing field with proposed approaches falling under either a subjective or objective methodology.

Subjective evaluation of resilience ranks alternative design approaches or plans against each of the four Rs using a three-step ranking system: high, medium, and low. The alternative design approaches or plans are then assessed by the individuals involved based on their sense of the relative merit of each of the four Rs and a final rating given to each.

The objective approach to quantifying resilience takes one of two forms. The first requires the individuals involved in assessing comparative proposals or plans prioritize each of the four R's on a one to five scale (robustness and recovery might both be a five, while redundancy might be a three and resourcefulness a two) and then rate the level of each of the four Rs on a one to 10 scale. The priority level and rank are then multiplied for each R and added together for the overall result.

A more analytical approach is to consider risk levels, cost of recovery, and length of time required for recovery for each type of extreme event. For example, if the probability of a 6.0 seismic event was estimated to be one occurrence every 50 years (0.02), the cost for repair to the building was estimated to be $10 million, and the time of lost occupancy was 120 days at a cost of $50,000 per day, then the resilience rating would be 0.02($10,000,000+120×$50,000) = $320,000. The overall rating would be the sum of all possible events. Structural alternatives are then compared with the lowest value indicating the greatest level of resilience.

While this approach may seem arbitrary and overly complex, it is exactly the same actuarial approach used by insurance companies to set insurance rates for buildings.

MATERIAL CHOICE AND RESILIENCE

The most common types of structural framing materials are wood, concrete, and structural steel. Of the three materials, steel consistently ranks as the most resilient and cost effective. While the initial cost of a structural steel framing system may be higher for a particular project, its ability to withstand a wide range of extreme events while allowing the structural frame to maintain its integrity during and after a disaster is the model of cost-effective resiliency.

The Insurance Industry Proxy

Insurance policies are purchased by a building owner to cover damage, replacement costs, and loss of use of the building in the event of a disaster. Addressing resilience in the design of the building through the proper selection of the structural frame using the appropriate structural framing materials is similar to purchasing insurance on the building. Spending money up front to address resilience can mean the difference between having a facility up and running shortly after a disaster or waiting months for reconstruction. The best measure of resiliency then becomes a measure of risk.

When determining how to quantify those risks, there is no need to look further than insurance rates based on today's market for builder's risk (insurance that insures the building during construction) and all risk (insurance purchased by the building owner insuring the building after occupancy). Insurance companies regularly assess the loss records of buildings subject to both anticipated and extreme events, and then they use those studies to set their rates. For a given set of risks, a lower rate means less likely damage and a lower cost of repair, providing an excellent proxy for comparing the resiliency of different structural framing materials.

The simple fact is that the insurance rates for structural steel-framed buildings are significantly lower than the rates for buildings framed in wood or concrete. The chart below illustrates current insurance rates per $100 of value in today's market for builder's risk and all risk insurance. These rates represent costs for the same building in the same location, the only difference being the framing materials. The rates for structural steel are consistently lower than the rates for wood or concrete, both before and after construction.

	Builder's Risk During Construction	All Risk After Occupancy
Wood	$0.22–$0.27	$0.20–$0.25
Concrete	$0.14–$0.18	$0.13–$0.16
Structural Steel	$0.08–$0.12	$0.08–$0.11

Typical Insurance Rates per $100 of Value by Framing Material

Since these rates are based on costs for the same building in the same location, they take into consideration the same external risk factors, including future impacts related to climate change. For example, in Florida, the risk could be based on calculations of a projected hurricane, storm surge, or flood damage, while in California, risk could be assessed based on calculations of projected wildfires or mudslides. These rates will change based on the project location and the particular risks associated with that locale. This also could change if the project has a specialized feature or aspect. Despite the fact that rates vary by location and project, the general trend is the same. Insurance rates for wood buildings are 2.3 times higher than for an equivalent structural steel-framed buildings, and the rates for a concrete building are 1.5 times higher than for a steel-framed building. The difference is not the level of risk to the building from an extreme event, but rather the resilience of the building in responding to that event. For a building valued at $100 million, the savings in insurance costs over a 50-year period would be $6.75 million for a structural steel-framed system when compared to a wood framing system. The actuarial studies performed by the insurance companies confirm that the structural steel-framed buildings are inherently more resilient than buildings framed in wood or concrete.

