The Impact of Material Selection on the Resilience of Buildings

A White Paper by the
American Institute of Steel Construction
April 2017

Executive Summary

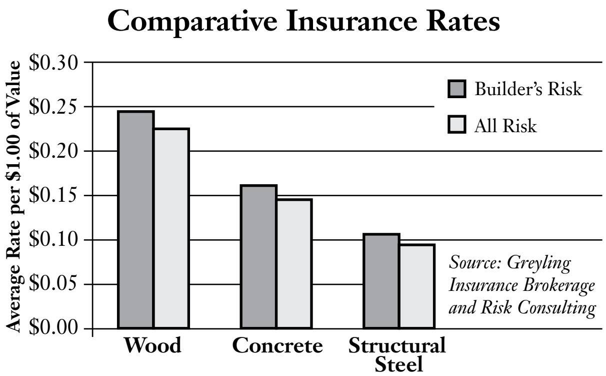
Resilience is the ability of an object or system to absorb and recover from an external shock. The material selection for a building's structural framing system impacts the resilience of the structure by reducing the cost of the risk associated with the ability of the structure to absorb and recover from the stress of an extreme event. Of all the materials used for structural framing systems, structural steel has demonstrated the greatest level of resilience relative to extreme events. This is verified by significantly lower Builder's Risk and All Risk premiums in the current insurance market for structural steel framing systems compared to concrete and wood. The reasons for these lower rates and the greater resilience of buildings built with structural steel is structural steel's inherent durability, strength, elasticity, non-combustibility, and resistance to decomposition. It also is helped by the capability of structural steel framing systems to resist extreme loads, be rapidly repaired, and adapt to changing structural requirements.

How can resilience be quantified?

Addressing resilience in building design is like purchasing insurance: you hope you don't need it but you're grateful if you ever do...[1] The difference is that instead of buying insurance throughout the life of a building to cover the risk of an extreme event, you design for resilience up front. And the result is that a building is better able to recover from an extreme event, be it natural (such as an earthquake or hurricane) or human induced (such as a terrorist attack or fire).It might seem that quantifying that risk and those damages would be difficult. It is not. Insurance companies regularly assess the loss records of buildings subject to both anticipated and extreme events. It is from those actuarial studies that insurance rates are set. For a given set of risks, a lower rate means less damage and a lower cost of repair. For the same building in the same location framed with different building materials, current insurance rates per $100 of value in today's market for Builder's Risk (insurance insuring the building during construction) and All Risk (insurance purchased by the owner insuring the building after occupancy) will be in the following ranges[2]:

	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

Obviously, these rates will change based on project location and the particular risks associated with that locale or if the project has a specialized feature or aspect. But the general trend is the same. Insurance rates for wood buildings and concrete buildings are 2.3 and 1.5 times higher, respectively, than for structural



steel framed buildings. 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 compared to a wood framing system.

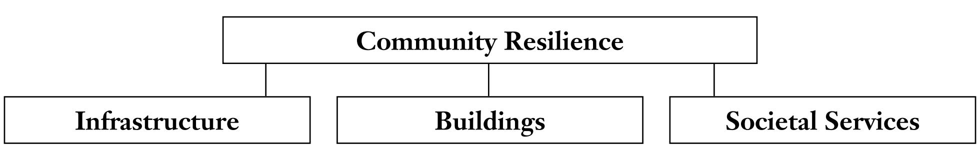
Why? The structural steel system is simply more resilient.

What is resilience?

Resilience is the ability of an object or system to absorb and recover from an external shock. A simple concept, but for today's design and construction professional resilience has taken on an increased level of importance and a broader context. Resilience has become the new buzzword supplanting the past decade's focus on sustainability. For some the discussion of resilience focuses on the resilience of a community to be able "to withstand or bounce back quickly following major disruptions ensuring that critical infrastructures have continuity of service (especially water, energy, transportation and communication lifelines); emergency services; and local governance."[3] Inherent in that definition is ability of critical infrastructure components to be resilient in their own right maintaining or rapidly recovering functionality from disruptive events such as earthquakes, intense storms, coastal flooding or terrorism.[4]

At the same time, all of the buildings in the community must be able to provide occupant safety during the event and a some of those building must be able to continue providing critical services. In essence, resilience is the ability of a community, an infrastructure system or a building to anticipate, prepare for and adapt to changing conditions, and withstand, respond to and recover rapidly from disruptions.[5] It is defined by the 4R's—robustness, resourcefulness, recovery and redundancy.[6]

Community resilience is built on the building blocks of its infrastructure, buildings and essential societal services such as police, fire, health and governance.



Any discussion of resilience becomes more complex when the discussion extends beyond the three building blocks of community sustainability to extreme events, often referred to as “stressors” that need to be accounted for. *Natural events* such as hurricanes, tornados, wildfires, earthquakes, flooding and tsunamis are generally included, yet not all of these stressors have the same likelihood of occurrence in every community; some may never occur in some communities. Events resulting from *human activity* including arson and terrorism also need to be considered. In some cases *technological events* with no direct natural or human cause such as the faulting of an electric grid or the overloading of a communications gateway are included. And finally the anticipation of *future environmental events* such as increased storm intensity, elevated water levels and increased snow loads driven by global climate change may also need to be taken into account. Clearly, any discussion of resilience is a multi-dimensioned challenge combining discrete components, stressors, risk assessments and future trends.

The result is that every group discussing resilience comes to the topic with its own perspective, develops its own definition, sets its own priorities and drives the discussion down a different path. Perhaps the definition of resilience developed by the Rockefeller Foundation summarizes resilience best by stating “resilience means different things across a variety of disciplines, but all definitions are linked to the ability of a system, entity, community or person to withstand shocks while still maintaining its essential functions. Resilience also refers to an ability to recover from catastrophe, and a capability of enduring greater stress.”[7]

How does framing system selection impact resilience?

So, why is the cost of risk less with a structural steel framed building compare to buildings framed with concrete or wood? What does that difference mean to an owner preparing to build a new building or to an architect or structural engineer selecting and designing the structural framing system of a building? And how does the demand for structural resilience balance with the inevitable consideration of cost? Simply put it means that selecting a structural steel framing system provides the greatest ability to withstand, respond to and recover rapidly from extreme events in a cost effective manner based on the level of anticipated risk.

At the same time the resilience of that structural framing system needs to take into account the underlying resilience of the material composing that framing system.

Building Resilience
Structural System Resilience
Material Resilience

Material Resilience

When the resilience of a material is assessed the primary attributes of the material must be evaluated. For a structural framing material like structural steel, concrete or wood these would include durability, strength, elasticity, combustibility and resistance to decomposition.

Durability is the ability of the material to withstand outside forces in a manner which results in minimal wear, fatigue or damage. Of the major building materials wood was ranked last in durability in a survey of 910 design and construction professionals conducted by FMI.[8] Both concrete and steel were rated highly with steel's durability considered its leading benefit. Durability was topped only by fire resistance as wood's leading weaknesses.

Strength – Steel is the strongest of the common framing 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 some common special applications using sections with strengths higher than 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% of concrete's compressive strength or in the range of 0.5 ksi.[9] 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.[10]

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. In addition, the actual strength of the structural steel exceeds the stated minimum compressive and tensile strengths of the specified grade providing additional strength to handle unanticipated loads.

	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)	

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).[11] NIST (National Institute of Science and Technology) 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 the progressive collapse of the building—85% of the damage—would not have occurred.[12]

The importance of material strength as a factor of resilience is not confined to 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 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 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

Combustibility – Structural steel and concrete are classified by the *International Building Code* as non-combustible materials: they do not burn. Wood is classified as a combustible material.[13] Under extreme fire loads concrete is subject to spalling which may expose steel reinforcement and reduce its load carrying capability. Structural steel also may lose load carrying capability during a fire and therefore 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, repairs made, and the building returned to service. This is not the case with wood. Wood burns. The resulting char reduces the cross-sectional area of the section, minimizing protection in the event of a second fire and reducing the cross-sectional area available to resist deflections and carry the structural load.