RESILIENT DESIGN CONSIDERATIONS

When selecting a structural framing system and material, there are many factors that must be considered.

Building Code Requirements

The resilience of a building's structural framing system is a function of both the material and the design of that system. Structural framing systems that meet the requirements of the building code can be built using steel, concrete, or wood. The purpose of building code provisions is to provide safety for occupants in the event of an extreme event. To ensure the best possible outcomes, all buildings are subject to building codes, such as the International Building Code (IBC).

In general, building codes do not directly address the resilience of the building by referencing either a subjective evaluation of the four Rs or an objective evaluation of the time and cost of repair and recovery. Section 1604 of IBC states that building structures and parts of the building must have the following considerations built into the design: strength, load and resistance factor, allowable stress, and empirical design or construction methods as permitted by the material.

However, IBC section 1604.5 begins to address the resiliency of buildings by including enhanced design requirements for high-rise buildings in risk categories III and IV. In those cases, structural integrity is evaluated independently. This means deformations in the material are allowed as long as failure does not occur. The goal is to allow for the redistribution of loads in the event of damage. This is possible to accomplish using structural steel, concrete, or wood. However, the question isn't whether it's possible to accomplish this goal; the question is, what is the most efficient way to meet this goal by maximizing design properties of the material specified in the design, getting the best return on investment from the system, achieving redundancy, and creating a system that is easy to repair after an extreme event?

Photo by James Steinkamp, Steinkamp Photography—IDEAS² Award submission

BUNKER APPROACH VS. SYSTEMS APPROACH

The STEM Wing of Mundelein High School in Mundelein, Illinois.

When designing a structural framing system, there are two different philosophies on how to increase the structure's ability to handle extreme events. They are commonly referred to as a "bunker" philosophy and a "systems" philosophy. The bunker philosophy attempts to handle an elevated level of potential loads by increasing the mass of the structure (i.e., build the bunker with thicker walls to handle larger forces applied to it). The increase in mass requires an increase in materials and an increase in cost. The systems philosophy maximizes redundant load paths by using a material's natural ductility and reserve strength. During the design process, the systems approach can integrate serviceability considerations. This allows for an emphasis on modularity and rapid repair.

A building designed following the bunker philosophy is not ideal because it is incredibly difficult to repair. By contrast, the systems approach provides a technical solution that addresses the challenges of resilient design. A systems solution would provide multiple options for lateral load resistance by utilizing a highly ductile environment that allows adequate member deformation while still keeping access to critical services intact and operational. The design of a system with special connections and buckling-restrained braces as structural fuses allow a structure to withstand an extreme event, such as an earthquake or an event resulting from high winds or a blast. If damage occurs to the structural system, these fuses can be efficiently removed and replaced, returning the structure to full functionality in a short period of time without major structure demolition or extensive retrofit.

In short, the bunker philosophy is a material-intensive solution and is not ideal for most applications, while the systems philosophy provides a technical solution and is much more practical.

MATERIAL ATTRIBUTES

There is no single physical measure of resilience for a building material. When the resilience of a material is assessed, the primary attributes of the material must all be evaluated. For a structural framing material like structural steel, concrete, or wood, these include: durability, strength, elasticity, toughness, combustibility, and resistance to decomposition.

Durability

Durability is the ability of a material to withstand outside forces while sustaining minimal wear, fatigue, or damage. In a 1994 paper written by Lewry and Creswdon, several factors were identified that impact the durability of a product. These include weathering, stress, biological attack, incompatibility, and use. Lewry and Creswdon suggest that a contextual evaluation of these causes is the best way to determine the significant causes of degradation and that the best metric that could be used to measure durability is the service life of the product.

Service life estimates for framing-system materials are available from a variety of sources but follow the same general pattern as indicated below.

Years	Non-Residential	Utility Poles	Architect Survey
Steel	83	80	78
Concrete	81	60	84
Timber	69	50	50
Laminate	65	-	
	costmodeling.com	IVL - SRI	Dovetail

Material Service Life Estimates

Steel had the highest years of service life in both nonresidential and utility pole construction when compared to concrete and wood, according to studies by costmodeling.com and IVL-SRI.