Resistance to Decomposition – Floods and rising water levels due to tsunamis and hurricanes can cause water to come in contact with portions of the structural framing system. While the wisest approach is to design the building above the floodplain (or anticipated floodplain due to the impacts of global climate change) to avoid this issue it may not be possible to do so and the structure must be designed to handle potential water inundation. Damage from water inundation does not typically result in the failure of the structure unless the foundation is compromised. Damage from water inundation is a long term problem slowly compromising the framing materials from a strength or health perspective. 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 comprise the structural integrity of the building while mold and mildew compromise the health of the occupants. Compared to wood, steel will not absorb water in a flood situation or provide a moisture reservoir when the flood condition has concluded and the humidity levels are receding. All concrete surfaces contain micro-cracks that can serve as path for water to migrate to the reinforcing steel inside the concrete and cause corrosion of the steel resulting in 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. To prevent corrosion from occurring in locations where the structural steel may be exposed to flooding or other corrosive factors, paint or galvanized coatings can be applied that will provide protection for an extended period which (often exceeding the anticipated service life of the structure). If corrosion is detected on structural steel members during regular maintenance inspections, it is usually a surface condition that does not compromise the strength of the member and unlike concrete reinforcing steel can be addressed by cleaning the steel and applying a protective coating, such as paint,to the affected area.

For a wood structures, decomposition can also be caused by pest infestation. Termite damage to buildings in the United States results in more than $5 billion annually.[14] Structural steel and concrete are not subject to termite and pest damage.

Structural System Resilience

Structural framing systems can be designed to satisfy building code requirements using structural steel, concrete and wood. The central purpose of building code provisions is to provide short-term human survivability and safety in the event of an extreme event. The *International Building Code* in Section 1604 even includes enhanced designed requirements and integrity checks for high-rise buildings in risk category III or IV.[15] In those cases structural integrity is evaluated independently, not in combination with other effects and deformations are allowed as long as failure does not occur. The goal is to provide for the redistribution of loads in the event of damage. A competent structural engineer can accomplish this using structural steel, concrete or wood. But the question isn't whether those design goals can be accomplished using any of these materials, but the efficiency of using that material in the design, the cost of the system, the level of additional redundancy gained by the system and the ease and speed of repair if the structural system is damaged in an extreme event.

It is not an efficient use of building materials if addressing the design requirements of high-risk buildings requires a bunker style solution necessitating significantly increased material quantities. Increasing the mass of a structure, particularly a concrete structure, to address the challenges presented by extreme events is not an efficient solution. In contrast, structural steel supports a multitude of design approaches and innovative systems that address the challenge of resilient design from a technical rather than an increased mass perspective. Steel provides multiple options for lateral load resistance in a highly ductile environment that allows adequate member deformation while still keeping access to critical services intact and operational. The use of systems with specially designed connections and buckling restrained braces as structural fuses allow a structure to withstand an extreme event resulting from an earthquake, high winds or blast. If damage occurs to the structural system these components (the "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.

An excellent example of a resilient structural steel framing system is the Tesla battery manufacturing facility, the Gigafactory, in Sparks, Nevada. The facility is designed with a fused rocking strongback frame that allows the lateral system to accommodate great variations in building configurations and equipment while ensuring that the building will not collapse and be readily repairable in a 2,500-year earthquake. The system uses buckling restrained braces and Krawinkler Fuses for maximum energy dissipation while the strongbacks and foundations remain elastic at full fuse yielding.

Unlike mix-dependent concrete or the variability of wood, structural steel provides additional redundancy and performs in a consistent and predictable manner as 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 (F_y and F_u) is not the actual strength of the steel. The average actual strength of steel which is greater than the design strength can estimated using the R_y and R_t multipliers found in the AISC *Seismic Provisions*.[16] While these values should not be used in routine design they can—and should—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.

Building Resilience

The resilience of the framing material and the selection of a structural framing system using that material contribute directly to the resilience of the building. Additional factors not related to the structural frame of the building also impact the overall resilience of the structure and in some cases the selection of the structural framing material can benefit those factors.

For instance, in an area at risk from flooding, hurricanes and tsunamis it may not be possible for the building to be located above the floodplain. The building can be built with the occupied floors elevated above the flood level. This can be accomplished by using slender members to create stilts to support the building or designing a lower level to function as a garage or utility space where the flood waters can pass through without harming the structure or any contents. As discussed previously, structural steel is the ideal framing material for such a system.

To fully appreciate the required resilience 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 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.

Community Resilience

Community resilience is the ability of the community to withstand the stress of an extreme event. Community resilience is a combination of infrastructure, building and societal resilience. As such, the selection of the material for a structural framing system of a particular building with a specified level of serviceability may seem rather distant from the community as a whole. It is. Yet, the proper selection of building materials does contribute to overall community recovery and performance. This is probably no more evident than in the area of waste management.

Extreme events that impact an entire community rather than just a single building generate significant amounts of waste of which the majority is wood. Wood waste will be either burned or landfilled. While some wood waste is reused or recycled 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.[18] Landfilling requires sufficient landfill volume to be available to handle the increased flow of waste. While concrete may be crushed and down-cycled for use as road base, it is also often 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 the community seeks to rebuild. Deconstruction of a structural steel building can often occur at no cost to the building owner as the demolition contractor will offset their costs with the income gained from the sale of the steel. This is not true for concrete framed buildings where a greater percentage of the waste flows to a landfill and particularly not true for wood framed structures where nearly all the waste must be landfilled.

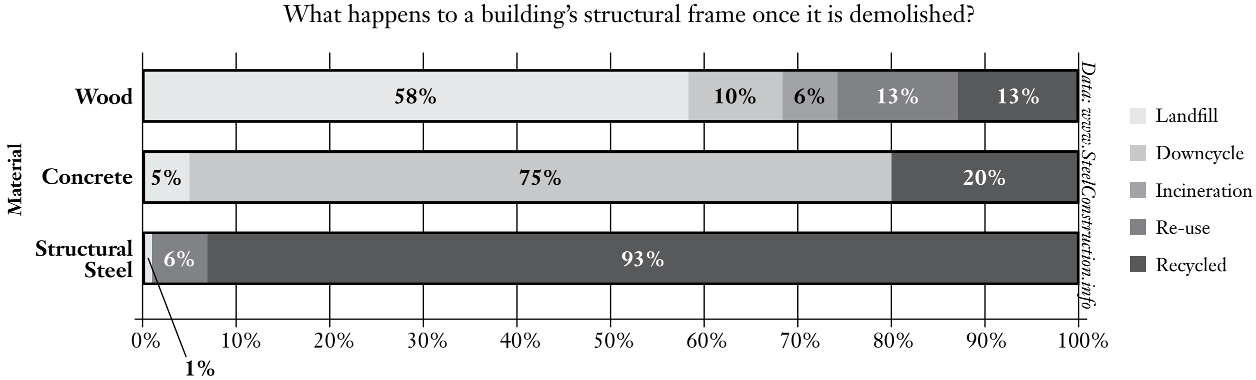
When structures have to be renovated, remodeled, or rebuilt after a devastating event, utilizing a material that can be reused or recycled is beneficial from a cost, convenience and sustainable standpoint. Materials, such as structural steel, that can be quickly retrofitted, replaced and eventually recycled make a positive impact on the environment and community. 100% of deconstructed steel structures can be recovered and recycled for the production of new steel (domestically produced structural steel has an average recycled content of 93% and a recovery rate of 98%).

There is also a balance point when it comes to sustainable design. The concrete industry has long argued that the load requirements in the building codes be increased to minimize the level of damage caused by extreme events and thereby minimize the amount of waste generated and replacement material required. While this may seem reasonable on the surface, there is a potential unintended consequence. By increasing the load requirements significantly, more material will be required to meet those requirements, particularly when a concrete framing system is used. Extreme events impact only a small percentage of structures, yet increasing the load requirements for buildings will impact all buildings. If this bunker mentality is adopted all buildings would need to be overbuilt resulting in greater construction costs and more material being required to build these buildings than would have been required to reconstruct the buildings damaged in an extreme event. The solution is not to build bunkers but to use resilient materials to address the challenge of resilient design from a technical rather than a mass based perspective.