In addition, of the three materials, wood was ranked last in durability in a survey of 910 design and construction professionals conducted by FMI Management Consultants. While both concrete and steel were ranked highly, steel's durability was considered its leading benefit.

Strength

Steel is the strongest of the typical building materials. The design strength of most hot-rolled structural steel sections in use today is 50 ksi (50,000 psi) in both tension and compression, with special applications using sections with strengths as high as 70 ksi. Compressive strength for concrete is typically between 3 ksi and 5 ksi, with some applications calling for high-strength concrete with compressive strengths as high as 15 ksi. Concrete tensile strength averages about 10 percent of concrete's compressive strength or in the range of 0.5 ksi. The weakness of concrete in tension requires the addition of reinforcing steel in a building's beams and columns. The compressive strength of wood varies by the variety of wood, moisture content, and whether the load is applied parallel or perpendicular to the grain of the wood. Hardwoods have compressive strengths parallel to the grain in the range of 7 ksi to 10 ksi (1 ksi perpendicular to the grain), while softwoods range from 5 ksi to 8 ksi parallel to the grain (under 1 ksi perpendicular to the grain). The tensile strength of wood perpendicular to the grain averages about 1 ksi. While wood is relatively weak in tension perpendicular to the grain, it is strong in tension parallel to the grain, exhibiting strengths in the range of 10 ksi.

	Compressive Strength		Tensile Strength	
	Parallel to Grain	Perpendicular to Grain	Parallel to Grain	Perpendicular to Grain
Hardwoods	7–10 ksi	1 ksi	10 ksi	<1 ksi
Softwoods	5–8 ksi	1 ksi	10 ksi	<1 ksi
Concrete	5 ksi (high strength 15 ksi)		0.5 ksi	
Structural Steel	50 ksi (as high as 70 ksi)		50 ksi (as high as 70 ksi)	

Material Strength Comparison

The fact that the compressive and tensile strengths of structural steel are identical is a major factor in the ability of a structural steel framing system to resist and respond to extreme events. In an extreme event, unanticipated loads are often experienced by the structure. In many cases, this is not just an increase in an anticipated load, but rather the structural member unexpectedly transitions from being in compression to being in tension. Steel's equal ability to handle compressive and tension loads helps to mitigate any failure that may result from this condition.

PREVENTING DISASTERS

A tragic example of an extreme event resulting in a building failure and a significant loss of life was the collapse of the Murrah Federal Building in Oklahoma City, Oklahoma, due to a terrorist bomb blast. A FEMA study of the failure (FEMA 277) concluded that several factors contributed to the cause of the progressive collapse, including the lack of continuity reinforcement in the concrete transfer girders and floor slabs and the detailing of the concrete columns, which did not provide the redundancy and ductility required for the additional demands on the columns. National Institute of Science and Technology (NIST) later conducted a study that demonstrated that had the building been framed in structural steel, the ductility and tensile strength of an equivalently designed steel column would not have resulted in the failure of the critical column and progressive collapse of the building.

Strength Predictability

The importance of material strength as a factor of resilience is not confined to the strength alone but also the predictability of that strength. Structural steel is produced as a manufactured product complying with an ASTM standard specifying a minimum strength. When it arrives on the project site it is at a predictable full strength. This is not the case with either concrete or wood. Concrete strengths are specified in the contract documents, a mix design is determined, and the material is placed in a wet state at the project site. The mix is typically designed to reach or exceed design strength 28 days after placement, which is verified by a testing service. During the 28-day period or following that period if the test specimen fails to reach the design strength, the structure under construction has a greater degree of vulnerability to the impact of extreme events. Wood is even more problematic in that the strength of a single variety of wood can vary greatly based on moisture content, growth patterns, and the alignment of the member with the grain of the wood. This unpredictability is reflected in the large number of reduction factors applied to wood strengths during design. With steel, the capacity you want is the capacity you get.