Community resilience also assumes that some buildings will be used to provide housing and work areas for the population even before energy based infrastructure services are reestablished. This requires these buildings to be able to maintain passive survivability during this period by maintaining livable temperature levels. It has been shown that structural steel buildings with concrete floor and wall systems designed to maximize the thermal capacity of the building and proper detailing of areas where thermal bridging may occur can effectively address the issue of thermal capacity.[18]

End-of-Life Scenarios

What happens to a building's structural frame once it is demolished?



What's the Bottom Line?

Structural steel contributes the most of any material you can choose to the resilience of the structural framing system, the building supported by that system and the community of which the building is a part.

It is not surprising that insurance rates for structural steel framed buildings are less than the rates for comparable wood and concrete framed buildings facing the same level of risk from extreme events. Compared to other building materials structural steel is a highly resilient material that can be effectively used in the design and construction of structural framing systems that are also highly resilient. The potential savings in repair costs and the rapidity of that repair reduces the exposure of the insurance carrier resulting in the lower rates.

All levels of resilience are often discussed in terms of the 4R's—robustness, resourcefulness, recovery and redundancy. Structural steel, structural steel framing systems and buildings supported by structural steel framing systems rank highly in each of those categories. Structural steel is a strong, durable material that provides for innovative, efficient structural systems with inherent redundancy that can be rapidly returned to service following an extreme event. A resilient outcome for the building owner and the community in which the building is located that is superior to that of wood or concrete.

References

[1] Alex Wilson, *The BuildingGreen Report*, "20 Ways to Advance Sustainability in the Next Four Years", January, 2017.

[2] Informational quote provided by Greyling Insurance Brokerage and Risk Consulting, Alpharetta, GA. Similar information relative to insurance rates for wood structures can be found in the *Claims Journal* (article online at **www.claimsjournal.com/news/international/2016/03/23/269612.htm**) and on the Steel Framing Industry Association at **https://sfia.memberclicks.net/assets/FactSheets/insurance%20savings%20with%20cfs.pdf**

[3] National Institute of Building Sciences (NIBS), "Critical Infrastructure Security and Resilience Risk Management", published at **https://www.nibs.org/?page=irdp_projects**

[4] National Institute of Science and Technology (NIST), *Community Resilience Planning Guide for Buildings and Infrastructure Systems*, Publication 1190, October, 2015.

[5] H.R. 2241 – Disaster Savings and Resilient Construction Act of 2013 (Pending Action)

[6] American Institute of Architects, Architectural Graphic Standards, 12th Edition, *Chapter 3 Building Resiliency*, page 108. John Wiley & Sons, 2016.

[7] Rockefeller Foundation, **https://www.rockefellerfoundation.org/our-work/topics/resilience/**

[8] FMI Management Consultants, *Structural Steel Market Assessment*, January, 2012 (not published)

[9] American Concrete Institute (ACI) 36-R10, "Report on High Strength Concrete", 2010

[10] **http://www.woodworkweb.com/woodwork-topics/wood/146-wood-strengths.html**

[11] Federal Emergency Management Agency (FEMA), The Oklahoma City Bombing, FEMA 277, August, 1996.

[12] Federal Emergency Management Agency (FEMA), Blast-Resistant Benefits of Seismic Design: Phase 2 Study: Performance Analysis of Structural Steel Strengthening Systems, FEMA P-439B, November, 2010.

[13] International Code Commission (ICC), International Building Code, 2015 Edition, Chapter 6.

[14] Orkin, Inc., **https://www.termites.com/information/statistics/recent-statistics-about-termite-damage/**

[15] International Code Commission (ICC), International Building Code, 2015 Edition, Section 1604.

[16] American Institute of Steel Construction (AISC), Seismic Design Manual, 2nd Edition, "Seismic Provisions for Structural Steel Buildings", 9.1-9, September, 2012.

[17] US Environmental Protection Agency (USEPA), "Wood Smoke and Your Health", **https://www.epa.gov/burnwise/wood-smoke-and-your-health**

[18] Gorgolewski, M., *Modern Steel Construction*, "Framing Systems and Thermal Mass", January, 2007.

There's always a solution in steel.

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