Elasticity

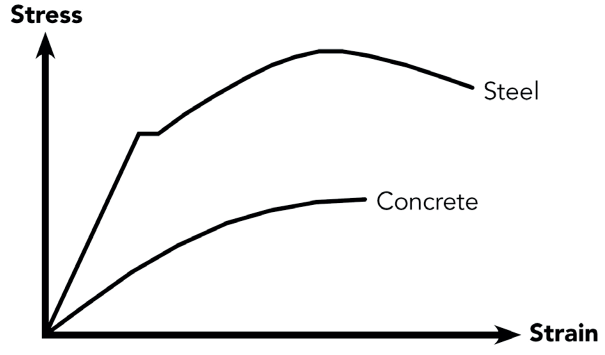
Elasticity is the ability of a material to be deformed and return to its original shape and maintain its material properties. The greater the resistance to change, the greater is the elasticity of the material and the faster it returns to its original shape or configuration when the deforming force is removed. In other words, elasticity is measured as ratio of stress to strain. For a given stress (stretching force per unit area), strain is much smaller in steel than in wood or concrete, resulting in a higher modulus of elasticity and an enhanced capability for handling extreme loads without cracking or permanently deforming. Similarly, the ductility of a material such as structural steel allows for the redistribution of forces to provide an alternate load path or to accommodate displacements caused by extreme events.

	Modulus of Elasticity
Wood	≈ 3.5 ksi
Concrete	≈ 1.5 ksi
Structural Steel	≈ 29 ksi

Comparison of Modulus Elasticity

Toughness

Toughness is a measure of durability that is actually a combination of the two attributes just discussed. Toughness is the ability of the material to resist permanent deformation, fracturing, and cracking. It can be best measured as the area under the stress-strain curve. In order to be tough, a material must be both strong and ductile. For example, brittle materials (like ceramics) that are strong but with limited ductility are not tough; conversely, very ductile materials with low strengths are also not tough. To be tough, a material should withstand both high stresses and high strains. Generally speaking, strength indicates how much force the material can support, while toughness indicates how much energy a material can absorb before rupturing.



Stress-Strain Curve for Steel and Concrete

Steel is a much tougher material than concrete. Wood toughness varies greatly by species, water content, and the alignment of the grain, but even the toughest of wood does not achieve the same level of toughness as structural steel.

Combustibility

Combustibility refers to a material's ability to burn. Materials that are combustible will burn; materials that are noncombustible will not burn. Structural steel and concrete are classified by the International Building Code as noncombustible materials. Wood is classified as a combustible material because it can burn. Under extreme fire loads, concrete is subject to spalling, exposing the steel reinforcement while structural steel's load-carrying capability will be reduced. To overcome the loss of load-carrying capability, an insulating covering may be placed around the structural steel to slow the loss of strength, allowing occupant departure and providing time for the fire to be extinguished. As the heat abates, the structural steel will return to its full strength, allowing the effects of the fire to be mitigated and the building returned to service. This is not the case with wood. Wood burns. And even if it is argued that wood simply chars, the cross-sectional area of the section is reduced, minimizing protection in the event of a second fire and reducing the cross-sectional area available to carry the structural load.

An unfortunate casualty of wood's combustibility was the Da Vinci apartment building in Los Angeles. In December 2014, the wood-framed apartment building still under construction burned to the ground. After the massive blaze that consumed the building, the only feature that remained intact were the noncombustible steel-framed stairs.


In December 2014, the Da Vinci Apartments that were under construction in Los Angeles burned down. After the massive blaze, only the steel-framed stairs remained.

When a building built from wood burns, the building burns. When a building built from steel or concrete burns, the structure remains intact while the contents of the building burn

Resistance to Decomposition

All materials are at risk of decomposition over time. Environmental factors such as humidity, moisture and air intrusion, mold, and mildew can cause a structure to deteriorate. When selecting a material, it is important to consider its resistance to decomposition in the climate zone where the construction will occur.

Steel and concrete, unlike wood, are inorganic and won't provide a source for mold, mildew, or structural deterioration (rot) to propagate. In wood structures, rot can compromise the structural integrity of the building, while mold and mildew compromise the health of the occupants.

One of structural steel's major advantages when compared to other materials is that steel will not absorb water in a flood situation or provide a moisture reservoir after the event. This is in contrast to concrete, where all surfaces contain micro-cracks that can serve as paths for water to migrate to the reinforcing steel inside the concrete, resulting in corrosion of the steel and spalling of the concrete. Structural steel is not immune to the impacts of water inundation, as corrosion on the surface of the steel may occur over time. This can be prevented from occurring in locations where the structural steel may be exposed to flooding or other possible corrosive factors, as paint or galvanized coatings can be applied that will provide protection. These coatings will provide protection for an extended period, which will often exceed the anticipated service life of the structural steel. Corrosion detected on structural steel members during regular maintenance inspections is a surface condition that does not compromise the strength of the member. This corrosion can be addressed by cleaning the steel and applying a protective coating such as paint to the affected area.

For a wood structure, decomposition can also be caused by pest infestation. Termite damage to buildings in the United States results in more than $5 billion annually. Structural steel and concrete are not subject to termite and pest damage.

While not actual physical properties, two additional factors contribute to the resilience of any particular material.

Design Redundancy

Unlike mix-dependent concrete or the variability of wood, structural steel provides additional redundancy and performs in a consistent and predictable manner as part of a structural system. Redundant load paths due to steel's natural ductility and reserve strength capacity provide additional structural capacity and resistance. In the design process, shapes are selected from a defined list, and if load requirements fall in between two shapes, the larger section is selected providing additional strength beyond the basic design requirement. The design strength of the steel (Fy and Fu) is not the actual strength of the steel. The average actual strength of steel, which is greater than the design strength, can be estimated using the Ry and Rt multipliers found in the AISC Seismic Provisions. While these values should not be used in routine design, they can be used to evaluate the resilience of the structure. Additional strength is also gained when beams are selected based on serviceability considerations of deflection criteria, floor vibration, or drift.

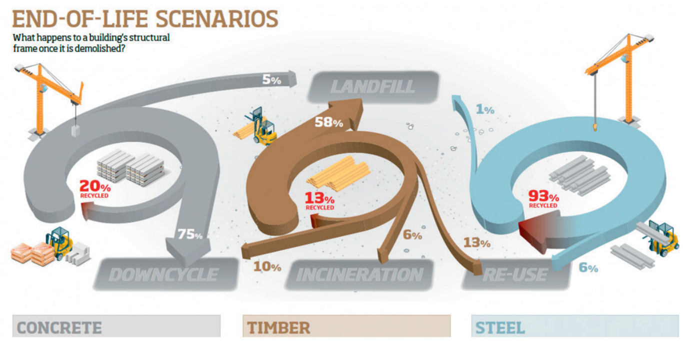
Rapidity of Repair

To fully appreciate the required resiliency of a building is not only to assess the level of damage and the cost of repairs but also the amount of time required to return the building to functionality. The required time to return to functionality is a function of the criticality of the services provided in the building and should be taken into account in the initial design of the building. The return of a building to functionality may require the repair of the structural system, the replacement of structural components, and the temporary removal of portions of the structural frame to gain access to other building service components that may need to be repaired or replaced. Unlike concrete framing systems that would typically require demolition and replacement or wood systems that face the challenge of replacing numerous structural members after a flood or fire, structural steel can be strengthened in place through the use of doublers and stiffeners, structural members can be added, and beams can be penetrated to allow the addition of other services. And this can be done using materials that are readily available through a network of local steel service centers and fabricators.

After the Extreme Event

Extreme events that impact an entire community rather than just a single building generate significant amounts of waste. The majority of this waste is wood. Wood waste will be either burned or landfilled. While some wood waste is reused in the normal construction cycle, it is most likely that the wood waste resulting from an extreme event will not be suitable for reuse.

Burning or landfilling wood releases greenhouse gases into the atmosphere. Burning also generates particulate matter harmful to human health. Landfilling requires sufficient landfill volume to be available to handle the increase flow of waste. While concrete may be crushed and down-cycled for use as road base, a significant portion is also landfilled. Structural steel on the other hand is a fully recyclable material with an active market for its sale. It will not end up in landfills but be returned to steel mills for recycling into new steel products. It will not be a burden on the community as it seeks to rebuild.



Graphic courtesy of BCSA

End-of-life scenarios for various building materials

When structures have to be renovated, remodeled, or rebuilt after a devastating event, utilizing a material that can be reused or recycled is beneficial from cost, convenience, and sustainability standpoints. Materials such as structural steel that can be quickly retrofitted, replaced, and eventually recycled make a positive impact on the environment and community. One-hundred percent of deconstructed steel structures can be recovered and recycled for the production of new steel. Currently, domestically produced structural steel has an average recycled content of 93 percent and a recovery rate of 98 percent.

CASE STUDY: TESLA GIGAFACTORY, SPARKS, NEVADA

The Tesla Gigafactory is being constructed with a fused rocking strongback frame.

The Tesla battery manufacturing facility, also known as the Gigafactory facility in Sparks, Nevada, is an excellent example of a building with a resilient structural steel framing system that draws on the robustness and redundancy of steel. The facility is designed with a fused rocking strongback frame that allows the lateral system to accommodate great variations in building configurations and equipment. The building was designed in multiple modules to minimize failure propagation throughout the overall structure and designed to be readily repairable in a 2,500-year earthquake. To ensure this level of resilience, the system uses buckling-restrained braces and Krawinkler fuses for maximum energy dissipation, with the strongbacks and foundations remaining elastic at full fuse yielding.

CONCLUSION

When considering building and community resilience, it is important to evaluate the contribution of framing materials to the overall resilience of the structure and its role in the community in terms of life safety, continuity of service, speed of recovery, and the cost of recovery. Structural steel is consistently the best choice for constructing resilient buildings that help support a community. Actuarially based insurance rates for steel compared to wood and concrete confirm the superiority of steel, as structural steel buildings are consistently less costly to insure due to the reduced risk of major damage, the cost of repair, and their ability to swiftly recover after an adverse event. In addition to insurance rate metrics, structural steel and structural framing systems consistently rank highly in each category of the four Rs: robustness, resourcefulness, recovery, and redundancy. Structural steel is a strong, durable material that allows the building to rapidly and economically return to service after an adverse event. The design and construction of resilient buildings requires a wise choice of framing material—structural steel is that stronger, smarter material.

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QUIZ

1. For the architectural community, which of the following is the most accurate definition of resilience?
   a. The ability of an object or system to withstand intense heat or cold
   b. The ability of an object or system to absorb and recover from an external shock
   c. The ability of an object or system to remain fully intact through any type of extreme event
   d. The ability of a community to successfully withstand high-wind events

2. Which of the following is not one of the four Rs of resilience?
   a. Radiation
   b. Robustness
   c. Resourcefulness
   d. Redundancy

3. For a building, how could redundancy best be illustrated?
   a. The ability to handle twice the normal load requirements
   b. The ability to prepare for and skillfully respond to a crisis or disruption.
   c. The ability of the structural framing system and the material from which the frame is constructed to provide additional load-carrying capacity
   d. The ability of critical services to maintain operations during and after an extreme event

4. What is one of the best measures of resiliency?
   a. Risk
   b. Efficiency
   c. Sustainability
   d. Cost savings

5. Insurance rates for structural steel-framed buildings are significantly lower than the rates for buildings framed in wood or concrete.
   a. True
   b. False

6. In the scope of resilience, how is durability defined?
   a. The ability of a material to withstand terrorist events
   b. The ability of a material to resist natural deterioration
   c. The ability of a material to be fireproof and waterproof
   d. The ability of a material to withstand outside forces while sustaining minimal wear, fatigue, or damage

7. What are the two strength measures used to evaluate a building material?
   a. Elasticity and durability
   b. Compressive and tensile
   c. Density and mass
   d. Strain and sustainability

8. For building materials, what is elasticity?
   a. The ability of a material to be deformed and return to its original shape and maintain its material properties
   b. The ability of a material to withstand extreme external shocks without any deformation
   c. The ability of a material to maintain security elements within the community
   d. The ability of a material to resist significant failure in all situations and exposures

9. Which of the following materials will not absorb water in a flood situation?
   a. Wood
   b. Concrete
   c. Steel
   d. All of the above

10. On average, what percentage of domestically produced structural steel is recycled content?
    a. 18 percent
    b. 42 percent
    c. 93 percent
    d. 100 percen
